Cassava
in the Third Millennium

Modern Production, Processing, Use, and Marketing Systems

CIAT 45
Centro Internacional de Agricultura Tropical
International Center for Tropical Agriculture
A Remarkable Record of Science for Change
Since 1967

CLAYUCA
Latin American and Caribbean Consortium to Support Cassava Research and Development

CTA

CIAT
The International Center for Tropical Agriculture (CIAT) – a member of the CGIAR Consortium – develops technologies, innovative methods, and new knowledge that better enable farmers, especially smallholders, to make agriculture eco-efficient – that is, competitive and profitable as well as sustainable and resilient. Eco-efficient agriculture reduces hunger and poverty, improves human nutrition, and offers solutions to environmental degradation and climate change in the tropics. Headquartered near Cali, Colombia, CIAT conducts research for development in tropical regions of Latin America, Africa, and Asia.
www.ciat.cgiar.org

CGIAR is a global research partnership for a food secure future. Its science is carried out by the 15 research centers of the CGIAR Consortium in collaboration with hundreds of partner organizations.
www.cgiar.org

CLAYUCA
The Latin American and Caribbean Consortium to Support Cassava Research and Development (CLAYUCA, Consorcio Latinoamericano y del Caribe de Apoyo a la Investigación y al Desarrollo de la Yuca) is a network operating through collaborative agreements between its members, public and private entities. The membership of CLAYUCA includes as of 2012, Colombia, Costa Rica, Ecuador, Guyana, Mexico, Nicaragua, Panama, Trinidad and Tobago, and Venezuela, as well as Ghana, China, and the United States.
www.clayuca.org

CTA
The Technical Centre for Agricultural and Rural Cooperation (CTA) is a joint international institution of the African, Caribbean and Pacific (ACP) Group of States and the European Union (EU). Its mission is to advance food and nutritional security, increase prosperity and encourage sound natural resource management in ACP countries. It provides access to information and knowledge, facilitates policy dialogue and strengthens the capacity of agricultural and rural development institutions and communities.

CTA operates under the framework of the Cotonou Agreement and is funded by the EU.
www.cta.int

ISBN (CIAT): 978-958-694-112-9
ISBN (CTA): 978-92-9081-503-7

Cassava
in the Third Millennium

Modern Production, Processing, Use, and Marketing Systems

Compilation and direction:

Bernardo Ospina, Agr. Eng., M.Sc.
Hernán Ceballos, Ph.D.

CIAT 45
Centro Internacional de Agricultura Tropical
International Center for Tropical Agriculture
A Remarkable Record of Science for Change
Since 1967

CLAYUCA
Latin American and Caribbean Consortium to Support Cassava Research and Development

CTA

ISBN (CIAT): 978-958-694-112-9
ISBN (CTA): 978-92-9081-503-7

Apartado Aéreo 6713
Cali, Colombia
Phone: +57 2 4450000
Fax: +57 2 4450073
E-mail: b.ospina@cgiar.org / h.ceballos@cgiar.org
Website: www.ciat.cgiar.org

CIAT Publication No. 377
Press run: 1250
Printed in Colombia
June 2012

Cassava in the third millennium : modern production, processing, use, and marketing systems / Compiled and directed by: Bernardo Ospina and Hernán Ceballos. -- Cali, Colombia : Centro Internacional de Agricultura Tropical (CIAT) ; Latin American and Caribbean Consortium to Support Cassava Research and Development (CLAYUCA) ; Technical Centre for Agricultural and Rural Cooperation (CTA), 2012.
574 p. -- (CIAT publication no. 377)
ISBN (CIAT): 978-958-694-112-9
ISBN (CTA): 978-92-9081-503-7

Original version in Spanish under the title *La Yuca en el Tercer Milenio: Sistemas Modernos de Producción, Procesamiento, Utilización y Comercialización.* © CIAT. 2002

This book is accompanied by the Practical Handbook for Managing Cassava Diseases, Pests, and Nutritional Disorders / Elizabeth Álvarez, Anthony Bellotti, Lee Calvert, Bernardo Arias, Luis Fernando Cadavid, Benjamín Pineda, Germán Llano, and Maritza Cuervo (115 p.).
ISBN (CIAT): 978-958-694-113-6
ISBN (CTA): 978-92-9081-504-4

Descriptors in English:
1. *Manihot esculenta*. 2. Cultivation. 3. Fertilizer application. 4. Soil conservation. 5. Weed control. 6. Disease control. 7. Pest control. 8. Genetic resources. 9. Plant breeding. 10. Harvesting. 11. Postharvest technology. 12. Byproducts. 13. Marketing. 14. Cassava.

Descriptors in Spanish:
1. *Manihot esculenta*. 2. Cultivo. 3. Aplicación de abonos. 4. Conservación de suelos. 5. Escarda. 6. Control de enfermedades. 7. Control de plagas. 8. Recursos genéticos. 9. Fitomejoramiento. 10. Cosecha. 11. Tecnología postcosecha. 12. Subproductos. 13. Mercadeo. 14. Yuca.

I. Tit. II. Ospina, Bernardo. III. Ceballos, Hernán. IV. Alvarez, Elizabeth. V. Bellotti, Anthony. VI. Calvert, Lee. VII. Arias, Bernardo. VIII. Cadavid, Luis Fernando. IX. Pineda, Benjamín. X. Llano, Germán. XI. Cuervo, Maritza. XII. Centro Internacional de Agricultura Tropical. XIII. Latin American and Caribbean Consortium to Support Cassava Research and Development. XIV. Technical Centre for Agricultural and Rural Cooperation.

AGRIS subject category: F01 Cultivation

LC classification: SB 211. C3 C3774

Contents

Foreword

When CIAT published *La Yuca en el Tercer Milenio* (Cassava in the Third Millennium) in 2002, new cassava technologies were on the verge of making remarkable impacts on the lives of small producers who rely on the crop for income and food security. In Africa, research had already resulted in successful biological control of the devastating mealybug and green mite (through the use of natural enemies introduced from the Americas), thus preventing widespread hunger and huge economic losses. In Asia, new cassava varieties were demonstrating significant yield and quality advantages over local landraces on a large scale, especially in Thailand. These developments generated benefits whose value is estimated in the tens of billions of dollars.

But the benefits have not been evenly distributed, and this has taught us important lessons about technology development, particularly the need for continuously readjusting priorities. Invariably, farmers have benefited most where three conditions exist: (1) expanding markets (e.g., for starch or animal feed), (2) government policies that favor cassava research and extension, and (3) an interdisciplinary research approach, which has long-term financial and technical support.

For many years, cassava research was financed almost exclusively by the public sector. Vegetative propagation of cassava has posed a significant barrier to private sector participation, offering little scope for profitable marketing of new varieties. Nonetheless, processing industries have begun to recognize the advantage of supporting public research or at least assisting in the multiplication of new varieties with superior quality traits. While private investment still accounts for only a small part of the total effort aimed at improving technology for cassava production, this portion is growing and should continue to grow, as science brings new value-added traits to the marketplace.

The cassava industry was once based almost entirely on general-purpose starch and animal feed. In recent years, however, market demand has begun to diversify – especially with respect to starch functional properties and nutritional factors – and this is creating opportunities for improvement through crop genetics and postharvest processing. CIAT's 2006 discovery of an amylose-free (*waxy*) starch has created the possibility of niche markets for cassava starch and has prompted investment in the development of high-yielding waxy varieties. In addition, a *small-granule starch* resulting from induced mutation shows potential for more efficient hydrolysis in ethanol production. Meanwhile, yellow cassava with high beta-carotene content is attracting donor interest as a possible solution for vitamin A deficiency, especially in parts of Africa where this is a major health problem.

One of the great challenges for cassava, as for many crops, has to do with environmental sustainability. The problem is especially serious with cassava because of its well-known adaptation to fragile marginal environments characterized by acid soils, low soil fertility, and low or erratic rainfall. Though technologies are available for reversing land degradation in cassava production and for keeping productivity high through improved management of soil fertility, much more must be done to make these technologies accessible to farmers and provide better information about the benefits.

Further challenges will result from ongoing expansion of cassava within current production areas and into new ones. Given the crop's long production cycle, more intensive culture will create more favorable conditions for pests and diseases. Over the longer term, climate change will worsen drought stress in some areas and flooding in others. Changes in temperature and rainfall could have a strong effect on pest and pathogen distribution and severity.

In the face of new opportunities and challenges, cassava's good adaptation to difficult agricultural environments should enable it to thrive in the coming decades. The crop has much potential to enter a wide array of markets, but it is also vulnerable to a wide range of biotic and abiotic constraints. Substantial effort will be required to ensure cassava's market success and also ward off disease and pest threats. Research capacity must be renewed; research must be targeted more appropriately; and policies must be put in place that enable farmers to adopt improved practices, which sustainably increase their cassava productivity and incomes.

This volume summarizes the accumulated knowledge and experience gained by scientists with CIAT, the Latin American and Caribbean Consortium to Support Cassava Research and Development (CLAYUCA), and many partner organizations over more than 40 years. It is impossible for a single volume to cover all the relevant developments, so extensive references are included that point the reader to additional reading.

This book will be a valuable resource for scientists, extension workers, cassava growers and processors, manufacturers of machinery, and policy makers. The world of cassava research and development is rising quickly on the foundation of previous accomplishments. This volume is essential for understanding what has been achieved so far and for defining how best to address future challenges and opportunities.

Clair H. Hershey
Leader, CIAT Cassava Program

Preface

The International Center for Tropical Agriculture (CIAT), established in 1967 with headquarters near Cali, Colombia, works to combat hunger, poverty, and natural resource degradation through agricultural research for development in tropical regions of Latin America, Africa, and Asia. Within the Center's portfolio of technology options, cassava, a versatile and rugged root crop, figures importantly because of its role as the main source of sustenance for hundreds of millions of people. While helping strengthen food security for these people, the crop also provides many of them with opportunities for income and employment, particularly in marginal areas, where smallholder farmers predominate and growing conditions are typically harsh, characterized by poor soils and frequent drought.

CIAT's Cassava Program consists of a multidisciplinary scientific team, which generates a continuous flow of improved technologies for the production, processing, marketing, and use of cassava. To make the products of this research widely available, the Program works with partner organizations engaged in technology transfer, training, and other activities that promote the adoption and adaptation of new technologies by farmers and other end users.

One of the most effective ways in which CIAT can promote the uptake of research results is to provide technical information in print and electronic form. Combining scientific content with practical guidance, this material enables our partners to enrich and strengthen the knowledge and abilities needed to transfer improved cassava technologies more effectively.

Among the most successful examples of this approach at CIAT is the book titled *La Yuca en el Tercer Milenio* (Cassava in the Third Millennium), which was published in 2002 with financial support from Colombia's Ministry of Agriculture and Rural Development and the National Federation of Poultry Producers. With the aim of facilitating information access and exchange, the book documented a wide range of cassava technologies, some of which were new while others had been tested and proven through years of experience. The book was distributed to a wide audience within the cassava sector of Latin America and the Caribbean (LAC) and rapidly proved its value as a resource for technological change across the region.

Since then, further challenges and opportunities for cassava have emerged, as familiar problems have grown worse and new ones have arisen while demand and uses for the crop have continued to expand in LAC as well as in the dynamic cassava sectors of Africa and Asia. For this reason, CIAT researchers decided it was time to provide an update on recent advances, so that our partners can more easily stay abreast of innovative solutions and alternative strategies.

Another factor that influenced the decision consisted of important developments in international agricultural research for development. As a result of major reforms in the CGIAR, of which CIAT forms a part, new global programs are being created – including one on roots, tubers, and bananas – which provide a useful framework for integrating research across disciplines and regions.

Against this background, it seemed necessary not only to update *La Yuca en el Tercer Milenio* but to translate the new version into English together with the field handbook that accompanies it. The final product of this effort represents an important contribution to the exchange of experience and knowledge between cassava-producing regions of the developing world in support of cassava modernization.

We are grateful to the Technical Centre for Agricultural and Rural Cooperation (CTA), based in the Netherlands, for the generous financial support that

enabled us to undertake this work. We also wish to thank scientific staff at CIAT, colleagues with the Latin American Consortium to Support Cassava Research and Development (CLAYUCA), and other partners in various institutions and countries for their assistance in updating the scientific and technical content of the publication. Thanks are due as well to CIAT's Corporate Communications team for its enthusiastic support in the editing, design, and production phases.

Bernardo Ospina, M.Sc.
CLAYUCA

Hernán Ceballos, Ph.D.
CIAT Cassava Program

CHAPTER 1

Cassava in Colombia and the World: New Prospects for a Millennial Crop

Hernán Ceballos[1]

Introduction

Cassava (*Manihot esculenta* Crantz), together with maize, sugarcane, and rice, constitutes the most important source of energy in the tropics. Native to South America (Olsen and Schaal 2001), cassava was domesticated about 5000 years ago and has since been extensively cultivated in the tropics and subtropics of the continent. The first European travelers quickly recognized this crop's virtues and distributed it throughout the colonies that European countries held in Africa and Asia.

In South America, particularly in Brazil, cassava is known as *mandioca* (or "manioc" in English). The English name "cassava" may have derived from the word *casabi*, which, among the Arawak Indians, signifies "root" (FAO and IFAD 2000), or else came from the word *cazabe*, which is a cake or dry biscuit produced by the indigenous populations of the Amazon Basin (Cock 1989). In English, cassava is also known as "tapioca".

Until a few decades ago, cassava and its products were little known outside the tropics, where it had been cultivated for many years. This crop received little interest in other regions, partly because its products were not exported, and because the species does not adapt to temperate climates. However, the Centro Internacional de Agricultura Tropical (CIAT)[2], in Colombia, and the International Institute of Tropical Agriculture (IITA), in Nigeria, were created around 1970. For the first time, efforts were coordinated to improve the scientific bases of the crop (Cock 1989). Numerous countries have since developed successful cassava programs.

Currently, cassava is a very important crop in the tropics, that is, at latitudes of less than 30 degrees, and from sea level to 1800 m above sea level. Although, the principal economic product are its roots, cassava leaves also have excellent potential and are extensively used in Africa and Asia, as either human food or animal feed. Cassava is the fourth most important commodity after rice, wheat, and maize, and is a basic component in the diet of many millions of people (FAO and IFAD 2000).

According to Scott et al. (2000), for the period 1995 to 1997, world annual cassava production was 165.3 million tons, with an approximate value of US$8800 million.

In addition to the economic value of the products and byproducts obtained from cassava, this crop offers other recognized advantages: tolerance of drought, capacity to produce in degraded soils, resistance to pests and diseases, tolerance of acid soils (which are predominant in most of the world's tropical plains), and flexibility in planting and harvesting times.

In preparing this Chapter, the author formally recognizes three papers on which many of the sections here developed were based. These are, first, the 1989 Spanish version of *Cassava: new potential for a neglected crop* by James H Cock (1985). Many of the concerns and observations presented here were first mentioned by Cock in his book.

Second, *The world economy of cassava: facts, trends, and outlook*, published in Spanish. It was one of numerous publications prepared for the Validation Forum on the Global Cassava Development Strategy, held in April 2000, in Rome, Italy, by the Food and Agriculture Organization of the United Nations (FAO) and the International Fund for Agricultural Development (IFAD). Many of the statistical data presented here appear in this publication.

1. Breeder, Cassava Program, CIAT, Cali, Colombia. E-mail: h.ceballos@cgiar.org
2. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, and Abbreviations, Technical Terminology*, this volume.

Finally, *Roots and tubers for the 21st century: trends, projections, and policy options* by GJ Scott, MW Rosegrant, and C Ringler. This document is the source of numerous data that were very useful for the preparation of this Chapter.

World production statistics

Much of cassava is grown on small farms and in marginal agricultural areas. As a result, a significant proportion of production is inadequately recorded and specified in statistics. The best statistics available are those of the FAO reports, but even so, errors in estimates can be still quite large (Cock 1989).

Africa holds almost 62% of the total world area (Table 1-1) where cassava is planted, but only about 50% of the world's harvest (Table 1-2). In contrast, Asia produces 30% of the world's cassava in an area that represents almost 23% of the total, thus indicating that continent's high productivity (Table 1-3). In fact, India has the highest yields in the world, producing, in the period 1993/95, about 24.0 t/ha (FAO and IFAD 2000). Latin America and the Caribbean (LAC) possess about 16% of the world's area planted to cassava, but produces a little less than 19% of the total.

The annual growth of world cassava production in the period 1961 to 1997 was 2.35% per year (Scott et al. 2000). This is comparable with that of other crops such as wheat (4.32%), potato (4.00%), maize (3.94%), yam (3.90%), rice (2.85%), and sweet potato (1.07%). Increase in productivity on a worldwide scale is estimated to be 1.1% per year for the period 1994–2005, although this value, as in the case of LAC, is only 0.7% (Table 1-3). This implies that the yields observed for the period 1993–1995 (11.9 t/ha) will reach, in 2005, 12.8 t/ha (Table 1-4). For the specific case of Colombia, forecasts suggest that yields will increase at a rate of about 0.8% per year, that is, slightly more than the

Table 1-1. Area (thousands of hectares) planted to cassava in the world, by region, 1973 to 1995.

Region	Planted area			Growth (annual percentage)	
	1973/75	1983/85	1993/95	1973/75 to 1983/85	1983/85 to 1993/95
Africa	7,030	7,518	10,158	9.7	3,1
LAC[a]	2,722	2,592	2,593	-0.5	0
Asia	2,928	3,730	3,775	2.5	0.1
World	12,693	13,855	16,450	0.9	1.8

a. LAC refers to Latin America and the Caribbean.
SOURCE: FAO and IFAD (2000).

Table 1-2. Production (thousands of tons) of cassava roots (or equivalent) in the world, by region, 1973 to 1995.

Region	Production			Growth (annual percentage)	
	1973/75	1983/85	1993/95	1973/75 to 1983/85	1983/85 to 1993/95
Africa	43,378	55,207	83,062	2.4	4.2
LAC[a]	31,628	28,690	30,804	-1.0	0.7
Asia	30,262	47,371	49,740	4.6	0.5
World	105,400	131,424	163,746	2.2	2.2

a. LAC refers to Latin America and the Caribbean.
SOURCE: FAO and IFAD (2000).

Table 1-3. Yield (tons per hectare) of the cassava crop in the world, by region, 1973 to 1995.

Region	Yield			Growth (annual percentage)	
	1973/75	1983/85	1993/95	1973/75 to 1983/85	1983/85 to 1993/95
Africa	6.2	7.3	8.2	1.6	1.2
LAC[a]	11.6	11.1	11.9	-0.4	0.7
Asia	10.3	12.7	13.2	2.1	0.4
World	8.3	9.5	9.9	1.4	0.4

a. LAC refers to Latin America and the Caribbean.
SOURCE: FAO and IFAD (2000).

Table 1-4. Forecasts for the year 2005 on cassava area, production, and yield in the world, by region.

Region	Period 1993/95			Forecast for 2005		
	Area (ha × 10^3)	Production (t × 10^3)	Yield (t/ha)	Area (ha × 10^3)	Production (t × 10^3)	Yield (t/ha)
Africa	10,158	83,062	8.2	11,961	114,202	9.5
LAC[a]	2,593	30,804	11.9	2,777	35,590	12.8
Asia	3,775	49,740	13.2	3,836	57,572	15.0
World	16,540	163,746	9.9	18,595	207,556	11.2

a. LAC refers to Latin America and the Caribbean.

SOURCE: FAO and IFAD (2000).

average for the region (FAO and IFAD 2000). These values coincide overall with what is observed for the period 1983–1995 (Table 1-3).

Uses of Cassava

Cassava is characterized by its great diversity of uses. Both its roots and leaves can be consumed by humans and animals in many varied ways. Cassava products, particularly starch and its derivatives, can also be used by industry. A brief description of the principal uses of cassava is presented below.

Human food

Both cassava roots and leaves are suitable for human consumption. The first constitute an important source of carbohydrates, and the second of proteins, minerals, and vitamins (particularly carotenes and vitamin C).

The presence of cyanogenic glucosides in both roots and leaves determine the use of harvested cassava. Many so-called "sweet" varieties have low levels of these glucosides and can be consumed safely after normal cooking processes. Other so-called "bitter" varieties, however, have such high levels of these substances that a more sophisticated process is needed to make them suitable for human consumption. These varieties are usually used for industrial purposes. The inhabitants of the American hemisphere identified, a long time ago, the problem of cyanogenic glucosides and have developed several methods for eliminating cyanide from bitter cassava.

Humans consume cassava in numerous ways. In Colombia, cassava is traditionally boiled 10 to 40 min in the preparation of *sancochos* (type of stew), soups, and gruels. The boiling time required depends on the variety, which thus becomes a factor to take into account in selecting varieties for this purpose. Only sweet varieties should be used, as bitter varieties conserve their flavor after cooking and, in addition, can still be toxic.

Cassava is also consumed fried. An interesting industry of precooked and frozen croquettes has recently been developed. This alternative solves the problem of the roots' fast perishability, thereby adding value through processing. This, in its turn, enables urban areas to access cassava, as the problems mentioned above make marketing fresh roots in these areas difficult.

Cassava can also be consumed as flours, which are either fermented or unfermented. Unfermented flour is prepared by milling peeled roots or cutting them into small pieces. The resulting material is then dried and ground to form flour (Cock 1989).

In Brazil, much of the cassava is consumed as *farinha* (toasted cassava meal) in the preparation of various typical plates. *Farinha* is obtained primarily by peeling, grating, and pressing the roots, thus ultimately eliminating cyanogenic glucosides. Various alternatives exist to press the mass of grated roots, from the traditional *tipití* to more sophisticated methods such as filter-presses. The pulp or mass is immediately grated again, then baked, dried, and ground. It is then packaged and marketed. Once the mass of the roots is pressed, it can be kneaded until it forms a flat cake, similar to a large *tortilla*, which is toasted on a plate to obtain a type of bread or biscuit called *cazabe*. It is commonly eaten in the Caribbean islands, Venezuela, and Colombia.

Another alternative for the human consumption of cassava, and which is creating its own interesting market, is as fried cassava chips, similar to the potato snacks, but with the advantage that the product absorbs less oil to cook. This makes it more attractive from the viewpoint of human health. This product is produced commercially in Colombia, Venezuela, Brazil, and other countries. It is also exported to those areas of USA where Latin populations are predominant.

In other regions of the world, cassava is consumed in highly diverse ways. Variants of traditional flours exist such as the *gaplek* of Indonesia or the *kokonte* of Ghana.

In countries such as Nigeria, *gari* is a very popular cassava product. Roots are washed, peeled, and grated, much as for *farinha* production in Brazil, but with the difference that the resulting mass is placed in bags and then pressed down with weights (stones or logs) placed on top of them. The process is slow with the mass remaining for several days, during which it ferments. The mass is then toasted or fried (often with palm oil), until it dries. It is then packed in bags for storage or marketing.

Animal feed

Because of its high energy value, cassava offers excellent opportunities for animal feed. One way, perhaps the best known on a worldwide scale, is to dry cassava pieces or chips, an activity for which Thailand is world leader. Alternatively, cassava pieces may be processed into pellets.

As either dried pieces or pellets, cassava may be incorporated into the formulation of balanced feed for poultry, swine, farmed fish, and other domesticated animals. In Asia, drying is carried out on patios, exposing the material to air and sun, meaning that the process is totally natural. This drying method employs many people, but the costs of construction of patios are currently exorbitant for most cases. Furthermore, a relatively prolonged period without rains is needed, which is not possible in many areas of Colombia. Along the Caribbean coast, however, particularly in the departments of Sucre, Córdoba, and Magdalena, considerable infrastructure for this type of drying exists, having been regularly exploited since the 1980s.

Cassava can also be used for animal nutrition without first being dried. In many places of the world, both roots and leaves are ensiled. This process allows the product to be stored over long periods and, at the same time, reduces the levels of cyanogenic glucosides, even if these are initially very high. This alternative benefits the significant swine production industry in Asia. It has the additional advantage of combining the energy source from the roots with the leaves' high protein content. Fresh broken pieces of cassava can be left out in the open for a few hours and then offered to swine and cattle, with excellent results (Buitrago 1990).

Starches

Without a doubt, a major use of cassava is starch production. Numerous sources of starch exist to meet humanity's growing demands: in addition to cassava, these are maize, potato, and wheat (Ellis et al. 1998).

Starch extraction can be carried out in artisanal plants with capacities of only a few tons per month, or in enormous plants with capacities of up to 400,000 t/year. In both cases, the process is essentially the same: roots are washed, peeled, and macerated finely. Immediately, the starch, together with the water that carries it, is separated from root fibers and proteins by means of different filtrate systems. The water and starch are then separated from each other by gravity or centrifuging. Finally, the starch is dried and ground for packaging and marketing.

As with the alternatives of normal and fermented cassava flours, starch can also be either unfermented (or *native*) or fermented (*sour*). Production of the latter type of starch is very popular in the *rallanderos* (artisanal starch extraction plants) of northern Cauca, Colombia.

Cassava starch has particular properties that make it especially suitable for certain industrial processes. Among the properties that define a starch's characteristics are the amylose-to-amylopectin ratio and granule size. These characteristics are described in more detail in Chapter 2 on taxonomy and morphology, this volume.

Demand for modified starches is growing. These are used for very specific purposes. Cassava starch offers opportunities, as, in some cases, chemical modification is simpler and less expensive than it is with starches from maize or potato. We point out that, recently, cassava is increasingly being used for starch production in countries such as Brazil and Thailand. This trend is expected to continue in coming years. Taking into account these opportunities, major efforts have been made recently to develop or identify cassava cultivars whose starch offers special morphological characteristics, biochemical, or functional properties. As a result, cultivars are now available that have starch with no amylose or else with small granules and increased amylose contents (Ceballos et al. 2007, 2008).

Alcohol

Cock (1989) gives an interesting account of cassava's potential to produce alcohol. After the 1970s oil crisis,

Brazil planned to partly replace gasoline with alcohol derived from sugarcane or cassava. Despite initial skepticism, results demonstrated that the Brazilian approach to resolve the energy crisis deserved considerable support. For example, in 1980, Brazil produced sufficient alcohol to replace 20% of the gasoline needed for its cars (Cock 1989).

The drop in oil prices during the 1980s and 1990s reduced interest in this strategy, until 2000, when another crisis developed through high prices. This crisis generated interest in establishing numerous ethanol production centers based on cassava roots. Although interest in producing alcohol as a substitute for oil (as described) may oscillate, it is nevertheless inevitable: as supplies of petroleum derivatives become more difficult to obtain, demand for substitutes will become stronger and more constant.

In the past, most alcohol produced for these purposes came from sugarcane. In the future, however, it is likely to come increasingly from cassava because of its capacity to grow in marginal soils, which sugarcane is unable to do. In this regard, the technologies generated in developed countries to reduce costs of hydrolyzing maize starch in the production of bioethanol have directly facilitated these processes carried out with cassava starch.

Problems of crop development

Despite its enormous production potential, its noteworthy adaptation to a great diversity of environments, its recognized tolerance of biotic and abiotic constraints to production, and its diversity of uses, cassava has not yet managed to fully develop its potential in tropical agriculture. Numerous factors explain this delay.

Influence of temperate-region technologies. The evolution of agriculture and of different agroindustries of tropical countries have frequently benefited from developments achieved in temperate regions. Maize has been, and continues to be, a major source of energy and starch for these latter regions. Most of the technology, machinery, industrial processes, and formulations for concentrated feed adopted by tropical countries were originally adjusted to those crops and processes predominant in temperate regions. This situation, without a doubt, favored the cereal sector of tropical countries, but resulted in a disincentive for the development of technologies appropriate to crops specifically adapted to the tropics such as cassava.

Lack of cultivars specifically developed for industry. Frequently, the objectives of genetic improvement programs and development of cassava varieties aim at "dual purpose" materials, that is, those genotypes that could be used either for human consumption or for industry. If fresh-root market prices are high, then farmers sell their products to this market. If not, then the roots are sold to industry, usually at considerably lower prices.

This strategy has, in fact, interfered with the industrial use of cassava because it does not permit constant and reliable supplies of raw materials.

In addition, the search for dual purpose varieties has resulted in materials that were not optimal for either one or the other end use. From the genetic viewpoint, making strides when too many goals are imposed is very difficult.

Maize presents a good example of a case that contrasts with the situation for cassava. Two very different and totally independent activities with this crop exist: common maize and sweet maize. The former is destined to provide, efficiently and competitively, for the needs for various agroindustries, which means productivity is the principal objective. The latter is basically a horticultural crop and the varieties or hybrids developed mostly seek culinary quality and product appearance rather than productivity. Improvement programs and seed companies dedicate themselves to one or the other type of maize, and are completely independent, having relatively little interaction among them.

This volume emphasizes the changes that have been implemented recently, with a view to developing varieties to meet specific needs of different industries.

Lengthy selection cycles and low reproduction rate. The genetic improvement of cassava is slow. Where a full-sib recurrent selection cycle of any grain can be completed in less than one year, cassava requires five. Two factors influence this: cassava is usually harvested 10–12 months after planting, and the reproduction rate is relatively low. For example, one hectare of maize produces sufficient seed to plant 100 or more hectares. For cassava, the ratio is much smaller, with one hectare producing seed for about 7 to 10 ha. Most of the time required for variety selection is used basically to obtain sufficient seed to conduct evaluations with replications and across several sites to complete each selection cycle. This situation also affects the rate of adoption of new varieties once the latter are officially released.

Governmental policies. Because of a conjunction of several factors, governments of developing countries have usually paid little attention to the cassava crop. Between the 1970s and 1990s, the policies of most governments in tropical and subtropical regions were oriented towards promoting grain production, following the successful experiences of the Green Revolution (FAO and IFAD 2000).

Data on investments in research in these countries, according to crop, are extremely difficult to obtain. However, Judd and co-workers demonstrated in a detailed study (1987) that "several staple crops, specifically cassava, sweet potato, and coconut palm have received very little attention in every region of the world." From the data, Cock published (1989), investment in cassava research has obviously been low, unjustly so, and in disproportion with other crops (Table 1-5).

These data continue to be in effect 2 decades later. For example, according to CIMMYT (1994), in 1992 a total of 372 scientists worked in the genetic improvement of maize (224 and 148 in the public and private sectors, respectively). In contrast, no more than three full-time breeders dedicated their activities to cassava (C Iglesias 1999, pers. comm.) in that same period. In other words, the region dedicated less than 1% of human resources to cassava, compared with maize.

For this period (Scott et al. 2000), the relationship between the value of maize production and that for cassava on a worldwide scale was about 3:1, that is, 32,500 million versus 8800 million dollars, respectively.

Table 1-5. Investments made by developing countries in research on amylaceous foods in 1975.

Product	Product value (US$10^6)	Research cost (US$10^6)	Cost-to-value ratio (%)[a]
Sorghum	1500	12	0.77
Maize	3000–4000	29	0.75
Potato	1000	8	0.68
Wheat	5000–6000	35	0.65
Sugarcane	5000–6000	30	0.50
Rice	> 13000	34	0.26[b]
Sweet potato	3000–4000	3	0.09
Cassava	5000–6000	4	0.07

a. Proportion of research costs with respect to product value.
b. In "shallow-flooding" rice, the ratio is 0.40.

SOURCE: Adapted by Cock (1989) from data of the National Academy of Sciences (1977).

Governmental policies are also and inevitably reflected in the private sector, which invested similarly, favoring grains and either ignoring root and tuber crops or relegating them to a lesser importance than they deserved.

Root bulk and rapid perishability. Cassava roots present two important constraints to extensive and dynamic marketing. The first is its bulk water content (nearly 65%), which make transportation costs of fresh roots high in terms of the dry matter they contain. Hence, cassava production should be located near processing centers. The second problem is the roots' short life after harvest. They need to be consumed or processed no later than 7 days after harvest, as they undergo a process known as postharvest physiological deterioration (PPD). Various sources of tolerance of PPD have recently been identified. These are described in later chapters of this volume.

Root characteristics also affect processing costs. According to Cock (1989), traditional cassava processing methods are so laborious that probably more work is invested in processing than in cultivating and harvesting the crop.

Limited market development. A problem, similar to the egg and chicken paradox, has always existed in the industrial use of cassava: markets for the industry do not exist because no guaranteed availability of raw material exist, and roots are not produced for these markets because they do not exist.

Marketing problems are more pronounced for cassava than for other crops, as it is cultivated mostly by small farmers, and thus demanding greater coordination for use in industrial processes. Production areas are also usually located in areas with poor or deficient infrastructures.

In addition, the low-input technologies that characterize most cassava cultivation imply increased environmental variability, which has the effect of varying root quality. The crop's low rate of multiplication creates difficulties in accelerating and up-scaling production. The absence of credit is a problem that rice, maize, or sugarcane farmers do not have.

New opportunities for cassava in tropical agriculture

Despite all the above-mentioned difficulties that prevent cassava reaching the most relevant ranking, it remains a crop of world importance. Steps are being made to

quickly solve some of the inherent problems, as briefly described below.

Cassava will be more relevant to agriculture of the 21st century. The clearest and widespread economic trend during the 1990s has been, without a doubt, globalization of economies. Markets for agricultural products have been a part of this trend. As a result, commercial tariffs and other protectionist barriers have been gradually reduced. For example, Colombia imported an insignificant quantity of maize (32,000 tons) in 1990 but, in 2000, this figure was close to 2 million tons. This represents an annual growth of 79.5% for imports. This situation is repeated in many other tropical countries, where local maize production is not competitive with that of temperate regions.

The annual growth of maize imports in African and Asian countries was, respectively, 5.53% and 4.58% (FAO and IFAD 2000) during the past decade. Maize is a building block for animal feeds and an important raw material for the starch industry. This means that maize competes directly with cassava. It also implies that the future of cassava production and use in tropical countries depends largely on local grain production and on the possibility of importing grain.

Numerous reasons explain the limited maize competitiveness in the tropics. Pandey and Gardner (1992) suggested that "maize yields in the tropics are mainly limited by the quotient between intercepted radiation and heat units. This quotient is much lower in lowlands comparative with higher areas and is smaller in the tropics than in temperate regions. Relatively, a smaller quantity of light is intercepted during the rainy season in the tropics, which coincides with the period of grain filling for the crop. The interception of light is reduced even more by low planting densities. The extreme climatic variations, erratic precipitations, high temperatures, particularly during the night, and low temperatures in high areas also reduce yields."

Other factors that limit maize productivity in the tropics are:

a. Low fertility of most soils in the region.
b. Low yield potential of tropical cultivars.
c. High pest pressure and less-than-optimal availability of water.
d. Diseases that frequently reduce production by as much as 30%–40%.
e. Weeds that, in low-input production systems, reduce yields by as much as 50%.
f. Poor farming practices, limited resources, inadequate application of inputs, and delayed technology transfer.

Many of the factors that reduce the competitiveness of maize in tropical areas are clearly very difficult or impossible to overcome. Hence, if the trend towards market aperture continues, still fewer opportunities will exist in the future for local competitive production, which needs be carried out in optimal areas with adequate soil fertility, reliable heavy rainfall, appropriate infrastructure, and efficient mechanization of production.

Also obvious is that many weaknesses of tropical maize production are, precisely, the strengths of cassava production. Indeed, cassava is characterized by the stability of its production. It has an innate tolerance of low soil fertility and water deficiencies. Its physiological metabolism is not as severely affected by the relationship between day and night temperatures as it is for maize. It is naturally tolerant of the typical edaphic conditions of acid soils. The stability of cassava production and the crop itself was proven during the 1983–1985 droughts that affected Africa, when grains deteriorated critically. Likewise, more recently, in Asia and South America, cassava has played a role of great importance in food security on the occasion of the scarcity of grains derived from the meteorological anomalies that occurred in 1997 and 1998, as a consequence of El Niño and La Niña, respectively (FAO and IFAD 2000).

As a result of this evolution, the Colombian Government is vigorously supporting cassava research and development through the Ministry of Agriculture and Rural Development. Numerous highly relevant projects have been supported and many of their initial results will be presented throughout this volume. Coinciding with changes in governmental policies, a similar situation is being observed with the processing sector, which is also vigorously supporting this initiative to recover lost time.

Strategies for Making the Cassava Crop Even More Competitive

Cultivars specifically oriented towards meeting various demands of the processing sector are being actively developed, while cultivar production for the fresh-root market is being maintained. This does not mean that the needs of the more traditional cassava markets are being put aside. Instead, a genotype is not ruled out when, for example, root appearance does not conform to these markets' criteria.

The productive potential of these varieties are detailed in Chapter 18, which considers cassava genetics. Here, it is enough to mention that, in the Department of Córdoba, Colombia, variety SM 1433-3, an industrial clone, had a commercial yield of more than 80 t/ha of fresh roots in an area of almost 10 ha.

In addition to redefining the improvement project's objectives, the scheme used was also modified to improve its efficiency. This new improvement scheme, on the one hand, permits substantial shortening of the duration of each selection cycle; and, on the other, improves the reliability of data on which selection is based. With these changes, those genetic materials that are available and fully competitive in most of the environments where cassava is cultivated can be expected to be replaced in the medium term by varieties that are genetically superior and more specifically adapted to meet the needs to which they are destined.

Genetic improvement will be very much favored by the implementation of new biotechnology tools. CIAT has developed a molecular genetic map of the species and has managed to identify molecular markers associated with traits of agronomic interest. In addition, the technology now exists for transferring genes from either within the cassava species or wild species, not through sexual crosses, but through genetic transformation. This permits faster transfer of useful genes from one cultivar to another.

In vitro culture techniques help solve problems associated with cassava's low reproduction rate. Although the costs per plant increase with these techniques, they make possible the mass reproduction of large volumes of seedlings whenever this should be necessary or advisable.

Advances in genetic potential will be accompanied, in parallel, by other strategies to improve the crop's competitiveness. Mechanization of planting and harvesting has been introduced, resulting in, on the one hand, reduced costs and, on the other, higher yields. This machinery is being adapted to the needs of different regions in Colombia where cassava is cultivated and where mechanization can be introduced without harming the environment.

One problem that the cassava-processing sector frequently meets is the seasonal nature of the product. In some situations, this implies that processing plants (drying patios, starch extraction plants, etc.) remain inactive for relatively long periods. The goal is to solve these problems by combining step-wise plantings and identifying materials that can be harvested at different ages to thus facilitate a more continuous product supply in those regions where this situation can be problematic, as for the Colombian North Coast.

Those steps needed to make economic use of foliage are also being taken, first by developing methods for mechanically harvesting the product. The development of varieties and cultural practices for high-density plantings exclusive to foliage production is being considered. The possibility of taking advantage of foliage residues when roots are harvested in normal crops is also being evaluated. This would add greater value to farmers' harvests, with an increase, albeit proportionately smaller, in production costs (derived from the additional activity of harvesting the foliage). For this operation, a mechanical harvester for foliage was designed, built, and evaluated.

Strengthening and creating new markets

Interest in cassava has been growing recently in Colombia, leading to highly creative solutions for some of the crop's typical problems. For example, PPD and the difficulties of marketing fresh roots in urban areas can be overcome by producing precooked and frozen croquettes. These food products have become very popular and are now consolidated as a value-added cassava product for consumption in large urban centers. This is a good example of establishing and consolidating a production chain, from production in the field to distribution to end consumers. The market for fried cassava chips, as part of the snacks sector, has followed the same road in the recent past.

For other cases, to strengthen a given market, technological innovations are needed such as artificial drying of cassava. As mentioned above, the best known way of drying cassava destined for animal feed is through drying patios. This technology, however, is unsuitable for regions where no relatively long rainless periods exist. As a result, the public and private sectors have invested resources to develop a solution that is economically viable and compatible with environmental conservation to artificially dry roots and foliage. The first step was to construct a pilot plant in which different variables were adjusted to measure their effects on product quality and drying costs. The construction of this pilot plant was made possible through an association of public and private sectors collaborating actively on different aspects related to cassava use and processing.

The economic feasibility of artificial cassava drying is important to organizations with a vertical integration of production such as the cassava drying plant or "*trapiche*" (a Spanish name borrowed from small sugarcane processing facilities). These organizations would use a centralized production model, similar to that of sugar plantations and their associated *trapiches*. A cassava plantation, ranging from 600 to 6000 ha in size, would provide a drying plant (or refinery) with raw materials in a more or less continuous manner throughout the year.

Associates of these drying centers may include poultry or pork industries that would consume the product of these centers and return fertility to the system in the form of manure. A fundamental concept of this system is the short distances that the products involved would travel. Cassava roots would be produced within a radius of about 30 km of the drying plant and would be transported in bulk. Dried cassava would also be transported in bulk to the poultry- or pig-raising centers that would also be located relatively close by.

This proposal would therefore help solve the problem of cassava roots' bulkiness—resulting from their high water content—by minimizing their transport.

Taking advantage of and increasing the crop's hardiness

Cassava is recognized for its hardiness, that is, for its excellent tolerance of different biotic and abiotic stresses. It is particularly tolerant of low fertility soils, water deficiencies, and acid soils. It can also grow in moist tropical environments with rains that exceed 3 M/year. All these characteristics confer cassava with significantly stable production. Moreover, these valuable characteristics can be improved even more.

Techniques of integrated pest-and-disease management (IPDM) have significantly contributed to stability of production. Genetic resistance or tolerance to principal pests and diseases has been incorporated into most improvement programs of the crop throughout the world. For example, resistance (reported to be antibiosis) to whiteflies (*Aleurotrachelus socialis*) of the local variety M Ecu 72 is the first reported for any commercial crop. In those few cases in which genetic resistance or tolerance does not offer adequate protection, numerous alternatives of biological control are available.

Practical methods are being actively developed to integrate these biological control methods into current practices of crop care. In addition to reducing production costs, these alternatives offer the advantage of being usually durable and contributing to environmental health by reducing or eliminating the need for agricultural chemicals.

Similarly, genetic improvement programs are continually selecting against the principal diseases of each ecoregion to develop resistant or tolerant cultivars. In cases where genetic resistance is not sufficient, other methods for pathogen control like that of thermotherapy are developed to "clean" cuttings of diseases such as cassava bacterial blight.

As with other activities, biotechnology offers tools that facilitate these efforts. At present, it is being used to identify molecular markers associated with genes for resistance to whiteflies. This methodology is also being used to better understand the population dynamics of the bacterial blight pathogen. Biotechnology also permits the development of serological diagnostic tests based on the polymerase chain reaction (PCR).

Adding value to the crop and increasing its profitability

In developing new varieties, the possibility of selecting for specific markets is also considered. For example, the cassava genome carries genes for orange-fleshed roots, so colored for possessing high carotene contents. Although this color may not be desirable for certain markets, it offers advantages for other uses, particularly poultry feed. Apparently, this component also delays the beginning of PPD. Such yellow-rooted or "egg yolk" cassava varieties would also be very useful for producing fried cassava chips because, according to preliminary studies, the product has a very appealing presentation.

CIAT holds genetic capital of enormous importance: the World Cassava Germplasm Bank, which carries about 6000 accessions that contain practically the crop's entire genetic variability. Studies are currently being carried out to evaluate starch properties and traits, and other agronomically relevant properties of roots and leaves in each accession. One possible result of this arduous effort would be the finding of genotypes that present new starch types with specific industrial applications.

Uniting research, production, and processing

A common factor runs through all those cases of successful cassava initiatives: close and active interaction between farmer, researcher, and processor. Similarly, when this "triangle of success" is not well established, failure was frequent. Cassava's current situation in Colombia is showing numerous positive cases where achievement entails such a paradigm.

Research has been favored, at very much the right time, by vigorous institutional support from the Ministry of Agriculture and Rural Development that, with the support of different trade associations, was an unconditional promoter for the creation of the Latin American and Caribbean Consortium to Support Cassava Research and Development (CLAYUCA, its Spanish acronym).

This Consortium is the clearest instance where interaction between processors, farmers, and researchers is harmonious and productive. The presence of the private sector and trade associations (particularly FENAVI and ACOPOR), promoting the crop with appropriate technologies, has been fundamental in bringing cassava closer to the position of importance that it deserves in tropical agriculture. In this interaction, the public sector has also contributed through CORPOICA's technical and logistical capability and ICA's continuous and timely intervention, when the situation so merited it.

Predicting the Future for Cassava

World cassava production grew at an annual rate of 2% between 1987 and 1997, which was slightly more than during the previous decade, when it grew at a rate of 1.7%. Expansion in area planted was the main way in which production increased (1.7% versus only 0.3% for increases in productivity). Projections for the period 1993–2020 estimate a similar growth rate as observed so far, ranging between 1.93% and 2.15% per year, but with a substantial change in terms of productivity increases (higher than 1%), with respect to planted area, which may range between 0.74% and 0.95% (CGIAR 1999).

Tables 1-6 and 1-7 present other projections extracted from Scott et al. (2000). Table 1-6 presents statistics derived from a base scenario, whereas data in Table 1-7 were obtained by assuming high demand for agricultural products. In general terms, these projections coincide with the ones described above: that, annually, production will increase between 1.74% and 1.95% per year, yields will increase about 1% per year, and planted area will increase between 0.73% and 0.94%.

References

Buitrago A, JA. 1990. La yuca en la alimentación animal. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 450 p.

Ceballos H; Sánchez T; Morante N; Fregene M; Dufour D; Smith AM; Denyer K; Pérez JC; Calle F; Mestres C. 2007. Discovery of an amylose-free starch mutant in cassava (*Manihot esculenta* Crantz). J Agric Food Chem 55(18):7469–7476.

Ceballos H; Sánchez T; Denyer K; Tofiño AP; Rosero EA; Dufour D; Smith A; Morante N; Pérez JC; Fahy B. 2008. Induction and identification of a small-granule, high-amylose mutant in cassava (*Manihot esculenta* Crantz). J Agric Food Chem 56(16):7215–7222.

Table 1-6. Projections of the planted area, production, and yield of cassava for the year 2020.

Region	Planted area			Production			Yield		
	Year		Exchange rate (%/year)	Year		Exchange rate (%/year)	Year		Exchange rate (%/year)
	1993	2020		1993	2020		1993	2020	
	(ha in millions)			(t in millions)			(t/ha)		
China	0.3	0.3	0.08	4.8	6.5	1.18	15.1	20.2	1.10
India	0.2	0.2	0.02	5.8	7.0	0.71	23.6	28.4	0.69
Asia	3.9	3.9	0.25	42.0	48.2	0.51	12.1	13.7	0.46
LAC[a]	2.7	2.7	-0.01	30.3	41.7	1.19	11.3	15.6	1.21
Africa	11.9	15.9	1.09	87.8	168.6	2.45	7.4	10.6	1.34
World	18.8	22.9	0.73	172.7	275.1	1.74	9.2	12.0	1.00

a. LAC refers to Latin America and the Caribbean.

SOURCE: Adapted from Scott et al. (2000).

Table 1-7. Projections (based on a scenario of high demand) of planted area, production, and yield for the year 2020.

Region	Planted area			Production			Yield		
	Year		Exchange rate (%/year)	Year		Exchange rate (%/year)	Year		Exchange rate (%/year)
	1993	2020		1993	2020		1993	2020	
	(ha in millions)			(t in millions)			(t/ha)		
China	0.3	0.3	0.09	4.8	6.6	1.21	15.1	20.3	1.12
India	0.2	0.2	0.03	5.8	7.1	0.76	23.6	28.7	0.73
Asia	3.5	3.5	0.03	42.0	48.2	0.51	12.1	13.8	0.49
LAC[a]	2.7	2.7	-0.01	30.3	42.0	1.22	11.3	15.7	1.23
Africa	11.9	17.2	1.39	87.8	183.8	2.77	7.4	10.7	1.36
World	18.8	24.2	0.94	172.7	290.8	1.95	9.2	12.0	1.00

a. LAC refers to Latin America and the Caribbean.

SOURCE: Adapted from Scott et al. (2000).

CGIAR (Consultative Group on International Agricultural Research). 1999. Annual report 1999: science for the poor and environment. Washington, DC.

CIMMYT (International Maize and Wheat Improvement Center). 1994. World maize facts and trends—maize seed industries revisited: emerging roles of the public and private sectors. Mexico, DF.

Cock JH. 1989. La yuca, nuevo potencial para un cultivo tradicional. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 240 p. *(Also available in English as Cock JH. 1985. Cassava: new potential for a neglected crop. Westview Press, Boulder, CO, USA.)*

Ellis RP; Cochrane MP; Dale MFB; Duffus CM; Lynn A; Morrison IM; Prentice RDM; Swanston JS; Tiller SA. 1998. Starch production and industrial uses. J Sci Food Agric 77:289–311.

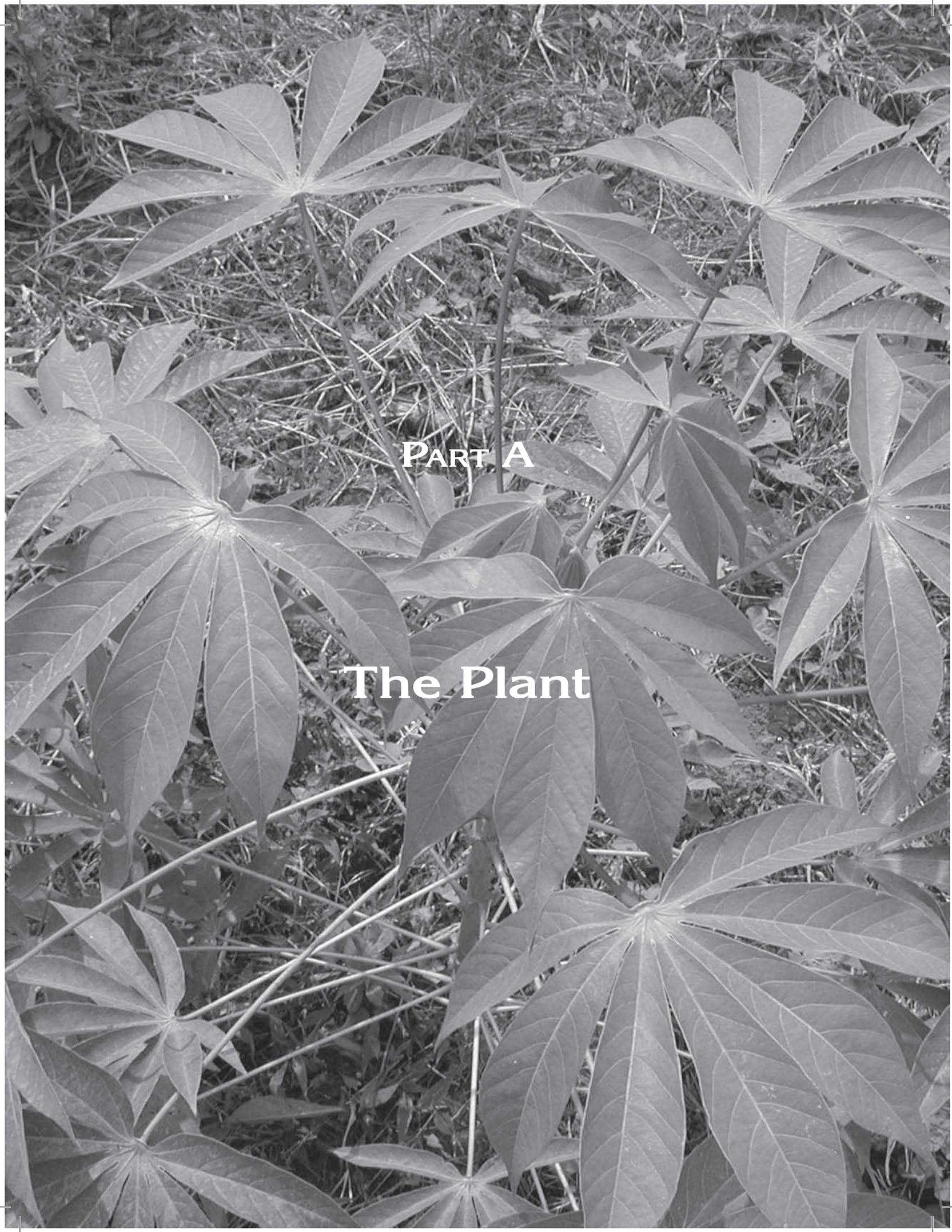
FAO; IFAD (Food and Agriculture Organization of the United Nations and International Fund for Agricultural Development). 2000. La economía mundial de la yuca: Hechos, tendencias y perspectivas. Rome, Italy. 59 p. (Also available in English as *The World Economy of Cassava: Facts, Trends, and Outlook*.)

Judd MA; Boyce JK; Evenson RE. 1987. Investment in agriculture. In: Ruttan VW; Pray CE, eds. Research and extension policy for agricultural research. Westview Press, Boulder, CO, USA. p 7–38.

Olsen KM; Schaal BA. 2001. Microsatellite variation in cassava *(Manihot esculenta*, Euphorbiaceae) and its wild relatives: further evidence for a southern Amazonian origin of domestication. Am J Bot 88(1):131–142.

Pandey S; Gardner CO. 1992. Recurrent selection for population, variety, and hybrid improvement in tropical maize. Adv Agron 48:1–87.

Scott GJ; Rosegrant MW; Ringler C. 2000. Roots and tubers for the 21st century: trends, projections, and policy options. International Food Policy Research Institute (IFPRI); Centro Internacional de la Papa (CIP), Washington, DC. 64 p.



Part A

The Plant

CHAPTER 2

Cassava Taxonomy and Morphology

Hernán Ceballos[1] *and Gabriel de la Cruz*[2]

Introduction

In preparing this chapter, advantage was taken of the knowledge base provided by other authors whose valuable contributions should be recognized. Of the publication *Cassava: research, production, and utilization* (edited by Carlos E Domínguez [1983]), the chapters used were written by Carlos E Domínguez, Luis F Ceballos, and Cilia Fuentes ("Morphology of the cassava plant"); Clair Hershey and Alvaro Amaya ("Genetics, cytogenetics, floral structure, and techniques of hybridization in cassava" and "Cassava germplasm: evolution, distribution and collection"); and James H Cock ("Physiological aspects of the growth and development of the cassava plant"). Of the book *Cassava in the face of hunger in the tropical world* (edited by Alvaro Montaldo 1996), information was extracted from the chapters written by Jocelyne Ascencio ("Some aspects related to the physiology of the cassava plant"); and JJ Castilloa, A Castillo, and LT Pino ("Notes on leaf and root histology of cassava").

All 98 species of the *Manihot* genus are native to the Neotropics from where cassava was introduced to other regions of the world (Rogers and Appan 1973). The origin of cultivated cassava is still unclear. Three relevant questions were raised by Allem (2002): its botanical origin (parental wild species that eventually led to the emergence of *M. esculenta*), the geographic area where this emergence took place, and the region where it was domesticated (agricultural origin). The prevailing hypothesis is that cultivated cassava originated in South America (Olsen and Schaal 2001; Allem 2002), but many questions remain unanswered.

1. Breeder, Cassava Program, CIAT, Cali, Colombia. E-mail: h.ceballos@cgiar.org
2. Formerly Vice-Rector, UN–Palmira. E-mail: gacruza@unal.edu.co

Taxonomy

Cassava belongs to the Euphorbiaceae family, which is made up of about 7200 species, characterized for their notable development of lactiferous vessels, themselves made up of secretory cells called lacticifers. These produce the milky secretion, or "latex", that characterizes the plants of this family. Plant architecture varies enormously within this family, ranging from arboreal types such as rubber (*Hevea brasiliensis*) to shrubs, also of economic importance, such as the castor-oil plant (*Ricinus communis*). Also representing this family are numerous weeds, ornamental plants, and medicinal plants. A highly significant genus of this family is *Manihot* to which cassava belongs.

The *Manihot* genus is native only to the Americas, with species being distributed from southwestern USA (33° N) to Argentina (33° S). Although all species of the genus can cross with each other, evidence suggests that, in nature, they are reproductively isolated. About 98 species have been described as belonging to this genus, of which only cassava (*Manihot esculenta* Crantz) has economic importance and is cultivated. Perhaps more than 100 common names now exist for this species, owing to its spread throughout the tropical world by early traders. In Latin America, it is usually known either as *yuca* (Spanish) or as *mandioca* (Portuguese). In Brazil, sweet cassava (*aipim*) is distinguished from bitter cassava (*mandioca*). Other names in different languages include manioc, manioca, tapioca, and *mhogo* (Cock 1989).

Cassava's scientific name was first given by Cranzt in 1766. It was then reclassified by Pohl (1827) and Pax (1910) as two different species, depending on whether it was bitter (*M. utilissima*) or sweet (*M. aipi*). However, the Italian R Ciferri (1938) recognized that, for cassava's scientific name, priority should be given to

Crantz's work in which he had proposed its current name of *M. esculenta*. Allem (1994) proposed that the species *M. esculenta* be divided into three subspecies: *M. esculenta* subsp. *esculenta,* subsp. *flabellifolia*, and subsp. *peruviana*. The author also suggests that the last two subspecies are wild forms of the cultivated version *M. esculenta* subsp. *esculenta*.

Cytogenetics

Very little is known of either cassava genetics or cassava cytogenetics. The basic chromosome number in the Euphorbiaceae family is usually 8, although this may vary between 6 and 11. About 50% of euphorbia species are polyploid (Martin 1976).

Although cassava is frequently considered as a polyploid species, analyses conducted during diakinesis and metaphase I indicate the presence of 18 small and similar bivalents in cassava (Hahn et al. 1990). Univalents, trivalents, and late bivalent pairings have also been observed in cassava. This plant is therefore a functional diploid, that is, $2n = 2x = 36$ (Jennings 1963; De Carvahlo and Guerra 2002; Nassar and Ortiz 2008). Magoon et al. (1969) have suggested that certain portions of the genome may be duplicated and, therefore, cassava may in fact be a segmental allotetraploid.

Describing the Plant

Every botanical description is based on the analysis of morphological characters that, where these are constant, typify the species. However, many characteristics are expression in a variable fashion and are profoundly influenced by environment. The effect of the variety-by-environment interaction is most notable in the case of cassava. For example, a given variety's architecture, known to be typical in a specific environment, will change drastically when that variety is grown in another site with different environmental conditions. This variety-by-environment interaction hinders both the morphological and varietal description of the species.

Cassava is a perennial shrub. It is monoecious, that is, a single plant may carry both male and female flowers, but these are separated from each other. The cassava plant has sympodial branching and variable plant height, ranging between 1 and 5 m, although maximum height usually does not exceed 3 m.

The stem

Stems are particularly important in cassava, as they are the means by which the species propagates vegetatively or asexually. Lignified parts of the stem, commonly called stakes or *cangres* (cuttings), serve as "seed" for the crop's commercial production. The mature stem is cylindrical, with a diameter that varies from 2 to 6 cm and coloring that may be silvery gray, purple, or yellow. Both stem diameter and color vary significantly with plant age and, obviously, with variety.

Stems are formed by the alternation of nodes and internodes. The oldest parts may show protuberances, which mark, within the nodes, the position that leaves had initially occupied. The node is that place where a leaf joins the stem, and the internode is that part of the stem between two successive nodes. Inserted into the node are the leaf petiole, an axillary bud protected by a scale, and two lateral stipules. The length of internodes in the principal stem is highly variable and depends, not only on the variety, but also on other factors such as plant age, drought, thrips attacks, and available soil fertility. In a certain sense, the stem provides a lasting record of the history of the plant's development, enabling one to deduce the conditions and events that had influenced it.

The presence of axillary buds in each node is important as, from these, a stake can produce a new plant. In theory, a stake can produce the shoot of a new primary stem from the bud in each node. However, the number of stems produced depends heavily on the way in which a given stake is planted. For example, when the stake is planted horizontally, all nodes tend to emerge, but if the stake is planted in a vertical position, usually only the apical bud is activated. The number of shoots from a stake also depends on the apical dominance that characterizes each variety. When it is strong, only the upper bud generates a primary stem. General conditions of the stake, particularly of the axillary buds, also determine the number of stems a stake will produce.

The typical phyllotaxis observed in cassava stems is 2/5. This means that the leaves are located in spiral fashion around the stem. If leaves are counted successively upwards from a given leaf (number 1), the sixth leaf will be exactly in the same position as leaf number 1, but farther up the stem. The fraction 2/5 also implies that two turns have to be taken around the stem before finding a leaf that perfectly overlaps leaf number 1 and that, in the process, five leaves are counted.

The primary stem, after a certain growing period, ultimately produces branches that may be either reproductive (producing inflorescences) or vegetative (producing lateral branches). The "reproductive" branches are important, as they constitute a very stable characteristic for varietal description. They also determine, to a great extent, the architecture that is characteristic of each variety. The latter, as will be seen in other chapters of this volume, is significant for defining the agronomic value of each material, as it influences the quantity of planting material or "stakes" that the plant produces, and other factors such as ease in carrying out tasks of cleaning and general care of the crop.

Although the reproductive lateral branch is induced by flowering of the principal axis (hence its name), reproductive branching may also occur without the presence of inflorescences. What factors determine the moment in which reproductive branches will be produced are not yet clear, as this event is very strongly influenced by the environment. Reproductive branching may give rise to two, three, and even four secondary branches, which, in their turn, may ultimately produce tertiary branches, and so on (Figure 2-1).

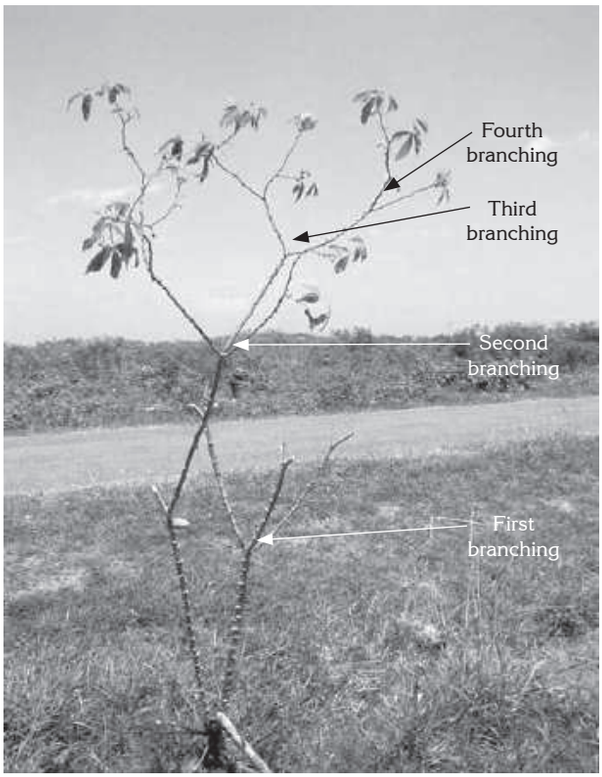


Figure 2-1. Plant stripped of leaves to show branching.

The number and promptness with which such branching occurs notably influence plant architecture. Early flowering results in the primary branches being located in relatively lower positions in the plant. Hence, early and multiple branching will therefore tend to produce a short plant that hinders the cleaning and care of the crop. However, it rapidly covers the soil, protecting it from, particularly, hydric erosion. Reduced and/or late branching tends to produce erect plants, with good stake production, that facilitate crop care, but leaves the soil exposed to erosion.

In addition to the number of reproductive branches, the angle of these also greatly affects the plant's general architecture (Figure 2-2). The greater the angle of incidence of the branches, the more open the plant architecture and the shorter it is. In general, this type of architecture is undesirable from the agronomic standpoint.

Lateral branches from the same node (called *chupones* in Spanish) are sporadic and depend on planting density, climatic conditions, soil fertility, and cultivar. They stem from the axillary buds of the principal stem, and are usually thinner than this stem, with long internodes and smaller leaves. Wounds or damage in the apical area (e.g., from lancefly [*Silba pendula*] or thrips) will also induce lateral buds into producing branches that will assume the role of the principal stem, replacing it.

The internal structure of the cassava stem is typically dicotyledonous. The outermost layer in young stems is the epidermis, followed by (going towards the interior) cortical tissue. Pigmentation in these two layers will define the color that the stem ultimately assumes. Internally, the layer is ligneous. The center of the stem is occupied by a prominent pith, composed of parenchymatous cells. As stem diameter increases, large quantities of xylem accumulate, giving the mature stem a ligneous consistency and generating the *suber* or cork that replaces the epidermis.

The leaf

Leaves are the organs in which photosynthesis mostly occurs, transforming radiant energy into chemical energy. Leaves are caducous, that is, with age they senesce, and fall from the plant as it develops. The total number of leaves produced by the plant, their longevity, and photosynthetic capacity are varietal characteristics, which are profoundly influenced by environmental conditions.

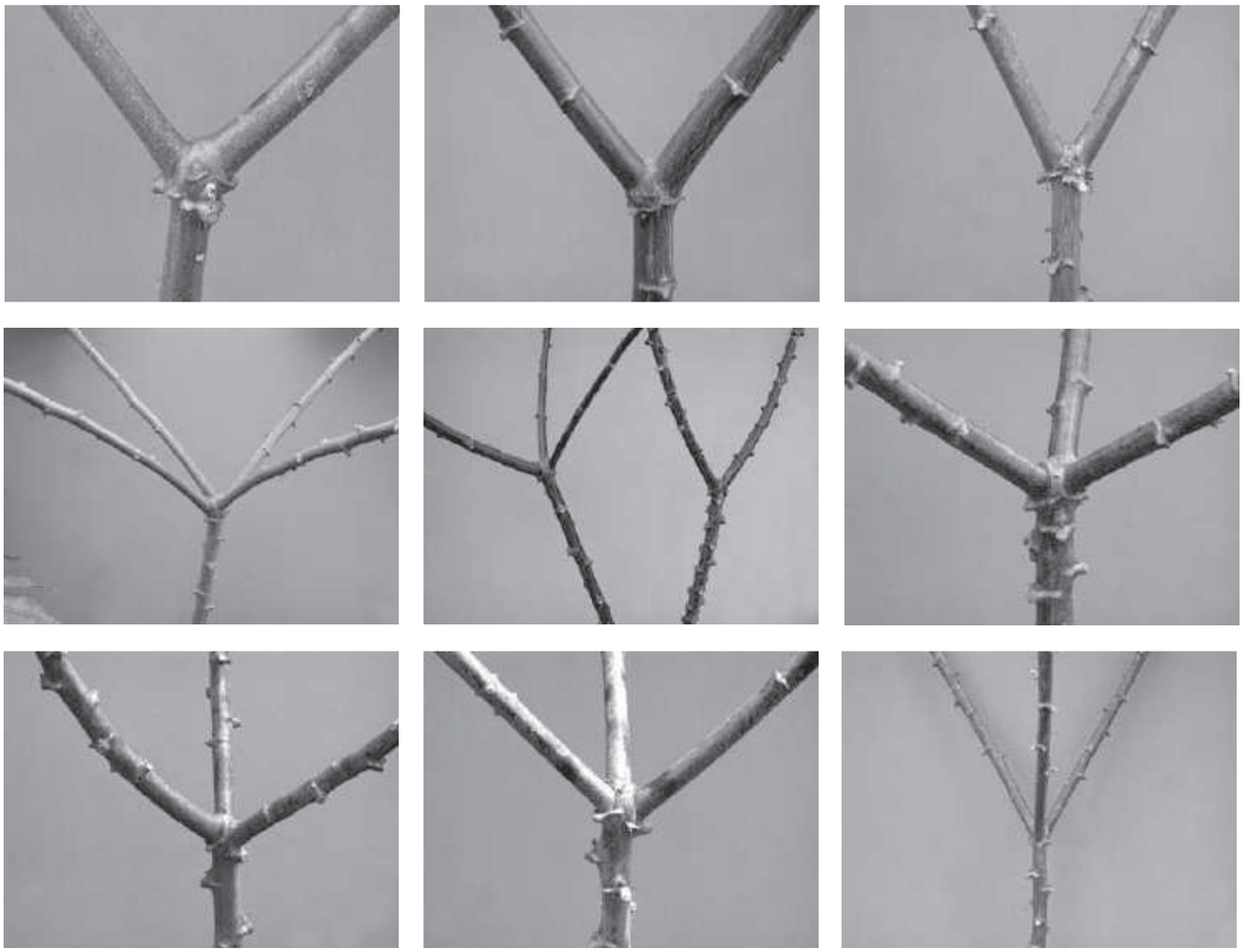


Figure 2-2. Variations in branching angle and number of branches.

Leaves are simple, consisting of the leaf blade and petiole. The blade is palmate with variable number of lobes, usually, odd, ranging between 3 and 9. Lobes measure between 4 and 20 cm long and between 1 and 6 cm wide. The central lobes are larger than the lateral ones. Lobe shape can be classified in different ways, with a variable number of categories. A simple classification distinguishes three types of lobes: linear or straight, obovate, and pandurate. But intermediate types also exist, encouraging the development of other classification systems to qualify such characteristics (Figure 2-3).

Leaf size is a typical characteristic of each cultivar, although it depends heavily on environmental conditions. Leaves produced in the first 3 to 4 months of the plant's life are larger than those produced after the fourth month. For example, in variety M Col 72, the average leaf area at 4 months old is about 250 cm^2; at 7 months, it is 130 cm^2; and at 10 months (harvest), only about 90 cm^2.

Leaf color is also a varietal characteristic but may vary with plant age. Mature leaves may be purple, dark green, or light green. Purple buds may, as the leaves grow and develop, ultimately become greenish in coloring. Bud color is a very useful characteristic for varietal identification, as it is relatively constant. The color of the nervure ranges between green and purple, and may also be used for varietal description. This color may be the same or different for the two sides of the leaf blade.

The leaf petiole may be between 9 and 20 cm long. It is thin, with variable pigmentation (green to purple), depending on variety. Petiole color does not always coincide with that of the nervure.

Mature leaves are always glabrous, that is, they lack pubescence. Leaves of buds, however, may or may not be pubescent—a relevant feature as pubescence in bud leaves is closely related to resistance to thrips. The upper surface of the leaf is covered by a brilliant waxy

Figure 2-3. Two types of leaf lobes.

cuticle, while the lower surface is opaque. Most stomata are found on the lower surface, although, in some varieties, abundant stomata may also appear on the upper surface.

At the petiole's point of insertion in the stem, two stipules, 0.5 to 1.0 cm long, can be found. These stipules may or may not remain adhered to the stem once the leaf is fully developed.

Although the principal economic product of cassava is the root, leaves are also important. In several regions of Africa and Asia, leaves are processed for human consumption. Cassava leaves have a valuable nutrient content with high protein levels that range between 18% and 22%, dry weight (Buitrago A 1990). Young cassava foliage also has several vitamins and minerals. Table 2-1 shows ascorbic acid and carotene contents for cassava roots and leaves. Data are based mostly on evaluations of more than 500 genotypes belonging to the core collection held by the cassava germplasm bank at the Centro Internacional de Agricultura Tropical (CIAT)[3]. Information on contents of principal minerals is also presented from the viewpoint of human and animal nutrition (Table 2-2), extracted from a representative sample of 20 varieties.

Table 2-1. Contents of ascorbic acid and carotenes in leaves and roots of more than 500 cassava varieties from the germplasm bank at CIAT.

	Ascorbic acid (mg/100 g fw)[a]		Carotenes (mg/100 g fw)[a]	
	In leaves	In roots	In leaves	In roots
Minimum value	0	0	23.28	0.100
Maximum value	419.25	37.52	86.22	1.040
Median	109.30	8.09	47.72	0.190
Average	120.16	9.48	48.26	0.230
SD	84.14	6.50	8.61	0.137

a. fw = fresh weight.

SOURCE: CIAT (1999).

The inflorescence

Not all cassava varieties flower under the same environmental conditions. Those that do show marked differences in flowering times and quantities of flowers produced. The environment greatly influences the induction of flowering. As with all plants of the *Manihot* genus, cassava is a monoecious plant, that is, it bears

3. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Table 2-2. Concentration of mineral elements in leaves and roots of 20 cassava clones evaluated at CIAT (unpublished data).

Element	Concentration in leaves (mg/100 g dw)[a]		Concentration in roots (mg/100 g dw)[a]	
	Average	SD	Average	SD
Fe	94.4	37.8	9.6	2.49
Mn	67.9	10.5	1.2	1.00
B	66.1	7.7	2.4	0.51
Cu	7.3	0.6	2.2	0.35
Zn	51.6	11.8	6.4	1.35
Ca	12,324.0	1761.0	590.0	120.00
Mg	7,198.0	888.0	1153.0	147.00
Na	11.4	3.0	66.4	27.00
K	10,109.0	903.0	8903.0	882.00
P	3,071.0	236.0	1284.0	113.00
S	2,714.0	145.0	273.0	40.00

a. dw = dry weight.

unisexual flowers, with some being male and others female, with both usually found on the same inflorescence.

Cassava undergoes cross pollination, which means that it is a heterozygous plant, with each individual being a hybrid. Pollination is typically carried out by insects. Self-pollination is prevented by the female flowers of a raceme opening first before the male flowers of that same raceme. This phenomenon is known as protogyny. However, occasionally, the male and female flowers of different racemes on a single plant may open simultaneously. When this happens, self-pollination may naturally occur.

Cassava "flowers" are produced in inflorescences. The basic arrangement of flowers is the raceme (Figure 2-4), where the female flowers occupy basal positions and the male the distal ones. The latter are smaller and usually more numerous than the female ones. Frequently, panicles are also produced, that is, from the botanical viewpoint, a raceme of racemes develops. In such cases, a principal raceme exists, which is composed of secondary racemes.

Each flower, whether male or female, has a primary bract and a bracteole. These foliaceous organs appear in the inflorescences and may either remain or drop off once the flowers develop.

In most cases, inflorescences are formed from buds at the point of insertion of reproductive branches. Occasionally, inflorescences may develop from buds in leaf axils in the plant's upper parts.

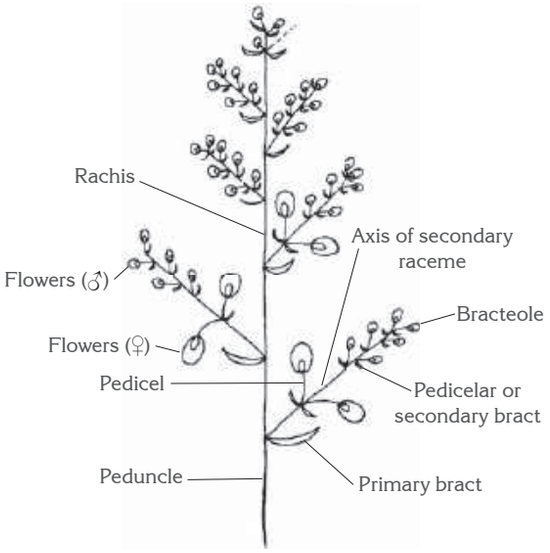


Figure 2-4. Diagrammatic representation of an inflorescence (from Domínguez et al. [1983]).

Male and female flowers

The evolution of flower structures in the Euphorbias is, compared with other flowering plants, remarkable. Cassava flowers are in fact apetalous, having no petals or sepals. They are also monoecious, that is, male and female flowers are separately found on the same inflorescence. Female flowers are single, and are reduced to a pistil that is protected by petal-like bracts. Male flowers are also reduced—to a single stamen—but, unlike female flowers, they form inflorescences of 10 single-stamen flowers. These inflorescences, known as cyathia (*sing.* cyathium), are also protected by bracts. Together, the female flowers and male cyathia form inflorescences of a secondary order known as *panicles*.

What are commonly called *tepals* (i.e., petal-like sepals) in cassava flowers are actually bracts. In this volume, the male cyathia will be treated as if they are single flowers, as the distinction is only relevant from the botanical point of view.

The male "flower" is about half the size of the female. It possesses a straight and very short pedicel, while that of the female flower is thicker and longer (Figures 2-4 and 2-5). Inside the male flower is a basal disk that is divided into 10 lobes. In the center of this disk a rudimentary ovary can be seen. At the points of separation of the lobes of the basal disk, arranged in two series, are the 10 stamens that support anthers. Of these stamens, the 5 outer ones are separate and longer than the 5 inner ones. Together, they form the

Figure 2-5. Cassava flowers: female (top) and male (bottom).

set of anthers. On each stamen is an elongated anther that inclines towards the central part of the flower. The anthers open along longitudinal apertures. Pollen release begins 2 or 3 h before the flower opens and may even end before the flower completely opens. Pollen grains are large and spherical, and only a few are produced in each sac. They are also sticky, which facilitates pollination by insects. Pollen remains viable for up to 6 days. A detailed description of microsporogenesis in cassava has been recently published (Wang et al. 2010).

Because cassava can reproduce vegetatively, reproductive dysfunction is not, from an evolutionary viewpoint, as negative as it would be in crops that have exclusively sexual reproduction. As a result, cases of male-sterility, for example, can be frequently found. Such cases are of two types: one where the flowers abort before reaching maturity, and the other when flowers mature but the anthers do not produce pollen. Genetics of such sterility, however, has not yet been fully studied.

The fruit

Once the female flower has been pollinated, fruit begins to form from the ovary. Fruit maturation requires about 3 months to complete. The fruit is a dehiscent capsule that is trilocular, and ovoid to globate, with a diameter of 1.0 to 1.5 cm and six longitudinal, narrow, and prominent ridges (Figure 2-6). Cross-sections of the developing fruit show a series of clearly discernible tissues: epicarp, mesocarp, and endocarp.

As the seed matures, the epicarp and mesocarp dry up. The endocarp, which is ligneous, opens abruptly when the fruit is mature and dried, releasing and dispersing seeds to a certain distance. During dehiscence tissues separate both, throughout the mid-vein of each fruit loculus and between the separations themselves.

The seed

The seed is the medium for the plant's sexual reproduction. While it is not important in reproduction and commercial multiplication, it has incalculable value for plant breeding, as only through sexual reproduction can new, genetically superior, cultivars be developed.

The seed is ovoid-ellipsoid in form and measures about 1 cm long, 6 mm wide, and 4 mm thick. The seed coat is smooth, coffee-colored, and mottled gray. In the upper part, especially of new seed, the caruncle is found. This structure is lost once the seed falls to the ground. At the other end of the seed, opposite the caruncle, a small cavity is found. A slender suture leaves from the caruncle and finishes in this basal cavity. Figure 2-7 shows the typical structure of a cassava seed.

The seed coat is the outermost part of the seed. Immediately inside the seed coat is the endosperm, which is formed of polyhedral parenchymatous cells that protect and nourish the embryo, itself located in the central area of the seed. Within the endosperm are found the cotyledons and embryonic axis that will give rise to the new plant after germination. The embryo is

Figure 2-6. Cassava fruit.

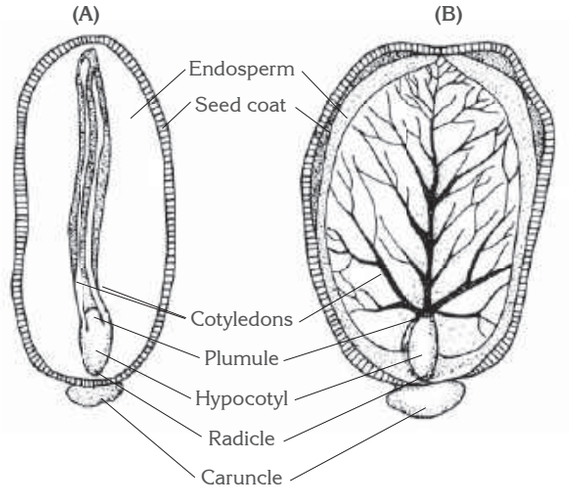


Figure 2-7. Diagram of two longitudinal sections of botanical cassava seed (from Domínguez et al. [1983]). **(A)** Cross-section cut across suture; **(B)** cross-section cut through suture.

made up of the two cotyledonous leaves, plumule, hypocotyl, and radicle. The cotyledonous leaves and endosperm occupy almost the entire interior of the seed; they are white, elliptical, and carnose.

Although currently seed does not play a predominant role in cassava multiplication, it may well do so in the future. A phenomenon in nature, especially among grasses, known as *apomixis*, consists of producing botanical seed without the usual sexual reproduction. In other words, the seed embryo produced by apomixis is genetically identical to the mother plant. This means that, when the embryo grows into a plant, it will also produce an individual plant that is identical to its mother. Apomixis has been reported for the *Manihot* genus (Nassar et al. 2000). It could be incorporated into commercial systems because of its appreciable advantages: it would enable seed storage for more than the month or 2 months that stems can be kept and the rate of multiplication of a material could be increased significantly. Also they are less likely to carry pathogens than stem cuttings.

The root system

The principal characteristic of cassava roots is their capacity for starch storage, which is the reason why, so far, it is the plant organ that has the greatest economic value. However, not all roots produced ultimately become storage organs.

When the plant grows from sexual seed, a primary root develops and then, several secondary ones. Apparently the primary root always evolves into a tuberous root, and is the first to do so. If the plant grows from a stake, the roots are adventitious, forming at (1) the lower end of the stake, which produces a callosity, and (2) from buds in that part of the stake that is buried in the soil. These roots initially form a fibrous system but, later, some (usually <10) begin thickening and become tuberous roots. The number of tuberous roots is determined, in most cases, by the plant's early growth.

Although root density is low, penetration into the soil is deep. This is a highly relevant characteristic, as it contributes to the plant having the capacity to endure prolonged droughts. Fibrous cassava roots can reach depths of up to 2.5 m. The plant absorbs water and nutrients through the fibrous roots, a capacity that is lost when they become tuberous.

Morphologically and anatomically no differences are found among fibrous and tuberous roots. What happens is that, as starch accumulation begins, the direction of root growth changes from longitudinal to radial. However, this does not necessarily mean that the root absolutely stops longitudinal growth. As mentioned above, tuberous roots come from secondary enlargement of fibrous roots. This means that the root system first penetrates the soil while roots are thin and only after such penetration, do roots begin thickening.

Externally, the parts that are distinguishable of tuberous roots of an adult cassava plant are the tuberous portion proper; its distal extreme, which may still retain its fibrous character (Figure 2-8); and its

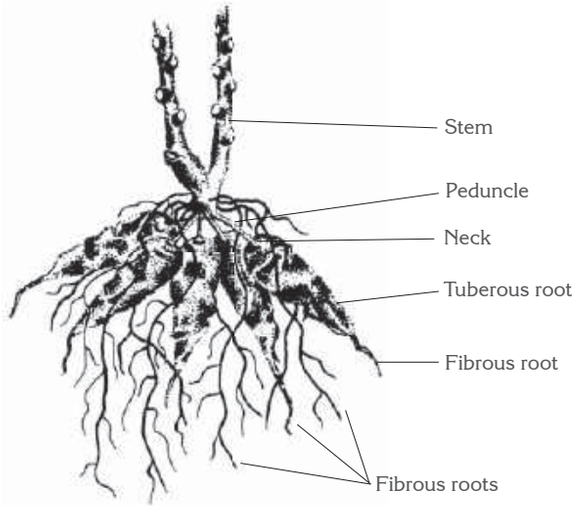


Figure 2-8. Drawing showing the components of the cassava root system (from Domínguez et al. [1983]). Ideally, with either short or long peduncles.

upper or proximal extreme, or neck or "peduncle", which also remains fibrous and joins the tuberous section to the stem. Neck size ranges from being absent or very short (<1 cm) to being longer than 8 cm. The depth at which the stake is buried affects peduncle length, which tends to be longer as stake depth is greater. Neck length is a characteristic of commercial interest. When it is very short it hinders separation of tuberous roots from their stems, resulting in injuries to the tuberous area and accelerating postharvest physiological deterioration (PPD). When the peduncle is too long, it results in higher losses, as the peduncle breaks more easily during harvest, leaving roots of commercial interest in the ground.

Roots may be highly variable in shape and size, depending on both variety and the environmental conditions under which the plants grow (Figure 2-9). However, when varieties are evaluated over numerous experiments, clear differences do appear, with some varieties tending to produce large roots and others having consistently smaller roots than the rest. The roots may be cylindrical, fusiform, or conical in shape, with intermediate forms such as cylindrical-conical frequently occurring.

The distribution of roots in the soil depends on both genetic and cultural factors. Varieties that tend to produce roots with long necks or peduncles also have their roots distributed in a scattered fashion, covering a greater area of soil than those varieties with "sessile" roots (i.e., with absent or very short necks). The way stakes are planted also affects the pattern in which roots will be distributed. When a stake is planted vertically, it produces roots around the callosity that forms at the stake's lower extreme. Some roots growing from lateral buds on the stake may also become tuberous roots. Tuberous roots tend to explore and be located in deeper strata of the soil. When the stake's position is at an angle to the soil's surface, tuberous roots again tend to form at the callosity and, as in the previous case, other roots may emerge from those lateral buds that are under the soil. If the stake is placed horizontally, then tuberous roots are distributed along the stake, as they are formed at both the lateral buds and the two extremes of the stake. Roots location also tends to be closer to the surface and more disperse, thus facilitating harvest.

Figure 2-9. Different shapes of cassava roots (conical, cylindrical, and long) with and without constrictions.

The tissues that compose a tuberous root are, successively from outside in, the peel, pulp, and central fibers (Figure 2-10). A highly relevant aspect in cassava use is the presence of a cyanogenic glucoside called linamarin. This glucoside, in the presence of an enzyme (mainly linamarase) and acids, is hydrolyzed to produce hydrocyanic acid in dosages that range from innocuous, through poisonous, to lethal. This reaction occurs spontaneously in decomposed plant tissues or in the digestive tract of animals. Hydrocyanic acid production is particularly high in root peel. Other plant tissues (including leaves) also have cyanogenic potential. Depending on cyanogenic glucoside levels, some publications will classify sweet cassava (low cyanogenic potential) as *M. utilissima*, while classifying bitter cassava (high cyanogenic potential) as *M. esculenta*.

The cyanogenic potential of different tissues of a cassava plant is greatly affected by the environmental conditions under which it grows and its age at harvest. Roots of a given cultivar can be sweet in a particular site, but bitter in other locations. Usually, however, the cyanogenic potential of bitter varieties tends to be

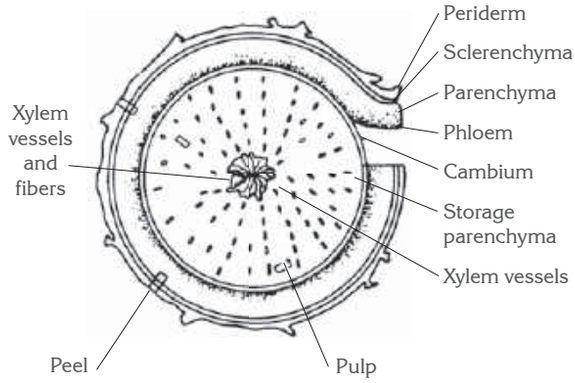


Figure 2-10. Cross-section of a tuberous cassava root (from Domínguez et al. [1983]).

consistently higher (to as much as 1000 mg of acid per kg of fresh roots) across numerous evaluations than for sweet varieties (20 mg/kg of root). Apparently, there are no cyanogen-free cassava varieties.

Root peel. This tissue comprises the periderm and cortex. The periderm consists of dead cork cells (suber or phellem) that envelop the root surface. As the root increases in diameter, the continuity of cellular layers breaks, causing longitudinal fissures that characterize the surface of the cassava root. The way in which these fissures are produced, and the resulting appearance, are frequently used to identify cultivars for marketing purposes. Underneath these fissures, new cork cells are formed from the phellogen, re-establishing the continuity of this type of tissue over the root's entire surface. In addition to the periderm's texture, which can be rugose to more or less smooth, external color is also used to identify cultivars, as it is a highly stable morphological characteristic. Root color may range from white or cream, through pale coffee-colored, to dark brown.

Below the periderm is the cortex or cortical layer (phelloderm). This tissue is 1 to 5 mm thick (Pérez et al. 2011), with a color of its inner layer ranging from white, through cream, to pink. This characteristic is also used, even by housewives, to identify cultivars. Within the cortex, compressed phloem tissues are found, containing the highest concentrations of cyanogenic glucoside. In this layer, lactiferous canals can also be seen, especially in young roots.

Pulp. This tissue constitutes the usable part of the root and is therefore the tissue of greatest economic interest. It appears as a solid mass, composed mainly of secondary xylem tissue derived from the cambium, the cells of which contain starch in abundance and in the form of round granules of unequal sizes. Pulp is also formed by parenchymatous cells that, in the case of cassava, develops to such a magnitude that the conductive xylem tubes remain reduced to small isolated groups scattered throughout the reserve parenchyma. The cambium from which pulp tissues are derived is found in the pulp's outermost part, separating the pulp from the cortex. This cambium also generates secondary phloem cells towards the exterior.

The parenchyma cells that form most of the cassava root pulp contain one to numerous amyloplasts. Within these, starch is accumulated as more or less spherical often truncated granules, although a great diversity of shapes exists such as cupuliform, biconcave-convex, and mitriform (Castilloa et al. 1982). Starch granule size is variable, and is, to some degree, determined genetically according to the variety. Starch granule shape and size are characteristics of great practical relevance to industry, as described below.

Central fibers. These fibers, forming the center of the root, comprise rows of parenchyma and xylem sclerenchyma vessels, whose hardness, length, and width are varietal characteristics of economic importance, as they affect the culinary quality and appearance of roots cooked for human consumption.

About 80% of root fresh weight corresponds to pulp. Dry matter content of cassava roots ranges between 30% and 40%, although this range can sometimes be exceeded. The dry matter found in the parenchyma mostly (90% to 95%) constitutes the non-nitrogenous fraction, that is, carbohydrates such as starch and sugars. The rest of the dry matter corresponds to fiber (1% to 2%), fats (0.5% to 1.0%), ashes or minerals (1.5% to 2.5%), and protein (about 2%). Finally, we point out that starch comprises most of the carbohydrates (96%) and is, therefore, the principal component of dry matter in the root.

Nutritional value of the roots. Without a doubt, the principal economic value of the cassava crop lies in its roots. Cassava roots, being storage organs for energy, have various uses as human food, animal feed, and starch extraction. Table 2-3 summarizes the principal chemical characteristics of cassava roots that have been chipped, dried, and processed into dry flour.

Most of the root content constitutes available carbohydrates. Compared with other energy sources such as maize, cassava roots have less protein (2% to 3% versus 8% to 10% for maize). This difference in protein

Table 2-3. Chemical composition of cassava flour from whole root and from root without peel (dry weight).

Component	Contents (%)	
	Root with peel	Root without peel
Dry matter	100.00	100.00
Available carbohydrates	83.80	92.40
Crude protein	3.05	1.56
Ether extract	1.04	0.88
Ash	2.45	2.00
Neutral detergent fiber	6.01	3.40
Acid detergent fiber	4.85	1.95
Hemicellulose	1.16	1.45

Data extracted from Buitrago A (1990).

content justifies cassava flour having a cost of about 70% that of maize, when it is used to formulate animal feed.

Postharvest physiological deterioration in cassava roots

Cassava roots undergo rapid deterioration once harvested, a process mentioned above as "postharvest physiological deterioration" (PPD). As a result, cassava roots must be consumed within a few days of harvest because, during the first 3 days, bluish spots begin appearing, concentrating on the root's periphery. The spots then extend to the entire tissue, turning it coffee-colored or brown and, in longitudinal sections of the roots, appearing as vascular streaks (Wheatley et al. [1983]). While little is known about PPD, its occurrence is directly associated with any mechanical damage that occurred during harvest and also on variety. Some evidence suggests that varieties with less dry matter content are more tolerant of PPD. Roots with high carotene content (the so-called "egg yolk" cassava) also tend to suffer less from PPD (Morante et al. 2010).

One cultural practice that does reduce the incidence of PPD or delay its appearance is to prune plants several days in advance of harvesting the roots (van Oirschot et al. 2000). However, pruning also notably reduces dry matter content and, as a result, starch content, while increasing total sugars content. These results illustrate the way in which these variables can be affected according to the conditions under which the plant grows and the cultural practices to which it is subjected.

Cassava starch and its properties

Starch is one of the dominant reserve substances in nature and is found as small granules deposited in seeds, tubers, and roots of different plants. Starch is a mixture of two polymers: amylose, which is linear, and amylopectin, which is branched. Table 2-4 lists some of the most relevant qualitative characteristics of cassava roots, with emphasis on starch. These results were consolidated, based on information published in several articles (Chávez et al. 2005; Ceballos et al. 2008; Morante et al. 2009; Sánchez et al. 2009).

The relative proportion of the polymers amylose to amylopectin in any starch, and their specific molecular weight, determines the physicochemical properties of the starch and its industrial properties (Sánchez et al. 2010). Analysis of these properties is fundamental to achieving an exact use of the existing genetic variability within the *Manihot* genus. Furthermore, the typical characteristics of cassava starch differ from that obtained from maize or potato, thus creating a niche whereby certain industrial processes may prefer the use of one starch over another. Two mutations affecting functional properties, granule morphology, and/or biochemical characteristics of cassava starch have also been reported (Ceballos et al. 2007, 2008).

Table 2-4. Qualitative characteristics of cassava roots.

Trait	Average	Minimum	Maximum
Dry matter content (%)	33.50	14.30	48.10
Cyanogenic glucosides (ppm)	325.00	14.00	3274.00
Starch (% of dry weight)	84.50	65.00	91.00
Amylose content (% total starch)	20.70	15.20	26.50
Starch granule size (μm)	16.29	13.97	18.73
Total sugars (% of dry weight)	3.75	0.20	18.80
Reducing sugars (% of dry weight)	1.31	0	15.70
Amylose (% of starch)	20.70	15.10	26.50
Total carotenoids (μg/g fresh root)	8.84	3.39	18.87

SOURCES: Chávez et al. (2005); Ceballos et al. (2008); Morante et al. (2009); Sánchez et al. (2009).

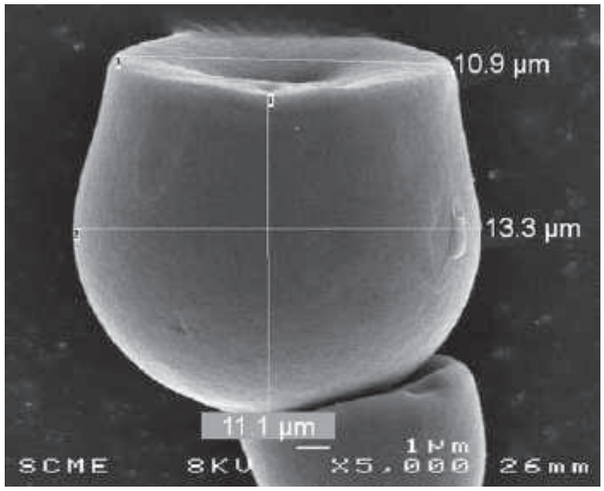
The principal physicochemical properties of a starch are proximal composition; granule characteristics (size and shape); crystalline nature; molecular weight; swelling power; solubility; relative amylose content; and characteristics of the starch paste.

The protein content of cassava starch (0.1%) is very low, compared with that of rice (0.45%) or maize starch (0.35%). Residual protein can impart a floury flavor and give these starches a tendency to foam.

Potato and cassava starch granules contain negligible amounts of fatty substances, compared with cereal starches such as maize (0.6%) and rice (0.8%). Such a composition favors cassava starch, as these lipids form a complex with amylose that tends to prevent starch granules from swelling and solubilizing, therefore requiring high temperatures (>125 °C) to break the amylose-lipid structure and dissolve the amylose fraction. The presence of fatty substances can also create problems of rancidity during storage.

Cassava starch granules are round, with truncated terminals and a well-defined nucleus (thread). Size varies from 5 to 35 μm, with averages between 15 and 18 μm. A mutation that severely affects granule size has recently been reported (Ceballos et al. 2008; Figure 2-11). Starch

(A)



(B)

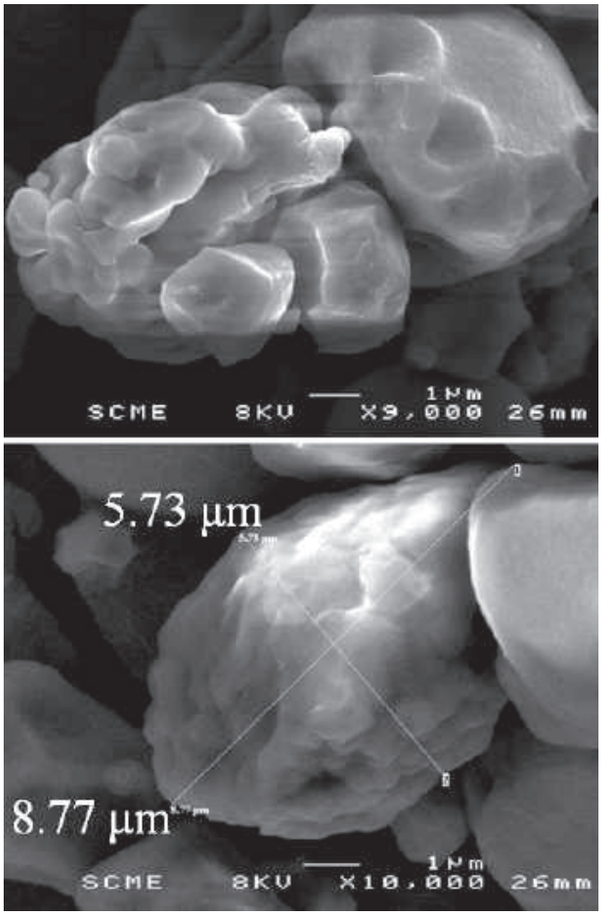


Figure 2-11. Scanning electron microscope photographs of **(A)** normal and **(B)** mutant cassava starch granules.

granules of rice, maize, and waxy maize have a polyhedral form, while potato starch granules are ovoid and larger, with sizes ranging between 5 and 100 μm, with an average of 33 μm. The granule size for maize and waxy maize starches is intermediate, between 3 and 26 μm, with an average of 15 μm, and similar to that of cassava starch granules. Rice starch granules are smaller, varying between 3 and 8 μm. They are regarded as more resistant to high-temperature processes such as sterilization and to be more digestible.

X-ray diffraction patterns of native cassava starch granules have been reported as intermediate (type C) between the characteristic patterns of cereal starches (type A) and fruit and tuber starches (type B). Crystallization levels in cassava starch are about 38% (Rickard et al. 1991). Granule crystallinity is essentially due to amylopectin. The small granule mutation of cassava affects crystallinity, branching pattern, and amylose content (Rolland Sabaté et al. 2012).

When an aqueous starch suspension is subjected to heating, granules slowly begin absorbing water and increasing in size. They initially hold their optical properties, including the ability to refract polarized light (birefringence), which is due to the alignment of molecules with no starch granules. Birefringence in cassava starch granules declines at temperatures between 58 and 64 °C, compared with that in maize starch granules, which declines between 62 and 68 °C.

Starch granules, as mentioned, are composed of two polysaccharides with glucan links: amylose and amylopectin. Amylose is basically a linear polymer of α (1-4) units. Amylopectin comprises the greater component and consists of a branched polymer of α (1-4) and α (1-6) units. In some starches, granule size is related to the amylose-to-amylopectin ratio (Delpeuch and Favier 1980). The average amylose content in the following starches are: for cassava, 20.9%; maize, 26%; potato, 24%; rice, 17%; and waxy maize, <1%. Amylose content of starches is very strongly related to some of their properties. For example, starches with high amylose content retrograde very quickly. In contrast, waxy maize, which is 100% free of amylose, is highly stable and resistant to retrogradation (i.e., the reorganization of amylose and amylopectin molecules in a crystalline structure when starch pastes are cooled). A mutation in cassava, resulting in amylose-free starch, has recently been reported (Ceballos et al. 2007).

Although varietal differences are found for rheological or functional properties of cassava starches, Brabender amylogram curves for cassava starch follow a similar pattern to that of starches with a high amylopectin content. Cassava starch gelatinizes, as do rice and waxy maize starches, at relatively low temperatures (60–67 °C), rapidly reaching the maximum peak. This implies that it is an easy starch to cook, requiring less energy for cooking. Furthermore, it has a low tendency towards retrogradation, and produces a very clear and stable gel.

Cassava starch gelatinizes in water at temperatures of more than 60 °C but, at more than 90 °C, although paste viscosity is initially high, it declines abruptly, with continuous solubilizing and agitation, and no gel is formed with subsequent cooling. Such behavior in cassava starch makes it technologically convenient as a substrate for hydrolytic processes, but inappropriate as a substitute for cereal starches in processes requiring retrogradation.

The cassava starch's properties of clarity and low retrogradation can be used in many food products. Its rheological characteristics closely resemble that of waxy maize starch.

Quality properties of starch pastes are modified during freezing, with the paste structure usually deteriorating through increased exudation of water or "syneresis". Some native starches like those of cassava and oca (*Oxalis tuberosa*) are regarded as resistant to this process (Rurales 1995; Sánchez et al. 2010).

Cassava starch pastes are stable in acid media where pH < 2.4. Normally, such acidity would destroy starch granules and the paste's physical aspect through partial or total hydrolysis.

References

To save space, the acronym "CIAT" is used instead of "Centro Internacional de Agricultura Tropical".

Allem AC. 1994. The origin of *Manihot esculenta* Crantz (Euphorbiaceae). Genet Resour Crop Evol 41:133–154.

Allem AC. 2002. The origins and taxonomy of cassava. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 1–16.

Buitrago A, JA. 1990. La yuca en la alimentación animal. CIAT, Cali, Colombia. 446 p.

Castilloa JJ; Ogura M; Quintero F. 1982. Vacuum drying: a fast and reliable SEM processing method to study starch grain racemes and morphology in fresh edible tropical roots and tubers. 10th International Congress of Electron Microscopy, vol. 3. Hamburg, Germany. p 507–508.

Ceballos H; Sánchez T; Morante N; Fregene M; Dufour D; Smith AM; Denyer K; Pérez JC; Calle F; Mestres C. 2007. Discovery of an amylose-free starch mutant in cassava (*Manihot esculenta* Crantz). J Agric Food Chem 55(18):7469–7476.

Ceballos H; Sánchez T; Denyer K; Tofiño AP; Rosero EA; Dufour D; Smith A; Morante N; Pérez JC; Fahy B. 2008. Induction and identification of a small-granule, high-amylose mutant in cassava (*Manihot esculenta* Crantz). J Agric Food Chem 56(16):7215–7222.

Chávez AL; Sánchez T; Jaramillo G; Bedoya JM; Echeverry J; Bolaños EA; Ceballos H; Iglesias CA. 2005. Variation of quality traits in cassava roots evaluated in landraces and improved clones. Euphytica 143:125–133.

CIAT. 1999. Improved cassava for a developing world—Annual report [of] Project IP-3. Cali, Colombia. 127 p.

Ciferri R. 1938. Saggio de classificazione delle razze di manioca (*Manihot esculenta* Crantz). Relaz. Monografie Agrar.-Colon. 44:1-59.

Cock JH. 1989. La yuca, nuevo potencial para un cultivo tradicional. CIAT, Cali, Colombia. 240 p. (Also available in English as Cook JH. 1985. Cassava: new potential for a neglected crop. Westview Press, Boulder, CO, USA.)

Crantz. 1766. Institutiones Rei Herbariae; nutum naturae digestae ex habitu. Vol. 1, p 167.

De Carvalho RD; Guerra M. 2002. Cytogenetics of *Manihot esculenta* Crantz (cassava) and eight related species. Hereditas 136:159–168.

Delpeuch F; Favier JC. 1980. Caracteristique des amidons de plantas alimentaires tropicales: action de l'alpha-amylase, gonflement et solubilité. Ann Technol Agric 29(I):53–57.

Domínguez CE; Ceballos LF; Fuentes C. [1983]. Morfología de la planta de yuca. In: Domínguez CE, ed. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (PNUD), Cali, Colombia. p 29–49.

Hahn SK; Bai KV; Asiedu R. 1990. Tetraploids, triploids, and 2n pollen from diploid interspecific crosses with cassava. Theor Appl Genetics 79:433–439.

Jennings DL. 1963. Variation in pollen and ovule fertility in varieties of cassava, and the effect of interspecific crossing on fertility. Euphytica 12:69–76.

Magoon ML; Krishnan R; Bai KV. 1969. Morphology of the pachytene chromosomes and meiosis in *Manihot esculenta* Crantz. Cytologia 34:612–626.

Martin FW. 1976. Cytogenetics and plant breeding of cassava. Commonwealth Bur Plant Breed Genet 46:909–916.

Montaldo A, ed. 1996. La yuca frente al hambre del mundo tropical. Universidad Central de Venezuela. Anauco Ediciones, C.A. Caracas, Venezuela. 570 p.

Morante N; Sánchez T; Ceballos H; Calle F; Pérez JC; Egesi C; Cuambe CE; Escobar AF; Ortiz D; Chávez AL. 2010. Tolerance to post-harvest physiological deterioration in cassava roots. Crop Sci 50:1333–1338.

Nassar NA; Dos Santos E; David SRO. 2000. The transference of apomixis genes from *Manihot neusana* Nassar to cassava, *M. esculenta* Crantz. Hereditas 132:167–170.

Nassar NMA; Ortiz R. 2008. Cassava genetic resources: manipulation for crop improvement. Plant Breed Rev 31:247–275.

Olsen KM; Schaal BA. 2001. Microsatellite variation in cassava (*Manihot esculenta*, Euphorbiaceae) and its wild relatives: further evidence for a southern Amazonian origin of domestication. Am J Bot 88(1):131–142.

Pax, F. 1910. *Manihot* Adans. In: Engle Pflanzenreich IV 147(Heft 44):21-111.

Pérez JC; Lenis JI; Calle F; Morante N; Sánchez T; Debouck D; Ceballos H. 2011. Heritability of root peel thickness and its influence in extractable starch from cassava (*Manihot esculenta* Crantz) roots. Plant Breed 130:688–693.

Pohl J. 1827. Plantarum Brasiliae Icones et Descriptiones 1:17–56.

Rickard JE; Asoka M; Blanshard MV. 1991. The physico-chemical properties of cassava starch. Trop Sci 31:189–207.

Rogers DJ; Appan SG. 1973. *Manihot* and manihotoides (Euphorbiaceae): a computer-assisted study. Flora Neotropica, Monograph No. 13. Hafner Press, New York.

Rolland-Sabaté A; Sánchez T; Buléon A; Colonna P; Jaillais B; Ceballos H; Dufour D. 2012. Structural characterization of cassava, maize and potato starches with low and high amylose contents. Food Hydrocolloids 27:161–174.

Rurales J. 1995. Caracterización de las propiedades reológicas y nutricionales del almidón nativo y gelatanizado de achira (*Canna edulis*). Conferencia Internacional en Biodisponibilidad de Nutrientes, March, 1995. Escuela Politécnica Nacional (EPN), Quito, Ecuador. p 179–188.

Sánchez, T; Mafla G; Morante N; Ceballos H; Dufour D; Calle F; Moreno X; Pérez JC; Debouck D. 2009. Screening of starch quality traits in cassava (*Manihot esculenta* Crantz). Starch/Stärke 61:12–19.

Sánchez T; Dufour D; Moreno IX; Ceballos H. 2010. Pasting and gel stability of waxy and normal starches from cassava, potato, maize, and rice under thermal, chemical and mechanical stress. J Agric Food Chem 58:5093–5099.

van Oirschot QEA; Quirien EA; O'Brien GM; Dufour D; El-Sharkawy MA; Mesa E. 2000. The effect of pre-harvest pruning of cassava upon root deterioration and quality characteristics. J Sci Food Agric 80:1866–1873.

Wang C; Lentini Z; Tabares E; Quintero M; Ceballos H; Dedicova B; Sautter C; Olaya C; Zhang P. 2010. Microsporogenesis and pollen formation in cassava. Biol Plant 55(3):469–478.

Wheatley C; Lozano C; Gómez G. [1983]. Deterioración postcosecha de raíces de yuca. In: Domínguez CE, ed. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (PNUD), Cali, Colombia. p 493–510.

CHAPTER 3

Cassava Productivity, Photosynthesis, Ecophysiology, and Response to Environmental Stresses in the Tropics:

A Multidisciplinary Approach to Crop Improvement and Sustainable Production

Mabrouk A. El-Sharkawy[1], *Sara M. de Tafur*[2], *and Yamel López*[3]

Introduction

Cassava (Euphorbiaceae: *Manihot esculenta* Crantz) is also called manioc, yuca, or mandioca. It is widely grown for its starchy roots, which are used as a staple food and animal feed. Crops are cultivated throughout the tropics and subtropics of Africa, Asia, and Latin America, between latitudes 30° N and 30° S, and from sea level to more than 2000 m above sea level (masl)[4]. Growers are mostly farmers who live in areas of marginal environments that characteristically possess highly eroded, low-fertility, acidic soils. Farmers are usually too resource-poor to afford applications of agrochemicals (El-Sharkawy 1993, 2004; Ruppenthal et al. 1997; Fermont 2009).

Because cassava has an inherent tolerance of various edaphoclimatic stresses, the crop is expanding into more marginal lands, particularly in sub-Saharan Africa (Romanoff and Lynam 1992), where other staple food crops yield poorly (El-Sharkawy 1993; de Tafur et al. 1997b; Cadavid et al. 1998; Flörchinger et al. 2000).

Cassava storage roots are used as a source of carbohydrates (protein is less than 3% in dried roots), mainly for human consumption. It is prepared fresh, as in the case of sweet cultivars, which have low contents of cyanogenic glucosides. It is also processed, particularly in the case of bitter cultivars, which are high in cyanogenic glucosides into dried products such as flour, starch, or animal feed (Dufour 1988; Essers 1995; Balagopalan 2002; Westby 2002). Cassava roots are highly perishable once harvested (van Oirschot et al. 2000), and must be used immediately or processed into dried products. Sometimes, however, pruning the crop 3 weeks before harvest can reduce deterioration.

Regardless of its attributes and potential productivity, the cassava crop has received little attention from policymakers or researchers in the developing countries where it is widely grown. Even so, limited work was carried out in parts of Africa, Asia, and Latin America until late 20th century (Verteuil 1917, 1918; Nijholt 1935; Cours 1951; James 1959; Hunt et al. 1977; Cock 1985), when cassava research increased exponentially.

Cassava is the most important source of dietary carbohydrates after rice, sugarcane, and maize for over 500 million people in the developing countries of the tropics and subtropics. Yet, the crop was overlooked by the so-called "Green Revolution" created through the efforts of international agricultural research centers in the 1960s. These centers aimed to improve major cereal crops such as wheat, rice, and maize with the help of and funding by a few international agricultural development and research agencies. In 1971, the Consultative Group on International Agricultural Research (CGIAR) was established under the sponsorship of the World Bank, the United Nations Development Programme (UNDP), and the Food and Agriculture Organization of the United Nations (FAO) (Wortman 1981). This Group gave high priority to research on other crops, including cassava, and on production ecosystems in the humid tropics of Africa (through the International Institute of Tropical Agriculture [IITA], based in Nigeria) and South America (through the Centro Internacional de Agricultura Tropical [CIAT], based in Colombia).

Given the necessary financial support, international multidisciplinary teams of scientists were able, for the first time, to conduct extensive research on cassava. They

1. Plant Physiologist, formerly of CIAT, Cali, Colombia. Present address: A.A. 26360, Cali, Colombia. E-mail: mabrouk99@hotmail.com
2. Plant Physiologist, Associate Professor of UN–Palmira, Colombia. E-mail: msmejiat@unal.edu.co
3. Plant Physiologist, Emeritus Professor of UN–Palmira. E-mail: lopezyamel@yahoo.com
4. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

collaborated with the few, already existing, national research programs to improve germplasm collection and characterization, breeding, agronomy, cropping systems management, pest-and-disease control, and crop use. These activities were based on increased understanding of the physiological processes involved. Various researchers reviewed results on many aspects of cassava research in Africa, Asia, and Latin America over the last 3 decades. These authors include Kawano (2003) and others, working on different continents, who contributed chapters to the book entitled *Cassava*: *biology, production and utilization,* edited by Hillocks et al. (2002).

In this chapter, we review research, both published and unpublished, conducted at CIAT during more than 15 years on cassava productivity, physiology, and ecophysiology in response to environmental stresses normally encountered in the tropics. The review addresses a need to assemble and integrate this dispersed information for scientists in general and for those concerned with cassava in particular. Focus is on the strategy adopted to improve the crop, taking into account the conditions faced by cassava growers who lack the resources to use high-production inputs. This approach contrasts with the capital-intensive practices used in the Green Revolution crops.

Original results were regularly documented and reported in progress annual reports that were exchanged across countries (CIAT Reports 1983 to 1998), and published in peer-reviewed technical journals, reviews, students' theses, proceedings, and books (Porto 1983; El-Sharkawy and Cock 1984, 1986, 1987a, 1987b, 1990; El-Sharkawy et al. 1984a, 1984b, 1984c, 1984d, 1985, 1990, 1992a, 1992b, 1993, 1998a, 1998b, 2008; Cock et al. 1985, 1987; Veltkamp 1985; Cock and El-Sharkawy 1988a, 1988b; Guzman 1989; El-Sharkawy 1990, 1993, 2004, 2005, 2006, 2010; Bernal 1991; Hershey and Jennings 1992; Caicedo 1993; López et al. 1993; Pellet and El-Sharkawy 1993a, 1993b, 1994, 1997; Tenjo et al. 1993; Tscherning et al. 1995; Cayón et al. 1997; de Tafur et al. 1997a, 1997b; Cadavid et al. 1998; El-Sharkawy and Cadavid 2000, 2002; Flörchinger et al. 2000; de Tafur 2002; El-Sharkawy and de Tafur 2007, 2010).

Cassava Research Strategy at CIAT

The multidisciplinary cassava program at CIAT was established in the early 1970s. Having a global mandate for cassava, the Center focused its research strategy on collecting, conserving, and characterizing worldwide available germplasm (most of it coming from Latin America). The program also selected and bred germplasm that was more broadly adapted to the various environments prevailing in the tropics and subtropics of both Latin America and Asia.

At first, breeding objectives were directed towards developing high-yielding cultivars for favorable conditions where biotic and abiotic stresses were absent (Kawano et al. 1978; Cock et al. 1979). This strategy focused on selecting for high yield per unit land area and comparing with traditional vigorous cultivars and/or landraces suitable for intercropping. Another trait selected for was high dry matter content (i.e., high starch content) in storage roots. Harvest indexes (HI, where HI = root yield/total plant biomass) were selected to be higher than those (<0.5) usually found in low-yielding traditional varieties and landraces (Kawano 1990, 2003). This early work showed that cassava germplasm is genetically diverse, with potential for high productivity in near-optimal environments and as having sufficient genetic resources for tolerating a range of pests and diseases. Thus, the need to transfer traits from wild relatives (advocated even as recently as 2010 by Nassar and Ortiz) is largely obviated.

However, most cassava production occurs in environments with varying degrees of stresses and with little, or no, production inputs from resource-poor farmers. Hence, later breeding strategy goals centered on selecting and developing cultivars with adequate and stable yields, and able to adapt to a wide range of biotic and abiotic stresses (Hershey 1984; Hershey et al. 1988; Hershey and Jennings 1992; Kawano et al. 1998; Jennings and Iglesias 2002; Kawano 2003). This strategy was stimulated by cassava's inherent capacity to tolerate adverse environments, particularly those where other major staple food crops such as cereals and grain legumes would fail to produce. The strategy also aimed to avoid and/or reduce the negative consequences on the environment caused when high-input (agrochemicals) production systems are adopted (El-Sharkawy 1993).

The strategy took advantage of the wide genetic diversity found within more than 5000 accessions that were conserved at the time at CIAT headquarters (CIAT HQ). These accessions were mostly of Latin American origin, or originated in the 7 or 8 edaphoclimatic ecozones in Colombia, each of which was also characterized by high pest and disease pressures. These ecozones represent most cassava production ecosystems in the tropics and subtropics (Hershey and Jennings 1992; El-Sharkawy 1993).

In light of this environmentally sound breeding strategy, research on cassava physiology has focused on

both basic and applied aspects of the crop under prevailing environments. The goal was to better understand and elucidate the characteristics and mechanisms underlying productivity and tolerance of stresses (Cock and El-Sharkawy 1988a, 1988b; El-Sharkawy 1993, 2004). Pingali (2010) suggested that molecular biology tools would certainly help in achieving this goal, as would a deeper understanding of the agricultural systems and biology of tropical crops (including cassava plant physiology). He pointed out that temperate-zone research laboratories in countries belonging to the Organisation for Economic Co-opreation and Development (OECD) are currently not investing in such knowledge.

Objectives included (1) characterizing materials from a core collection of cassava germplasm held at CIAT for tolerance of extended water shortages, either natural or imposed, and of low-fertility soils; (2) studying leaf photosynthetic potential in relation to productivity under various edaphoclimatic conditions; and (3) identifying plant traits that may be useful in breeding programs. The multidisciplinary and interinstitutional research approach adopted was pivotal in achieving these objectives.

Exchange of Gas between the Cassava Leaf and the Environment

Responding to air humidity and water stress

Under controlled laboratory conditions, leaves, still attached to their plants, were sampled from both well-watered and water-stressed cassava grown in large pots left outdoors. The leaves' central lobes were inserted into clip-on chambers connected to an infrared gas exchange system and then exposed to high air humidity. This was followed by a short period of low humidity. Rates of CO_2 uptake at saturating photons and normal air declined sharply. The response was more pronounced in stressed plants (Figure 3-1; El-Sharkawy and Cock 1984). This effect of short exposure to dry air was totally reversible. This reaction was also observed in several woody species (Davies and Kozlowski 1974), but was only partially reversible after a much longer exposure to dry air. It resulted in about an 80% reduction in leaf photosynthesis.

Terminal leaf water potential was measured with a pressure chamber and compared with that of the free lobes of the same leaves. The lobes tested in both

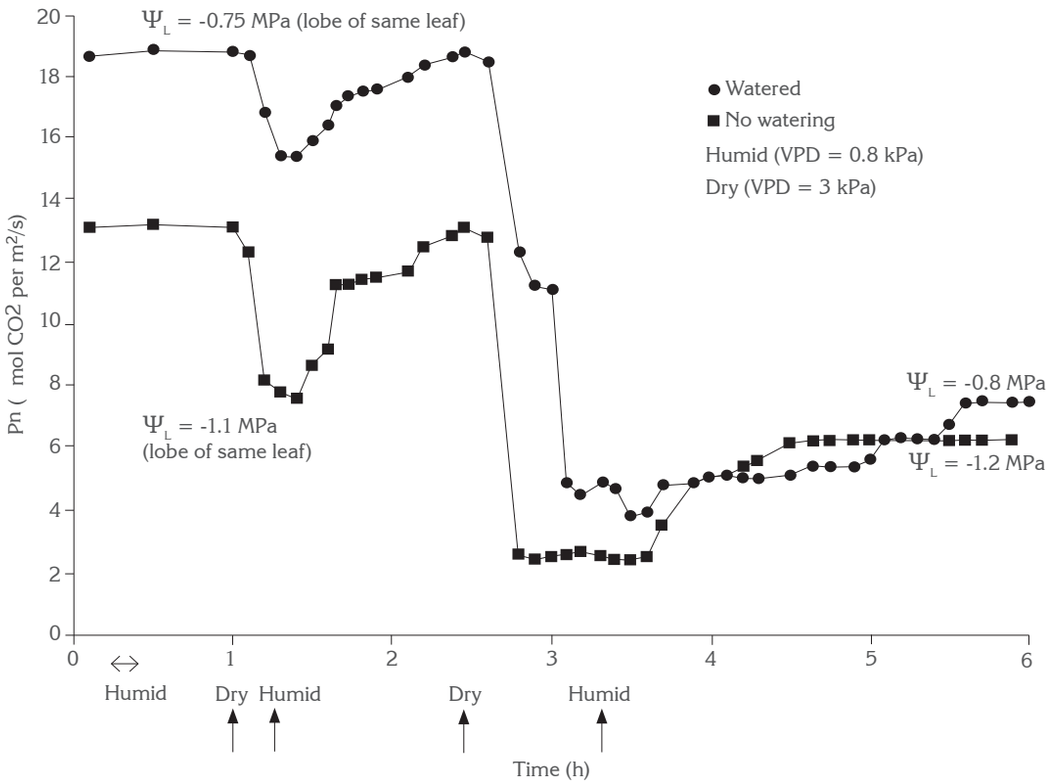


Figure 3-1. Response of leaf photosynthesis (Pn) to changes in air humidity, using plants of cassava cultivar M Col 88 grown in 40-liter pots (El-Sharkawy and Cock 1984).

well-watered and water-stressed plants remained unchanged during several hours of gas exchange monitoring. Results indicated that cassava stomata directly responded to changes in air humidity. This response was previously termed a feed-forward reaction (Cowan 1977; Farquhar 1978). It differs from the feed-backward response to changes in bulk leaf water potential. However, we did not determine abscisic acid (ABA) levels in leaves in this case. It was therefore not clear if ABA played a role in stomatal closure during this short exposure to dry air without changes in leaf water potential (Henson 1984).

When leaves were exposed to stepwise rises in leaf-to-air vapor pressure deficits (VPD), CO_2 uptake rates remained stable in the range of 1 to 1.5 kPa, and then rapidly declined above that range (Figure 3-2A). Transpiration initially increased with rising VPD up to 2 kPa, and then leveled off or declined with further increases in VPD (Figure 3-2B; Berg et al.1986; El-Sharkawy 1990). Leaf conductance also declined sharply at VPD greater than 2 kPa (Figure 3-2C).

These observations clearly showed that cassava is sensitive to changes in atmospheric humidity, irrespective of plant- or soil-water status. Furthermore, compared with several woody and herbaceous species, cassava was more sensitive to changes in air humidity (El-Sharkawy et al. 1984d, 1985; El-Sharkawy and Cock 1986; Cock and El-Sharkawy 1988b). The response was related to stomatal density and maximum leaf conductance (El-Sharkawy et al. 1984d, 1985; El-Sharkawy and Cock 1986). Cassava leaves possess large numbers of stomata on the abaxial epidermis (>400 stomata/mm^2; Pereira 1977; Connor and Palta 1981; El-Sharkawy et al. 1984b; Guzmán 1989), which may underlie its strong response to humidity (El-Sharkawy et al. 1985; El-Sharkawy and Cock 1986).

The phenomenon of direct stomatal response to air humidity was observed since the last century (Haberlandt 1914; Thoday 1938; El-Sharkawy and Cock 1986). Numerous reports showed that several herbaceous and woody plant species tended to close their stomata in response to dry air, whether within plant communities, attached leaves, or isolated epidermal strips (Hoffman and Rawlins 1971; Hoffman et al. 1971; Lange et al. 1971; Schulze et al. 1972; Aston 1976; Hall and Hoffman 1976; Lösch 1977, 1979; Rawson et al. 1977; Sheriff and Kaye 1977; Lösch and Schenk 1978; Ludlow and Ibaraki 1979; Tibbitts 1979; Farquhar et al. 1980; Hall and Schulze 1980; Jarvis 1980; Tazaki et al. 1980; Bunce 1981, 1982, 1984; Leverenz 1981; Lösch and Tenhunen 1981; Fanjul and

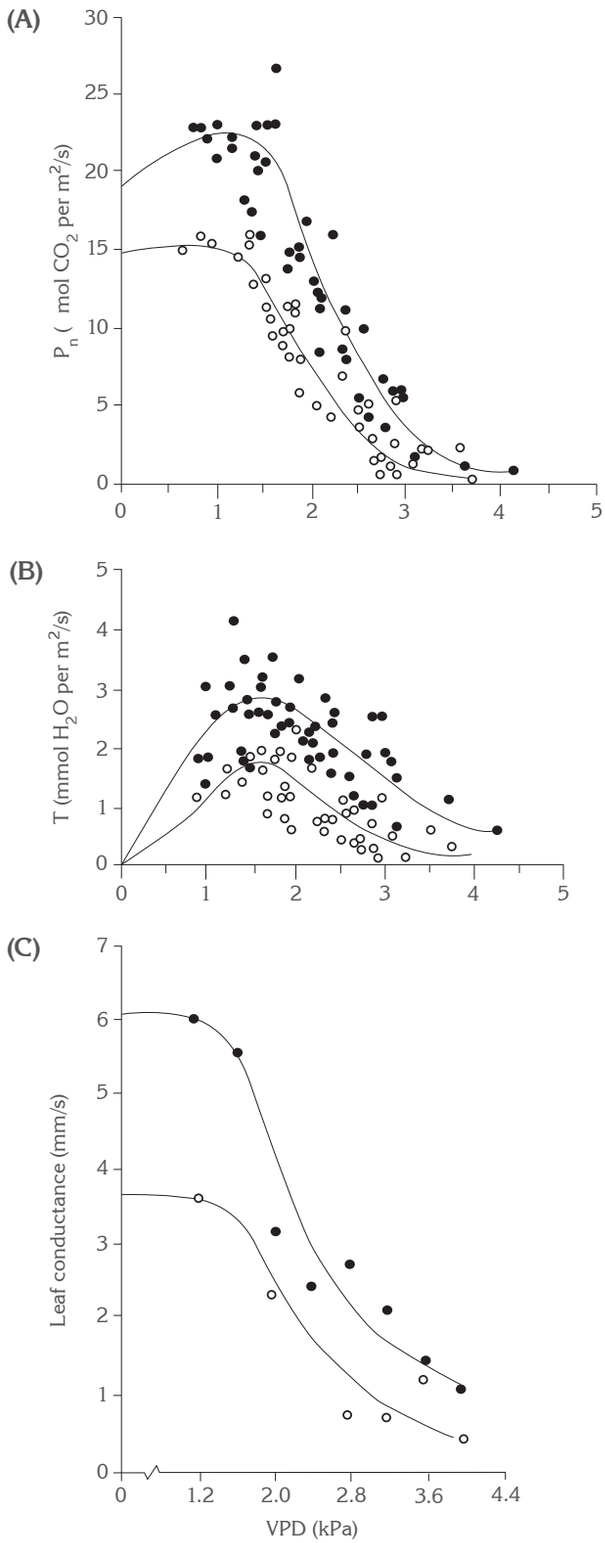


Figure 3-2. Responses of leaf photosynthesis (Pn) (**A**), transpiration (T) (**B**), and leaf conductance to water vapor (**C**) to stepwise increases in leaf-to-air vapor pressure deficit (VPD) in cassava cultivar M Col 90 (El-Sharkawy and Cock 1984).
○ refers to no watering; ● to well watered.

Jones 1982; Kaufmann 1982; Meinzer 1982; Schulze and Hall 1982; Gollan et al. 1985; Körner 1985; Körner and Bannister 1985; Jarvis and McNaughton 1986; Schulze 1986; Ward and Bunce 1986; Bongi et al. 1987; Hirasawa et al. 1988; Pettigrew et al. 1990; Held K 1991; Kappen and Haeger 1991; Tinoco-Ojanguren and Pearcy 1993).

This apparently widespread phenomenon indicated the need for detailed studies and for its consideration when modeling plant community/environment ecosystems (Jarvis and McNaughton 1986).

Mechanisms underlying stomatal response to air humidity

Stomatal movement is controlled by (1) stomata sensing changes in air humidity and (2) the so-called "peristomatal transpiration", first hypothesized by Seybold (1961/1962), where water is lost from the cuticle of the guard and subsidiary cells and their adjacent epidermal cells. The possible mechanisms underlying these activities were reviewed and discussed by many workers (Meidner and Mansfield 1968; Lange et al. 1971; Meidner 1976; Sheriff 1977, 1979, 1984; Lösch and Schenk 1978; Maier-Maercker 1979a, 1979b, 1983; Tyree and Yianoulis 1980; Lösch and Tenhunen 1981; Zeiger 1983).

Support for Seybold's hypothesis on the role of peristomatal transpiration was demonstrated through extensive research by German workers who used intact leaves and isolated epidermal strips systems without water stress (Lange et al. 1971; Maier-Maercker 1979a, 1979b, 1983; Lösch and Tenhunen 1981). Meidner and Mansfield (1968) argued that stomatal movements are unlikely to be affected by changes in atmospheric humidity, but instead by the water status of mesophyll tissue (feedback reaction).

Kramer (1983) cautioned against the hypothesized role of peristomatal transpiration until more information became available on the degree of cutinization of the mesophyll tissue (where most evaporation presumably takes place), and the inner and external walls of guard cells. Appleby and Davies (1983) demonstrated possible sites of evaporation from cuticle-free areas in the walls of guard cells of oak (*Quercus robur*), poplar (*Populus nigra*), and *Pinus sylvestris*, when these areas were exposed to the outside of the leaf during stomatal closure in dry air. Körner and Cochrane (1985) also reported relatively less cutinization of the external walls of guard cells in *Eucalyptus pauciflora*, which may underlie its stomatal sensitivity to changes in air humidity.

Sheriff (1977, 1979, 1984) suggested that the mechanism underlying direct stomatal response to low humidity involves both evaporation from the epidermis and a lower hydraulic conductivity within the leaf that probably accelerates water stress in the epidermis, regardless of leaf water content. Recently, Pieruschka et al. (2010) reported that the water balance in the epidermis is very sensitive to differences between the transpiration rate and the rate at which absorbed radiation produces water vapor inside the leaf. These authors suggested that leaf heat load is tightly linked to water transport from mesophyll cells, through the epidermis, to the leaf's environs.

This important finding further explains why cassava leaves orient themselves towards the sun in early morning and late afternoon (also called heliotropism or sun tracking) when VPD is lowest, and droop at mid-day (sun avoidance) when VPD is highest (El-Sharkawy and Cock 1984; Berg et al. 1986), thus optimizing water-use efficiency.

Tyree and Yanoulis (1980) used physical models of substomatal cavity to calculate water vapor diffusion patterns. They concluded that, because of high evaporation from guard cells, stomata could close in direct response to low humidity. They suggested that localized water stress or dehydration in guard cells may take place because of high leaf resistance to flow of water from minor leaf veins to guard cells.

A strong association between stomatal density (i.e., exposed epidermal areas) and the degree of sensitivity to changes in air humidity was observed in well-watered plants across many herbaceous and woody species (El-Sharkawy et al. 1985). Such an association may indicate the occurrence of localized dehydration in the stomatal apparatus and adjacent exposed epidermal cells. Hence, it supports a role for peristomatal transpiration in controlling stomatal movement. Moreover, the poor physical connection between the numerous stomatal areas (where evaporation may take place) and the mesophyll tissue observed in cassava leaf (El-Sharkawy and Cock 1986) may accelerate water stress in the epidermis and stomatal apparatus. Hence, the striking sensitivity to changes in atmospheric humidity without any noticeable decrease in bulk leaf water potential (Figures 3-1 to 3-3; Connor and Palta 1981; Porto 1983; El-Sharkawy et al. 1984d, 1992b; El-Sharkawy and Cock 1986; El-Sharkawy 1990; Cayón et al. 1997; de Tafur et al. 1997a).

This conclusion was further substantiated by the closure of stomata in field-grown cassava in response to

high wind speed, despite conditions of high soil moisture and high bulk leaf water potential (El-Sharkawy 1990). Bunce (1985) also reported greater water loss from the outer surface of epidermis of herbaceous species under high wind speed, thus providing further evidence to support peristomatal transpiration.

Responses of field-grown cassava to air humidity, and implications for breeding for different edaphoclimatic zones and ecosystems

Cassava stomatal sensitivity to atmospheric humidity was also observed in field-grown cassava in soils with high moisture content at two sites: the mid-altitude, Palmira experiment station at CIAT HQ, Department of Valle del Cauca; and the low-altitude Carimagua ICA–CIAT station, Department of Meta (Figure 3-3A; Cock et al. 1985; Berg et al. 1986; El-Sharkawy 1990).

An array of cultivars, representing the core collection of cassava germplasm from different habitats, was grown at a third site: CIAT's mid-altitude experiment station at Santander de Quilichao, Department of Cauca. The cultivars showed significant differences in stomatal sensitivity to humidity (Figure 3-3C; El-Sharkawy 2004). Furthermore, total biomass and storage root yield were greater in high

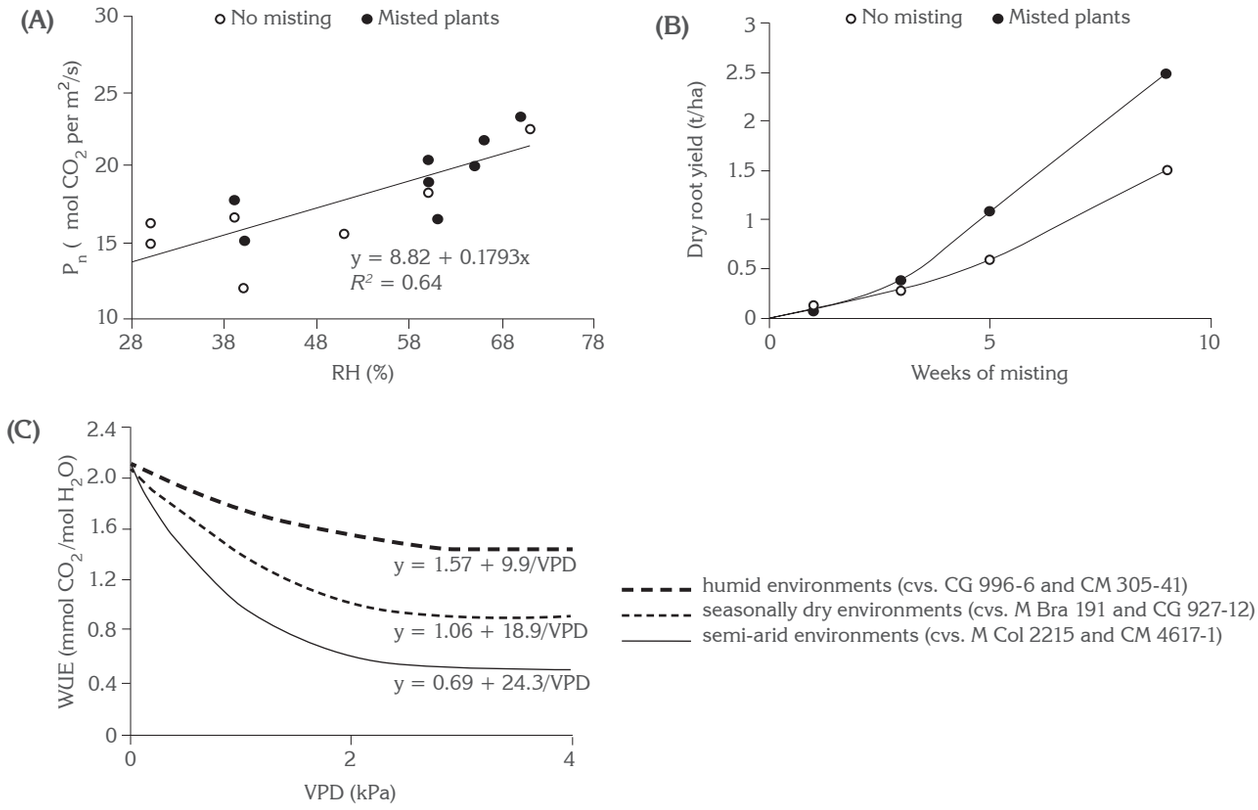


Figure 3-3. **(A)** Response of leaf photosynthesis (Pn) in cassava cultivar M Col 1684 to changes in air humidity in the field, with or without misting (Cock et al. 1985; El-Sharkawy and Cock 1986). (**B**) Oven-dried storage root yield of cv. M Col 1684 at periodic harvests after 3, 6, and 9 weeks of misting. Ages of plants at harvest were 65, 85, and 105 days, respectively. The differences in yield between the two crops were significant for all harvests ($P < 0.01$). Top biomass and leaf area index did not differ, whereas total biomass was significantly higher after 6 and 9 weeks of misting (Cock et al. 1985; El-Sharkawy and Cock 1986). **(C)** Response of leaf water-use efficiency (WUE) to vapor pressure deficit (VPD) in field-grown cassava in a mid-altitude, warm, subhumid climate. Levels of VPD progressively increased from morning to mid-day. Thirty-three clones were evaluated and were grouped according to humid, subhumid/seasonally dry, and semi-arid habitats. Sensitivity to VPD increased from humid to semi-arid habitats. Differences between plant groups illustrate the genetic diversity within cassava germplasm for response to changes in atmospheric humidity.

Adapted from El-Sharkawy 2004; MA El-Sharkawy, MC Amézquita, HF Ramírez, and G Lema 1991, unpublished.

humidity environments, particularly when enhanced by misting, leading to higher leaf photosynthesis. These findings indicated that stomatal sensitivity to changes in VPD was translated into growth at the canopy level (Figure 3-3B; Cock et al. 1985; El-Sharkawy and Cock 1986). Recent research on whole-plant-water relations of field-grown cassava under prolonged natural water deficit in Ghana (West Africa) showed that both canopy conductance and transpiration declined with increasing VPD (Oguntunde 2005; Oguntunde and Alatise 2007).

These findings have important practical implications for cassava breeding and improvement for different ecosystems and edaphoclimatic zones. For example, less sensitive cultivars should be selected and bred to maximize productivity in wet or humid zones such as the Amazon Basin, equatorial western Africa, and western Java in Indonesia; and in zones with short intermittent water deficits. For these cases, optimizing water-use efficiency is not of importance (El-Sharkawy and Cock 1986; El-Sharkawy 2004).

Less sensitive cultivars are those with hypostomatous leaves, that is, possessing lower stomatal density on leaf undersurfaces, and/or amphistomatous leaves, which possess equal conductance on both sides of the leaf blade. For more information on (1) leaf ontogenesis; (2) the impact on photosynthesis of stomatal density, size, and distribution patterns on both leaf sides; and (3) the comparative adaptive advantages of amphistomatic versus hypostomatic leaf characteristics, see Parkhurst 1978; Pospisilová and Solárová 1980; Mott et al. 1982; Tichá 1982; Gutschick 1984.

However, in subhumid or seasonally dry and semi-arid zones that characteristically have 3 months or more of water deficits, breeding and selecting for more sensitive cultivars is more advantageous. Such cultivars can conserve and deplete limited soil-water supplies more slowly. Thus, they optimize water-use efficiency, rather than maximize productivity, over a longer period during the growth cycle.

Because new leaf formation is highly restricted under prolonged drought (Connor and Cock 1981; Porto 1983; El-Sharkawy and Cock 1987b; El-Sharkawy et al. 1992b), higher degrees of stomatal sensitivity should be combined with greater leaf retention. That is, leaves both live and last longer (El-Sharkawy 1993, 2004). Leaf retention was recently found, over a wide range of cultivars and breeding lines, to be positively correlated with productivity under naturally extended water deficits (Lenis et al. 2006). Moreover, leaves of plants subjected to imposed prolonged water stress (>2 months) in subhumid zones had 40% of the net photosynthesis found in well-watered plants. Yet, they were capable of completely recovering once the stress ended (CIAT Reports 1987 to 1994; El-Sharkawy 1993). Selecting for longer leaf life span helps save dry matter already invested in leaf canopy formation (Chabot and Hicks 1982). More assimilates would therefore be diverted towards storage roots, resulting in the crop having higher HI and harvestable yield (Cock and El-Sharkawy 1988a; El-Sharkawy 1993).

For seasonally dry zones, de Tafur et al. (1997b) reported a wide range of variation in net leaf photosynthesis among rainfed cassava, as measured in the field during the driest months. The photosynthetic rate (Pn) ranged from 27 to 31 μmol CO_2 per m^2/s, with significant differences among cultivars. In semi-arid zones, Pn ranged from 7 to 20 μmol CO_2 per m^2/s, with significant differences among cultivars. Such variation could be exploited to breed improved genotypes. Host-plant tolerance or resistance to pests and diseases must also be incorporated in cultivars targeted for seasonally dry and semi-arid zones to maintain, as much as possible, a functioning leaf canopy over an extended time (Byrne et al. 1982; Hershey and Jennings 1992; Bellotti 2002; Calvert and Thresh 2002; Hillocks and Wydra 2002).

Within cassava germplasm, a wide genetic diversity, useful for breeding programs, also exists for stomatal density, with a percentage of materials possessing amphistomatous leaves. Several accessions with a significant number of stomata on upper leaf surfaces have been identified. These, however, comprised less than 5% of more than 1500 landraces and cultivars that were screened in the field. The techniques used were the transient porometer and microscopic observations of leaf-surface replicas that were made by spraying leaves with collodion solution (El-Sharkawy et al. 1984b, 1985; Guzmán 1989).

Both porometry (Kirkham 2005) and leaf-surface replicas, combined with microscopic observation, are easy to handle in screening large numbers of breeding materials in the field for stomatal characterization. The leaf-replica method, however, has some limitations where leaves are hairy and stomata sunken (North 1956; Slávik 1971). The leaf-surface replica method was effective, using tissue-cultured young seedlings (El-Sharkawy et al. 1984b). It may facilitate early screening of larger populations. Zelitch (1962) described a similar technique for obtaining stomatal impressions, using silicon rubber, combined with cellulose acetate solution.

Response to Temperature

Responses of potted cassava grown outdoors in a high-altitude cool climate and in a mid-altitude warm climate

Cassava requires a warm climate for both optimal growth and productivity. However, it is also cultivated in cool climates at high altitudes in the tropics (>1700 m) and at low altitudes in the subtropics (Irikura et al. 1979). Growth and productivity depend largely on the leaf canopy's capacity to intercept solar radiation during most of the growth cycle. They also depend on leaf photosynthetic potential and performance under prevailing field conditions (Cock et al. 1979; El-Sharkawy et al. 1990; de Tafur et al. 1997a, 1997b; El-Sharkawy 2004). We therefore studied the effects of temperature on leaf photosynthesis during growth.

To obtain temperature differences under natural conditions, we took advantage of the nearness of a high-altitude site (2000 m; 17 °C mean annual temperature), located 18 km from CIAT HQ, itself located at about 965 masl, with a mean annual temperature at 24 °C. Several cultivars, representing several habitats, were grown in large pots (>40 L), which contained a mixture, by weight, of 40% top soil, 33% compost, 27% sand, and sufficient fertilizer. The potted plants were left outside and kept well-watered throughout their growth at the two sites. Solar radiation at the high-altitude location was similar to that of CIAT HQ in terms of duration and intensity (El-Sharkawy et al. 1992a, 1993).

Measurements of leaf gas exchange were conducted under controlled conditions in the physiology laboratory at CIAT. An open-ended, infrared, CO_2 analyzer was used to test responses to both leaf temperature at saturating photons levels (>1800 μmol per m^2/s) and to light intensity. Figures 3-4A to 3-4C (El-Sharkawy et al. 1984c, 1992a, 1993; El-Sharkawy and Cock 1990) illustrate responses of leaves grown in the cool climate and then acclimated for 7 days to the warm climate. They also show responses of leaves of the same plants that were later developed in the warm climate. The two cultivars were adapted to contrasting habitats: M Col 2059 from a cool, humid, high-altitude zone (Colombia) and M Bra 12 from a hot, humid, low-altitude zone (Brazil).

In both cultivars, net leaf photosynthetic rates were substantially lower in leaves that had developed in the cool high-altitude climate than for those that developed in the mid-altitude warm climate (Figures 3-4A and 3-4B). Leaves that had developed first in the cool climate and were then acclimated for 7 days in the warm climate partially recovered their photosynthetic capacities. Rates, however, remained much lower than those of the leaves developed in the warm climate.

In the hot-climate cultivar (M Bra 12), maximum rates in all sets of leaves were higher than those in the cool-climate cultivar (M Col 2059). This trend was also observed over the wide range of leaf temperatures tested. A wide temperature optimum of 25–40 °C and peaks at 30–35 °C were observed in the hot-climate cultivar for all sets of leaves. In the cool-climate cultivar, there was an apparent upward shift in optimal temperature in both the acclimated and warm-climate leaves. In contrast, a wide plateau occurred for the non-acclimated cool-climate leaves. In both cultivars and in all sets of leaves, rates declined rapidly at temperatures higher than 40 °C, reaching zero at 50 °C.

During the 7 days of acclimation in the warm climate, changes in non-stomatal components of photosynthesis (photosystems I and II, and CO_2 fixation reactions) were more likely than changes in physical stomatal characteristics (Berry and Björkman 1980). Moreover, the photosynthetic rates in cool-climate leaves were much lower at all photon levels and had less saturation irradiance than either the acclimated or warm-climate leaves (Figure 3-4C).

The differences in radiant energy saturated rates among these sets of leaves may be attributed mainly to differences in CO_2 fixation capacity (Björkman et al. 1980). Warm-climate leaves were not photon-saturated at 1800 μmol per m^2/s. The same phenomenon was observed in several field-grown cassava cultivars in a warm climate when leaf photosynthesis was measured during the high rainfall period (Figure 3-5; El-Sharkawy and Cock 1990; El-Sharkawy et al. 1992a, 1993). Pereira (1977) also reported increases in cassava leaf net photosynthesis with rising photon flux density up to 2000 μmol per m^2/s. Maximum photosynthetic rates of several cultivars of field-grown cassava were more than 40 μmol CO_2 per m^2/s, with a mean C_i/C_a ratio of 0.42 (Table 3-1). These values are comparable with those observed in C_4 species and much less than those obtained in C_3 species.

These data indicate that cassava possesses high photosynthetic capacity, which is fully expressed only in hot humid climates with high solar radiation. Thus, when grown in environments, either natural or artificial, that deviate from these fundamental climatic

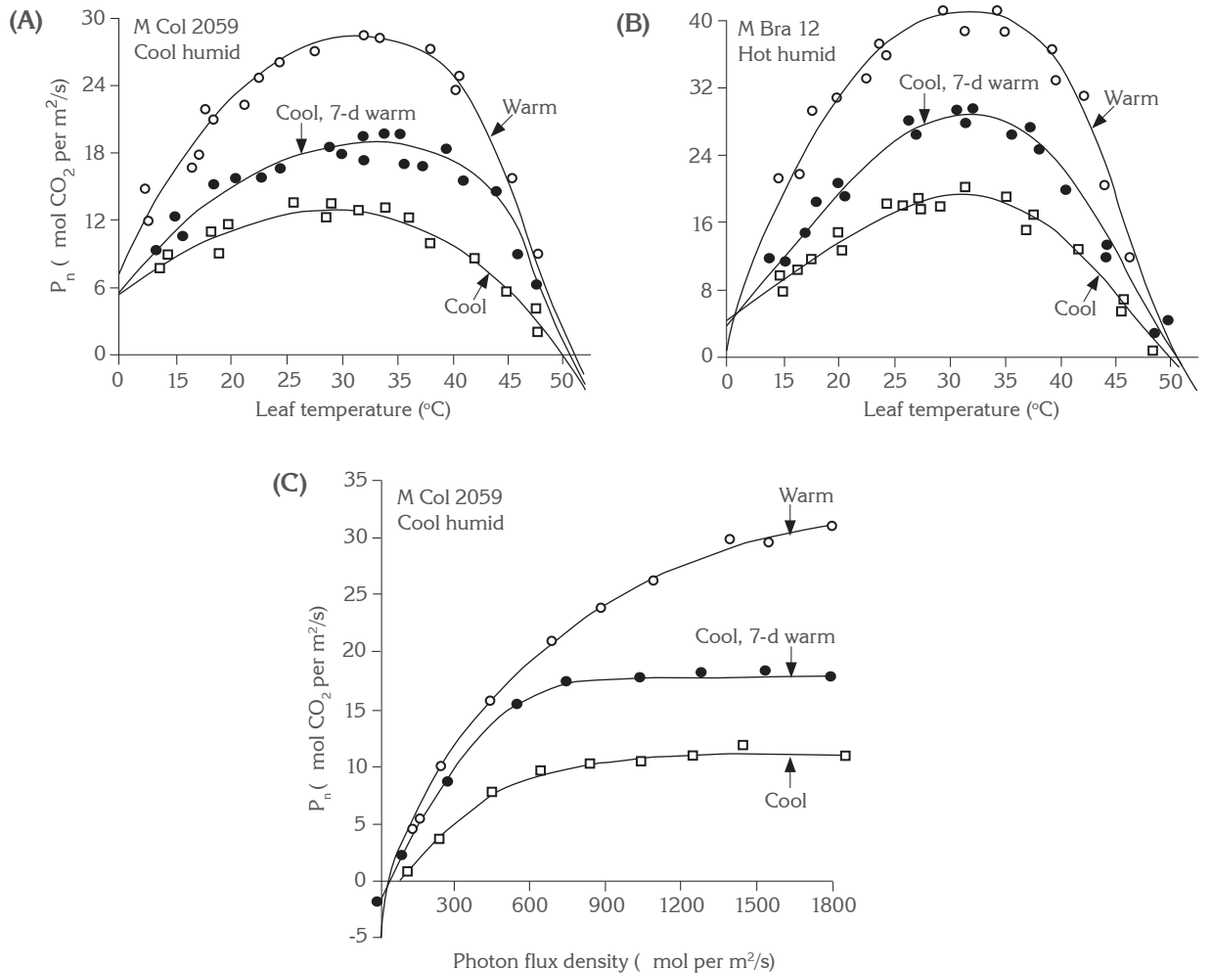


Figure 3-4. Response in terms of net photosynthetic rate (Pn) of cassava to leaf temperature. **(A)** Cultivar M Col 2059 in a cool habitat; **(B)** cv. M Bra 12 in a hot humid habitat; **(C)** response in terms of net photosynthetic rate (Pn) to PAR irradiance in cv. M Col 2059. □ refers to leaves developed in a cool climate; ● to leaves developed in a cool climate and then acclimated for 1 week in a warm climate; ○ to newly developed leaves in a warm climate.
Note that (1) an apparent upward shift in optimal temperature is observed from cool to warm-acclimated and warm-climate leaves; (2) the lack of light saturation in warm-climate leaves, compared with cool-and-warm-acclimated leaves; and (3) the higher maximum photosynthetic rates in all sets of leaves of cv. M Bra 12 from the hot-humid habitat, compared with the cool-climate cv. M Col 2059.
References: CIAT Report 1992; El-Sharkawy et al. 1992a, 1993.

requirements, its photosynthetic capacity is not fully expressed (Gleadow et al. 2009).

Studies of plants grown in the greenhouse or growth chamber showed much lower photosynthetic rates (from 15 to 20 μmol CO_2 per m^2/s), lower saturation radiation, lower optimal temperatures, and lower photosynthetic enzyme activity (Aslam et al. 1977; Mahon et al. 1977a, 1977b; Edwards et al. 1990; Angelov et al. 1993; Ueno and Agarie 1997; Gleadow et al. 2009). These studies are of limited value if their results are to be interpreted in relation to cassava's real potential and to the underlying mechanisms controlling the overall photosynthetic process (El-Sharkawy and Cock 1987a; El-Sharkawy et al. 1992a, 1993; El-Sharkawy 2004).

Lower photosynthetic rates of potted cassava grown in growth chambers or greenhouses probably resulted from lower activities of photosynthetic enzymes. Such results have been long observed in other plant species. Other factors may have also played a part such as changes in leaf anatomy because of exposure to suboptimal irradiance and air temperatures during leaf development; imbalances in source-sink relations in the whole plant system; and pot size, which

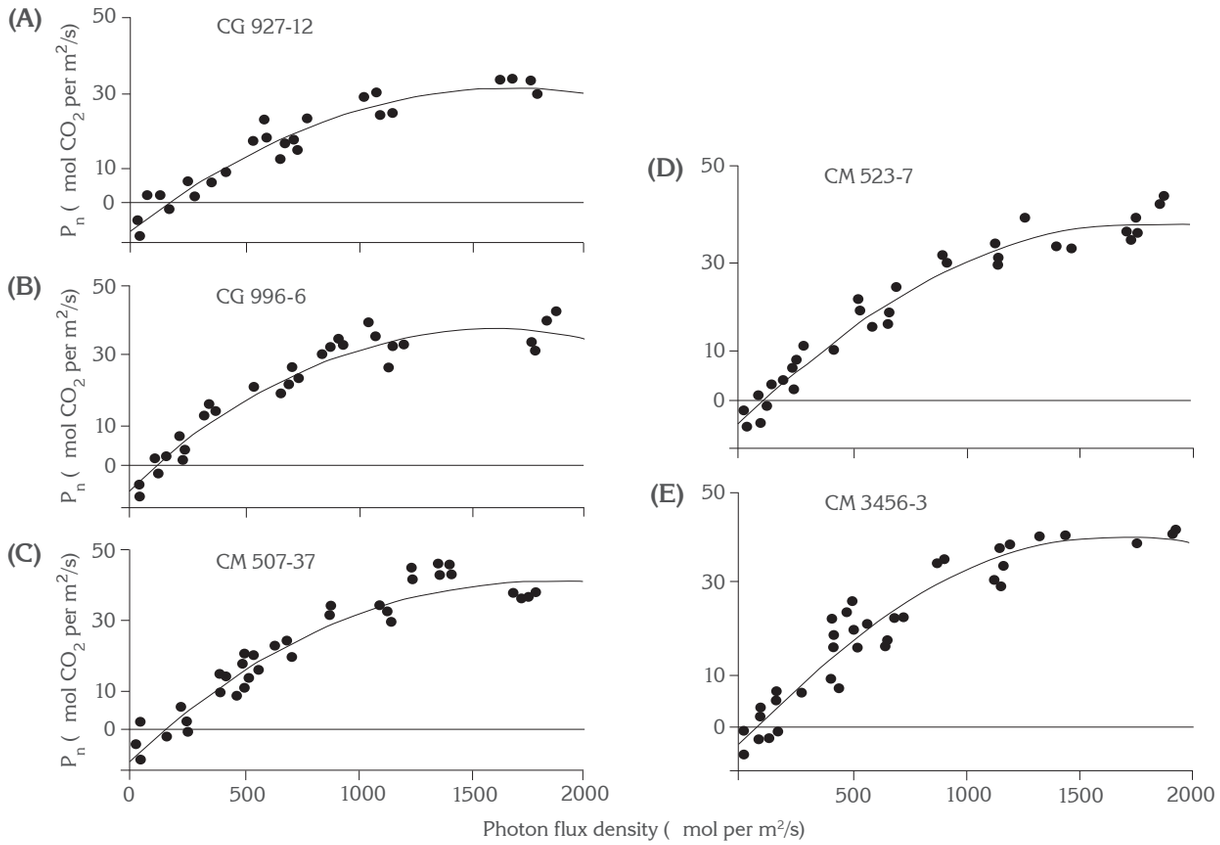


Figure 3-5. Responses in terms of leaf photosynthesis (Pn) to PAR irradiance in upper-canopy leaves of five cultivars of field-grown cassava during the rainy season (CIAT Report 1992; El-Sharkawy et al. 1992a, 1993).

may have encouraged feed-back inhibition of leaf photosynthesis because of restricted root sinks for assimilates (Nösberger and Humphries 1965; Humphries 1967; Neales and Incolls 1968; Moss and Musgrave 1971; Nobel 1976, 1980; Boardman 1977; Björkman et al. 1980; Herold 1980; Nobel and Hartsock 1981; Sesták 1985; Bunce 1986; Ho 1988; Wardlaw 1990; Evans 1993; Pellet and El-Sharkawy 1994; Gleadow et al. 2009).

El-Sharkawy (2005) recently reviewed and discussed the problems of plant acclimation/adaptation to environments that are normally encountered but bewilder scientists in general and plant photosynthesis researchers in particular. He pointed out the limited value of data collected on plants grown in environments that are inappropriate for optimal growth. He also emphasized their invalidity for use in crop modeling or extrapolating and predicting responses in natural environments if the necessary calibration is not carried out, that is, field data collected under the conditions in which plants or crops are normally grown must be taken into account for these purposes.

This conclusion on the invalidity of data obtained with plants inappropriately grown was further substantiated by recent findings in a wide range of long-term CO_2-enrichment field trials (Long et al. 2006). In these trials, the degree of enhancement in both leaf photosynthetic rate and yield of various crops by elevated CO_2 (as compared with crops grown at ambient CO_2) were much less than those previously observed with plants grown in greenhouses, growth chambers, or field enclosures, where air humidity and temperatures were probably also elevated. Such findings confirmed the limitations of using data from inappropriately grown plants for crop modeling or predicting anticipated effects of rising atmospheric CO_2 levels and air temperature on plant photosynthesis and productivity (i.e., the effects of global climate change) (Gleadow et al. 2009).

Table 3-1. Net leaf photosynthesis (P_n) of field-grown cassava at Santander de Quilichao, Department of Cauca, Colombia (warm subhumid), during the 1990/91 season. Maximum photosynthetic rates were obtained during wet periods and high air humidity. Note the C_i/C_a values, which are comparable with those of C_4 species and much lower than those of C_3 species, indicating cassava's high photosynthetic capacity, as expressed in near-optimal environments. In this group of cultivars, the average seasonal P_n was correlated with final root yield.

Cultivar	Maximum net photosynthesis (n = 6) μmol CO_2 per m^2/s	C_i/C_a (n = 6)	Seasonal average net photosynthesis (n = 30) μmol CO_2 per m^2/s
CG 996-6	49.7	0.37	33.8
M Bra 191	47.4	0.37	35.5
CM 4864-1	45.1	0.39	34.0
CM 4145-4	43.9	0.40	31.7
CM 3456-3	43.7	0.43	31.9
CM 507-37	43.7	0.38	28.7
CM 4716-1	43.6	0.42	31.8
M Col 1684	43.0	0.42	30.9
CM 4575-1	42.8	0.39	33.2
CM 4617-1	42.8	0.46	31.4
CM 523-7	42.3	0.45	30.1
CMC 40	42.3	0.44	30.3
CM 4701-1	42.2	0.45	30.9
CM 4711-2	41.3	0.45	30.9
CG 927-12	39.3	0.43	26.2
Mean of all cultivars	43.5	0.42	31.4
$LSD_{0.05}$	1.70	0.08	1.80

C_i/C_a = intercellular CO_2 divided by atmospheric CO_2. This ratio is commonly used to differentiate plant species according to their photosynthetic capacities, that is, the lower the ratio, the higher the capacity.

SOURCES: El-Sharkawy et al. (1992a, 1993).

Screening Cassava Germplasm for Leaf Photosynthesis

Field evaluation of cassava germplasm for leaf photosynthesis in subhumid, high-altitude, cool climates, and mid-altitude warm climates

Once we ascertained the importance of field research and the need to assess cassava's potential photosynthesis under representative environments, we studied photosynthesis in recently matured upper-canopy leaves. The germplasm used was selected from a core collection of the cassava genebank held at CIAT. Materials comprised groups of cultivars, landraces, and improved CIAT breeding materials grown at three sites used by CIAT's cassava breeding program to evaluate genetic performance. We wanted to identify, in the field, those cultivars and lines with high photosynthetic potential. They would then be used as parental materials in crosses and breeding procedures to improve productivity (El-Sharkawy 1993) in combination with other major breeding objectives such as yield stability; broad adaptation; and tolerance or resistance to edaphoclimatic stresses, pests, and diseases (Hershey and Jennings 1992; Jennings and Iglesias 2002).

This objective was justified by our previous research at different sites in subhumid, seasonally dry, and semi-arid environments. We measured photosynthesis in the field, using portable infrared gas analyzers across a wide range of germplasm and edaphoclimatic conditions.

Results showed significant correlations between upper-canopy leaf photosynthesis and total biomass and storage root yields (Figure 3-6; CIAT Reports 1987 to 1995; El-Sharkawy and Cock 1990; El-Sharkawy et al. 1990, 1993; Pellet and El-Sharkawy 1993a; de Tafur et al. 1997b; de Tafur 2002; El-Sharkawy 2004, 2006). Moreover, the findings at CIAT were corroborated by later research at IITA (Nigeria), where photosynthetic rates of upper-canopy leaves were correlated with storage root yields across diploid, triploid, and tetraploid cassava cultivars (Ekanayake et al. 2007).

Tables 3-2 to 3-4 present data on upper-canopy leaf photosynthesis measured in two climates: (1) the

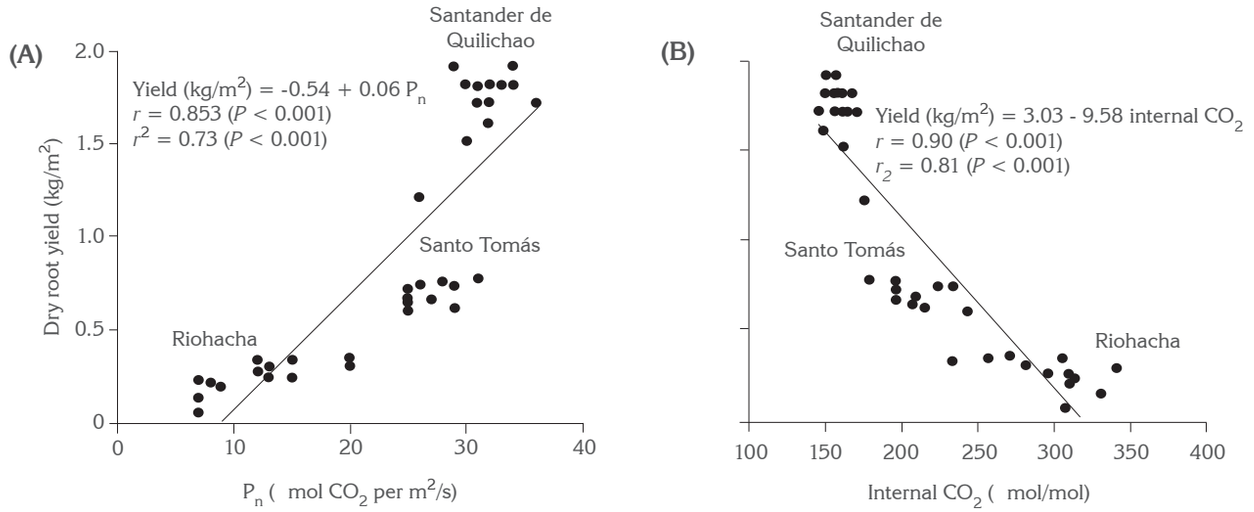


Figure 3-6. Relationships between dry root yield and upper-canopy leaf photosynthesis (P_n) **(A)** and intercellular CO_2 **(B)** for 38 cassava cultivars grown at three sites in Colombia: Santander de Quilichao (subhumid, 15 varieties), Santo Tomás (seasonal dry, 10 varieties), and Riohacha (semi-arid, 13 varieties) (El-Sharkawy et al. 1993; de Tafur et al. 1997b; de Tafur 2002; SM de Tafur and MA El-Sharkawy 1995, unpublished).

Table 3-2. Net leaf photosynthesis (P_n; μmol CO_2 per m^2/s), stomatal conductance (mmol per m^2/s), and internal CO_2 (μmol CO_2/mol) for some cassava clones with relatively high photosynthetic capacity. Note that, for this group of clones, the P_n rates are higher, and the stomatal conductance and internal CO_2 are lower than the trial means. The values indicate the importance of non-stomatal factors (i.e., biochemical and anatomical) in selecting for enhanced photosynthetic capacity. This group of clones will improve the genetic base of cassava for the cooler ecosystems of high-altitude tropics and subtropics.

Clone	P_n	Stomatal conductance	Internal CO_2
SM 1061-1	17.3	196	98
SM 526-12	16.7	320	154
SM 1054-4	16.6	225	114
M Per 501	16.4	391	166
SM 1053-9	15.7	225	122
Mean of all accessions (n = 107)	12.3	312	183
$LSD_{0.05}$	1.3	32	14

SOURCE: CIAT Report (1994).

high-altitude cool climate of Cajibío, Department of Cauca (about 1800 m; mean annual temperature at about 19 °C); and (2) the mid-altitude warm climate at two sites (CIAT Quilichao experiment station, Cauca, and CIAT Palmira station at HQ, Valle del Cauca), where altitudes range between 965 and 1000 m, and the mean annual temperature is about 24 °C. Crops were grown under rainfed conditions with minimal applications of fertilizer. Measurements were made on several occasions, mainly during dry periods, and averaged. Chambers enclosing central leaf lobes or part thereof (depending on the type of equipment and leaf chambers used) were always directed towards the sun between 09:00 and 12:00 local time when photon flux densities were greater than 1000 μmol per m^2/s. The plants used were 4 to 6-month-old plants, that is, of an age when leaf canopies nearly close (i.e., high leaf capacity source) and rates of storage root bulking are at their highest (high root sink demand).

At all sites, average leaf photosynthesis varied significantly among screened cultivars and landraces, but with rates greatly reduced in the high-altitude cool climate, thus confirming results and patterns observed with potted cassava grown in a high-altitude cool climate (Tables 3-2 to 3-4 and Figure 3-4). The accessions evaluated in the high-altitude cool climate were local traditional cultivars or landraces collected from cool-climate regions in several countries. They also included improved CIAT materials bred and selected for better adaptation to high-altitude cool climates.

The materials with rates (15.7 to 17.3 μmol CO_2 per m^2/s) that ranked higher than the overall mean photosynthetic rate (12.3) were four CIAT improved clones and a Peruvian cultivar (M Per 501) (Table 3-2). This finding indicates a narrow genetic base for this ecosystem. It also shows the relative effectiveness of the CIAT cassava program's strategy to breed for specific

Table 3-3. Net leaf photosynthesis (P_n; μmol CO_2 per m^2/s) in the upper-canopy leaves of cultivars from the core collection of cassava germplasm and grown at Santander de Quilichao in 1993/94. Measurements were carried out 5 to 6 months after planting, using portable infrared gas analyzers. Values are means of 7 to 11 measurements made during the dry period. Compare these higher P_n values, obtained within a warm subhumid habitat, with those obtained in the cool subhumid habitat shown in Table 3-2. Cultivar M Mal 48, from Malaysia, had the highest P_n rate and the highest dry root yield in this trial.

Clone	P_n	Clone	P_n
M Mal 48	27.6	M Tai 1	24.4
M Bra 900	27.6	M Pan 51	24.3
M Bra 12	26.8	M Bra 383	24.2
M Bra 191	26.7	M Ind 33	24.1
M Mal 2	26.4	CM 849-1	23.6
HMC-1	26.0	M Col 1684	23.4
CMC 40	25.8	M Mex 59	23.2
M Col 2061	25.4	M Ven 25	23.2
M Gua 44	25.4	M Bra 885	23.1
M Chn 1	25.3	M Cub 51	22.8
M Col 22	25.1	M Col 2215	22.3
M Arg 13	25.0	M Cub 74	22.3
M Ven 45A	24.8	M Per 205	22.0
M Col 1505	24.8	M Ptr 19	21.3
M Bra 110	24.6	M Ecu 82	21.0
$LSD_{0.05}$	4.8		

SOURCE: CIAT (1994).

edaphoclimatic zones and ecosystems. It also points out the importance of including leaf photosynthesis as a selection criterion for parental materials when enhancing productivity (El-Sharkawy and Cock 1990; El-Sharkawy et al. 1990; El-Sharkawy 2004).

The enhanced photosynthesis in these few clones could not be attributed to stomatal control because their average stomatal conductance (271 mmol per m^2/s) was significantly lower than the overall mean of accessions (312 mmol per m^2/s; Table 3-2). However, the intercellular CO_2 concentration was much reduced in these clones, thus indicating possible control by non-stomatal factors such as leaf anatomy and biochemistry (e.g., enzyme activity). As leaf formation is much slower but leaf life much longer in high-altitude cool climates than under warm-climate conditions (Irikura et al. 1979), selection for enhanced photosynthesis and tolerance of low temperature becomes even more important in this case. In the mid-altitude warm-climate sites, particularly at CIAT–HQ, average photosynthesis rates were much higher than in the cool-climate site (Tables 3-3 and 3-4). Measurements were all made during the dry period, when rates were lower than the maximum rates observed under wet conditions (Table 3-1).

Most of the materials evaluated at CIAT–HQ comprised cultivars and landraces from Brazil, with eight accessions from Argentina and one accession each from Colombia (HMC-1) and Bolivia (M Bol 1). The mean photosynthesis rate was significantly higher in the smaller group of germplasm materials from Argentina (26 μmol CO_2 per m^2/s) than in the germplasm from Brazil (Table 3-4), many accessions of which had lower rates than their original overall mean of 22 μmol CO_2 per m^2/s. Even so, several Brazilian accessions fell into the highest photosynthesis range, particularly M Bra 12 (Figure 3-4B) and M Bra 110.

These two materials could be used for crossing and breeding for warm-climate ecosystems. In contrast, the accessions from Argentina, presumably more adapted to subtropical ecosystems, better tolerated low winter temperatures than the warm-climate germplasm from tropical ecosystems. They could therefore be used in crossing and breeding for enhancing photosynthesis in germplasm for high-altitude cool-climates.

The P_n of this group of accessions was highly and negatively correlated with intercellular CO_2 (Figure 3-7). As P_n was measured in normal air, the calculated intercellular CO_2 concentration represents the balance

Table 3-4. Net leaf photosynthesis (P_n; μmol CO_2 per m^2/s) of upper-canopy leaves and intercellular CO_2 (μmol CO_2/mol) for 53 accessions from the core collection of cassava germplasm and grown at CIAT headquarters, Palmira, Colombia, in the 1991/92 season. Measurements of 4-month-old plants were made, using portable infrared CO_2 analyzers during dry periods. Compare these higher P_n rates in the warm subhumid habitat with those obtained in the cool subhumid habitat, as shown in Table 3-2. Note that most accessions from Argentina and Brazil had relatively high P_n rates, compared with trial means. Note that, in this group of clones, P_n was highly negatively correlated with intercellular CO_2 ($r^2 = 0.90$, $P < 0.0001$), indicating that differences in P_n were caused by non-stomatal factors, that is, anatomical and/or biochemical factors such as enzyme activity and leaf anatomy. Regression: intercellular $CO_2 = 315 - 7.83\ P_n$.

Accession	P_n	Intercellular CO_2	Accession	P_n	Intercellular CO_2
		Accessions with high P_n			
M Arg 11	32	73	M Bra 85	26	112
M Bra 12	30	82	M Arg 9	26	110
M Bra 110	30	74	M Bra 190	26	97
HMC-1	29	87	M Bra 124	26	100
M Arg 2	28	95	M Bra 403	25	131
M Bra 132	28	88	M Bra 162	25	108
M Bra 172	27	83	M Arg 5	25	115
M Arg 13	27	105	M Bra 242	24	133
M Bra 359	27	127	M Bra 299	24	133
M Bra 71	26	111	M Bra 165	24	114
M Arg 7	26	119			
		Accessions with intermediate to low P_n			
M Bra 243	23	132	M Bol 1	21	147
M Bra 405	23	143	M Bra 309	21	148
M Bra 73	23	134	M Bra 453	21	159
M Bra 217	23	140	M Bra 400	21	169
M Bra 404	23	151	M Bra 329	20	159
M Bra 125	23	129	M Bra 435	20	173
M Bra 258	22	143	M Bra 337	19	177
M Bra 273	22	128	M Bra 158	19	137
M Bra 77	22	145	M Bra 325	18	169
M Bra 233	22	144	M Bra 237	17	173
M Arg 12	22	146	M Bra 355	17	195
M Bra 416	22	151	M Bra 450	17	196
M Arg 15	22	139	M Bra 328	17	182
M Bra 356	22	156	M Bra 311	16	188
M Bra 191	21	145	M Bra 315	16	191
M Bra 383	21	162	M Bra 335	14	187
$LSD_{0.05}$	6.2	23			

SOURCE: CIAT Report (1992).

between the supply from outside air via stomata and the demand from carboxylation reactions within the mesophyll. The lower intercellular CO_2 in accessions with high Pn indicates a faster carboxylation rate, probably because of higher rubisco activity inside the chloroplasts and/or higher activity of phospho*enol*pyruvate carboxylase (PEPC) in the cytosol of mesophyll cells. This finding indicates the need to select and breed for higher activity of key photosynthetic enzymes.

The accessions screened at Quilichao were a mix of cultivars and landraces, mostly from Latin America, but also from Asia (Table 3-3). Again, average photosynthesis rates varied widely among cultivars, with several high-ranking accessions from Brazil, Colombia, and Malaysia. The highest ranking accession from Malaysia (M Mal 48) also had the highest dry root yield (15.6 t/ha versus the overall mean for the trial at 10.6 t/ha). This clone has already been used for crossing and breeding at CIAT.

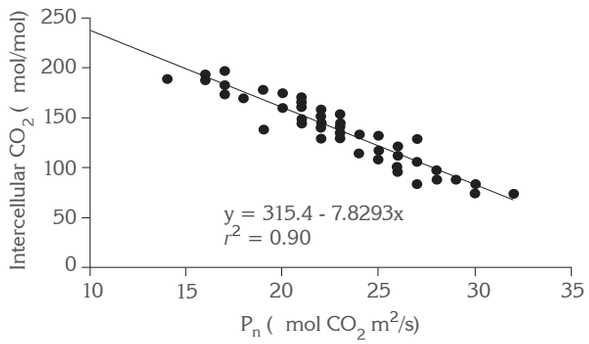


Figure 3-7. Relationships between P_n and intercellular CO_2 concentration (C_i) in 53 cassava accessions (Table 3-4). Note the negative correlation between P_n and C_i, which indicates that the association was caused by non-stomatal factors (i.e., biochemical and/or anatomical mesophyll traits) (SM de Tafur and MA El-Sharkawy 1995, unpublished).

Evaluating cassava germplasm for leaf area duration (seasonal average leaf area index) and productivity in a mid-altitude warm climate

To complement the joint physiology/breeding efforts to characterize cassava germplasm from the core collection and identify useful yield-determinant traits, a field trial was conducted at the CIAT–Quilichao experiment station (mid-altitude warm climate). Thirty clones were evaluated for leaf duration across the growth cycle (seasonal average leaf area index as measured with a leaf canopy analyzer). Table 3-5 (CIAT Report 1995) presents data on yield, shoot and total biomass, seasonal average leaf area index, and root dry matter content.

Wide variations among clones were found for standing shoot (i.e., top biomass, excluding dropped leaves) and total biomass, yield, dry matter content in roots, and seasonal leaf area index. Notably, several accessions from Brazil were among the highest ranked in terms of yield, total biomass, and dry matter contents in storage roots, thus highlighting the importance of Brazilian germplasm (El-Sharkawy and de Tafur 2010).

CIAT, to diversify the genetic base of the cassava genebank, has incorporated many of these accessions for their useful plant traits. Outstanding among these is clone M Bra 12, with its high leaf photosynthesis under both potted (grown outdoors in a mid-altitude warm climate) and field-grown conditions (Table 3-4; Figure 3-4B), high yield, and resistance to mites (Byrne et al. 1982). Two other accessions of Brazilian origin, M Bra 383 and M Bra 191, which ranked high in this group of clones, were also reported as being among the highest ranked clones (fourth and fifth, respectively, among 33 clones evaluated) for tolerance of soils low in phosphorus (CIAT Report 1990; El-Sharkawy 2004).

In this group of accessions, standing shoot biomass correlated with root yield ($r = 0.7$; $P < 0.001$). This finding confirms previous findings, and suggests the use of this trait as a proxy for leaf area formation and duration when evaluating large breeding populations (CIAT Report 1990; El-Sharkawy et al. 1990; El-Sharkawy 2004). In this group of clones, dry root yield also correlated with seasonal leaf area index (Figure 3-8; $r = 0.65$; $P < 0.001$), further corroborating earlier reports (Pellet and El-Sharkawy 1993a). It also supports the concept of breeding for longer leaf life and optimal leaf area duration to maximize productivity under favorable conditions and to ensure sustainable yields in stressful environments (El-Sharkawy and Cock 1987b; Cock and El-Sharkawy 1988a, 1988b; El-Sharkawy et al. 1992b; El-Sharkawy 1993, 2004; Lenis et al. 2006).

In conclusion, although leaf photosynthesis can be used as a selection criterion in cassava improvement programs, it may be difficult to handle when evaluating large breeding populations. It should be included at least in the evaluation and selection of parental materials in combination with other important yield-related traits, particularly relatively high HI (>0.5; Kawano 1990, 2003), large root sink (using root number per plant as a criterion; Cock et al. 1979; Pellet and El-Sharkawy 1993a, 1994), and longer leaf life (greater leaf retention and duration over the growth cycle; El-Sharkawy and Cock 1987b; Cock and El-Sharkawy 1988a, 1988b; El-Sharkawy et al. 1992b; El-Sharkawy 1993, 2004; Lenis et al. 2006). Recent advances in molecular biology and the development and manufacture of more precise techniques, methods, and equipment can only enhance and speed up the elucidation of fundamental mechanisms underlying photosynthetic potential and associated beneficial traits, and their controlling genes.

Responses to Extended Water Shortages Imposed at Different Growth Stages in the Field

Unlike grain crops, cassava does not have specific water-stress sensitive growth stages beyond crop establishment. It is therefore highly tolerant of prolonged drought in areas that typically have low (<600 mm annually) and erratic precipitation, dry air and high temperatures (i.e., potential for high

Table 3-5. Seasonal average leaf area index (LAI), dry root yield, top and total biomass, and root dry matter content of 30 clones from the core collection of cassava germplasm. Plants were grown at Santander de Quilichao, Colombia, in the 1994/95 season. Leaf area duration, as estimated by seasonal average LAI, was significantly correlated with root yield (Figure 3-8), indicating the importance of this trait in selecting and breeding for improved cultivars (Lenis et al. 2006).

Clone	Seasonal average LAI (m^2/m^2)	Dry top biomass (t/ha)	Dry root (t/ha)	Total biomass (t/ha)	Root dry matter (%)
M Bra 383	1.3	6.0	15.5	21.5	41.7
M Bra 12	1.0	5.3	15.3	20.6	38.2
M Pan 51	1.8	10.2	14.7	23.9	40.8
CM 849-1	1.4	6.3	14.1	20.4	41.7
M Bra 191	1.5	5.7	14.0	19.7	41.3
M Mal 48	1.9	4.2	13.9	18.1	41.0
M Bra 885	1.6	5.4	13.8	19.2	41.6
M Ven 25	1.1	4.9	12.6	17.5	40.0
HMC-1	1.6	4.8	12.2	17.0	38.5
M Ind 33	1.6	5.9	11.6	17.5	36.6
M Bra 100	1.9	6.4	11.3	17.7	40.6
M Gua 44	1.2	4.6	11.2	15.8	38.9
M Cub 74	0.9	3.9	10.8	14.7	39.8
M Tai 1	1.2	5.6	10.6	16.2	37.5
M Mex 59	1.6	6.8	10.3	17.1	40.7
M Arg 13	0.9	2.4	9.3	11.7	39.1
M Mal 2	1.8	6.9	8.4	15.3	36.2
M Chn 1	1.0	1.9	8.0	9.9	36.2
M Col 22	1.4	1.7	7.8	9.5	37.8
M Ven 45A	1.0	5.1	7.7	12.8	37.4
M Col 1684	0.8	2.2	7.0	9.2	34.6
M Ecu 82	0.8	3.4	6.7	10.1	38.6
M Ptr 19	1.1	4.0	6.1	10.1	40.0
M Col 2215	0.7	2.4	5.9	8.3	40.3
CMC 40	0.9	1.9	5.6	7.5	36.7
M Col 2061	0.9	3.5	5.3	8.8	30.7
M Per 205	1.0	3.8	5.3	9.1	38.7
M Col 1505	0.7	2.1	5.1	7.2	40.6
M Cub 51	0.7	3.1	4.9	8.0	39.9
M Bra 900	0.9	1.3	4.7	6.0	31.4
Mean of all clones	1.2	4.4	9.7	14.0	39.6
$LSD_{0.05}$	0.5	2.0	3.5	4.6	3.6

SOURCE: CIAT Report (1996).

evapotranspiration), low-fertility soils, and high pest-and-disease pressure. Examples of areas with such conditions include Northeast Brazil, Colombian North Coast, the Peruvian coastal regions, some areas of sub-Saharan Africa, and parts of Thailand (El-Sharkawy 1993).

Under these conditions, other staple food crops such as grain cereals and legumes, will rarely survive and produce. That cassava can grow in such areas is contrary to the common assumption that it originated in the hot humid climates of the Amazon forests. Indeed, Allem (2002) suggests that cassava may, in fact, have originated in the open savanna forests of Brazil. This inherent capacity to withstand drought is also behind the crop's expansion into more marginal lands across many parts of Africa, Asia, and Latin America, where it is grown by resource-poor farmers.

We have already mentioned some inherent plant mechanisms that may underlie such tolerance. Most notable among them is the cassava plant's striking sensitivity to both changes in atmospheric humidity and soil-water deficits. It reacts by partly closing its

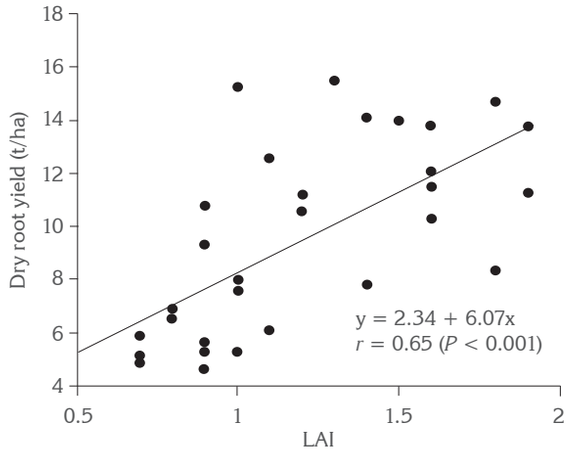


Figure 3-8. Relationships between final dry root yield of 30 clones from the core collection of cassava germplasm and seasonal average leaf area index (LAI). The significant correlation indicates the importance of leaf area duration for yield formation. Because of the small leaf area canopy in the first 3 months and in the final 8 to 12 months, the seasonal average canopy area still limits yield. It indicates the need to select and breed for a higher and more sustainable canopy that would last most of the growth cycle, combined with enhanced leaf photosynthesis, high harvest index, and strong root sink (larger storage root number/plant). Cultivar M Bra 12 had a notably higher yield with an LAI that was less than the overall average of the trial, indicating its high leaf photosynthetic potential (CIAT Report 1995; El-Sharkawy 2006).

stomata and restricting water losses, once it is exposed to dry air and/or dry soils. Thus, the leaf is protected from severe dehydration. Such sensitivity is also coupled with the leaf's ability to partly retain its photosynthetic capacities under prolonged water shortages (El-Sharkawy et al. 1992b; El-Sharkawy 1993; Caýon et al. 1997; de Tafur et al. 1997a, 1997b).

Moreover, the cassava plant, despite its sparse fine-root system, is able to penetrate soil layers at 2 m or deeper, unlike other crops such as cereals and tropical grasses (Tscherning et al. 1995). Thus, the plant can endure long periods of drought. Moreover, it is slow to deplete the deeper stored water, resulting in higher seasonal crop water-use efficiency, although at reduced productivity (Connor et al. 1981; El-Sharkawy and Cock 1986, 1987b; El-Sharkawy et al. 1992b; El-Sharkawy 1993, 2004).

We report here on further research with diverse germplasm that was exposed at various growth stages to long periods (3–6 months) of water shortages. We used a large field drainage lysimeter (30 × 15 × 2.3 m deep) at CIAT–Quilichao, which was excavated and refilled with the same soil layers (El-Sharkawy and Cock 1987b). We also used adjacent undisturbed larger areas.

Water stress was always initiated by covering soil with high moisture content with caliber-6 white plastics, which were manually kept free of rainwater and of ruptures or leaks during stress periods. Soil water was periodically monitored by sampling or by using a calibrated neutron meter at a 1.8–2 m depth. Leaf water potential was assessed with the standard pressure chamber technique (Kirkham 2005). Leaf gas exchange was measured with portable infrared gas analyzers, and leaf area coverage/index was measured with a solar-irradiance sensing analyzer (leaf canopy analyzer; LI-COR Biosciences, Inc., Lincoln, NE, USA). Periodic harvests were also conducted to determine yield and biomass (CIAT Reports 1987 to 1995; El-Sharkawy and Cock 1987b; El-Sharkawy et al. 1992b, 1998b; Cayón et al. 1997; de Tafur et al. 1997a, 1997b; El-Sharkawy and Cadavid 2002).

Evaluating Germplasm under Mid-Season Water Stress in a Field Drainage Lysimeter

Relationship between productivity and hydrocyanic acid (HCN) levels

Sixteen cultivars from a core collection of cassava germplasm were evaluated across two cropping cycles in a field drainage lysimeter. For each cycle, at 90 to 100 days after planting, 3 months of water stress was initiated (mid-season stress). Figure 3-9 illustrates dry root yield accumulation patterns for four representative accessions affected by stress during the growth cycle.

Water stress significantly reduced yield and shoot biomass in all accessions at the end of the stress (data not shown; CIAT Reports 1991, 1992; El-Sharkawy et al. 1992b). On recovery from stress, however, final yields of some accessions were equal to those of well-watered plants, while final yields in others were reduced (Table 3-6; El-Sharkawy 1993). Significant differences for final root yield were also found among cultivars, with the hybrid CM 489-1 having the highest yield under both stress (18 t/ha oven-dried roots) and non-stress (19 t/ha) conditions. Also noteworthy is CM 489-1, which showed high PEPC activity in leaf extracts under extended field water shortages.

In a group of cultivars, high PEPC activity correlated with leaf photosynthesis (P_n) (El-Sharkawy 2004). The parameter P_n also correlated with high

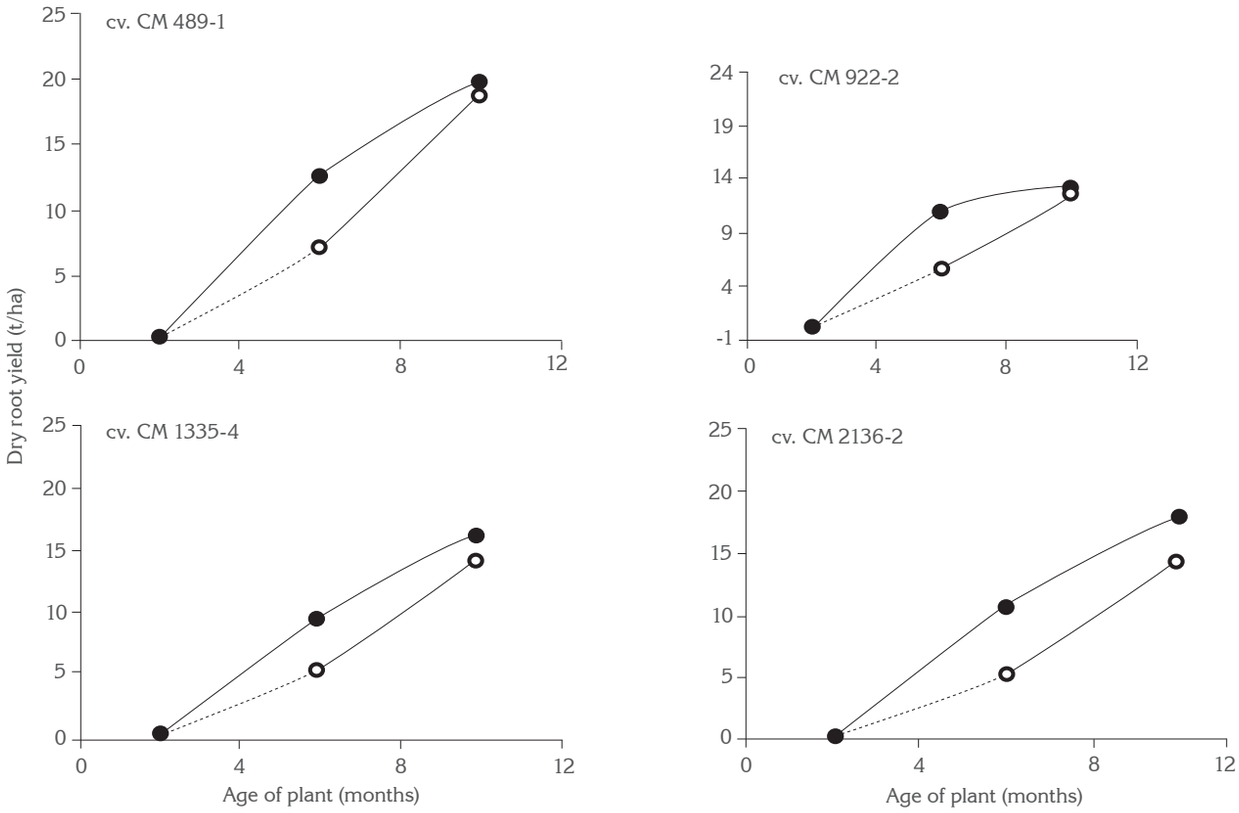


Figure 3-9. Dry root yield in a group of clones affected by 3 months of water stress, starting 90 days after planting (mid-season stress). Yield was significantly lower at the end of stress, but recovered rapidly with watering, so that final yields were approaching those of the controls. There were differences among cultivars, with cv. CM 489-1 having the highest yield in both water regimes (CIAT Report 1992; El-Sharkawy 2006). —●— refers to unstressed clones; —○— to stressed clones.

values for yield, nutrient-use efficiency in terms of root production, radiation-use efficiency in terms of total biomass production, and many harvestable storage roots per plant across a range of phosphorus fertilizer levels in acidic soils in subhumid warm climates (Pellet and El-Sharkawy 1993a, 1993b, 1994, 1997).

Across accessions, reductions as a result of water stress were much higher for shoot biomass (28%) than for roots (9%). However, HI increased about 6%, thus indicating cassava's potential to tolerate prolonged mid-season stress in subhumid zones and its ability to recover and compensate for possible losses in productivity. This is an advantage over other staple food crops (El-Sharkawy and Cock 1987b; CIAT Reports 1991, 1992; El-Sharkawy et al. 1992b). The genetic variability existing for stress tolerance should be exploited in breeding and improving cassava germplasm for dry environments (CIAT Reports 1991 to 1995; Hershey and Jennings 1992; El-Sharkawy 1993).

When exposed to extended water deficits, most cassava cultivars show increased HCN content (which indicates cyanogenic potential) in their storage roots. Thus, the roots become less suitable for human consumption if they not properly processed to eliminate most, if not all, HCN (Dufour 1988; Rosling 1994; Essers 1995). Some crop management practices can greatly reduce HCN in cassava roots, for example, where moderate amounts of N-P-K fertilizers and/or plant residues such as mulch are applied to low-fertility sandy soils in zones with long dry periods (Cadavid et al. 1998). Another practice is to apply K to clayey acidic soils low in K in subhumid zones (El-Sharkawy and Cadavid 2000). Selection for low HCN cultivars, however, remains a major objective of most breeding programs, particularly those targeting germplasm for stressful environments (El-Sharkawy 1993).

In our case, those less sensitive genotypes with low HCN that we identified (Table 3-6) offer adequate genetic sources for breeding sweet cultivars. Nassar (1986) also reported some wild species with low HCN

Table 3-6. Yield, top biomass (dry, t/ha), and hydrocyanic acid (HCN) content in roots at final harvest (11 months after planting) after 3 months of mid-season water stress, starting 90–100 days after planting. Averages are from the 1987/88 and 1988/89 seasons at Santander de Quilichao, Colombia. Note the increase in HCN contents due to stress and the differences among cultivars. Clones with lower HCN under stress are good genetic sources for selecting and breeding materials suitable for fresh consumption by humans, particularly in dry and semi-arid zones.

Clone	Unstressed			Stressed		
	Roots	Tops	Total HCN (mg/kg dry root)	Roots	Tops	Total HCN (mg/kg dry root)
CM 489-1	19.1	7.2	214	18.0	7.1	401
CM 922-2	14.8	7.6	142	15.0	5.9	190
CM 1335-4	18.1	7.8	107	16.5	5.1	123
CM 2136-2	19.3	12.4	166	15.5	7.3	338
Average	17.8	8.8	157	16.2	6.4	263
% change due to stress				-9	-28	+68

SOURCES: CIAT Report (1991); El-Sharkawy (1993).

and high protein in storage roots. In addition to traditional breeding, transgenic approaches have been used to produce cassava with reduced HCN levels (i.e., >90% reduction in cyanogenic contents in storage roots) in transformed cv. M Col 22 (Jørgensen et al. 2005). "Acyanogenic" (i.e., cyanogen-free) clones have also been generated (Siritunga and Sayre 2003). However, the role of cyanogenesis in cassava, as a potential deterrent to pests that feed on leaves and roots, needs to be assessed in the developed "acyanogenic" materials before they are released (Riis et al. 1995, 2003).

Pereira (1977) and Poulton (1990) have argued that high levels of HCN in plants may function as a defensive mechanism to protect crops against predators, herbivores, and rodents. HCN may also serve as a source of stored nitrogen, particularly for seeds. The presumably defensive role of HCN against pests and diseases has not been observed (Brekelbaum et al. 1978). Despite normally higher elevations of leaf HCN levels in most cultivars, water-stressed cassava crops in Northeast Brazil and North Colombia (which typically have several months of water shortages) showed higher rates of infestation by mites than did non-stressed crops (MA El-Sharkawy 1992, pers. comm.).

Thrips also fed on cassava, regardless of HCN levels in leaves (Schoonhoven 1978). Other pests with different feeding habits, whether on shoots or roots, may present different responses. Recent work at CIAT (Bellotti et al. 1988; Bellotti and Arias V 1993; Bellotti and Riis 1994; Bellotti 2002) showed that the subterranean burrower bug (*Cyrtomenus bergi*) preferred to feed on cassava roots low in HCN than on bitter cassava, particularly in soils with high moisture content, even though several sweet cultivars were determined as having potential resistance or tolerance of the bug (Riis 1997). One mechanism that may deter or prevent the bug from feeding on sweet cassava is high HCN content in the storage root peel instead of the parenchyma tissue (Riis 1997). The first two nymphal instars have short stylets, thus confining feeding mainly to the root peel (Riis 1990; Riis et al. 1995). Hence, selection for sweet cultivars having high HCN in the thicker root peel may be advantageous in this case.

Some cultural practices such as intercropping cassava with sunn hemp (*Crotalaria* sp.), which possesses natural insecticidal substances, was found to effectively reduce bug attack and damage to cassava roots. However, cassava yield was reduced because of competition and crowding by the *Crotalaria* (Bellotti et al. 1988; Bellotti 2002).

A social study was recently conducted on the Tukano Indians in northwestern Amazon Basin, Brazil. The Tukano cultivate more bitter cultivars, which are high in HCN, than they do sweet cultivars, perhaps because they are more prevalent rather than because of any inherent adaptive advantages. That is, no consistent relationships or patterns were demonstrated to exist for the Tukanos' preferring bitter cultivars over sweet ones, whether for resistance to predators, particularly pests and diseases, or other reasons (Wilson 2003). However, Wilson and Dufour (2002) suggest that higher yields, often observed in bitter cultivars grown in that region, form the Amazon Basin Indians' likely criterion for choosing high-HCN cassava.

However, to our knowledge, no conclusive evidence, based on sound research, exists as to whether bitter cultivars do, in fact, have an inherent and superior potential for productivity than sweet ones. That no consistent relationship exists between productivity and HCN contents in roots is furthermore supported by data in Table 3-6 and findings of trials with 14 other cultivars. These materials were tested across five consecutive growth cycles under different application rates of K fertilizer in acidic clayey soils in subhumid zones of Colombia (El-Sharkawy and Cadavid 2000).

Moreover, several tested clones, including HMC-1, HMC-2, M Cub 74, M Pan 70, M Col 1505, CM 91-3, CM 523-7, CMC 40, CM 1585-13, and those shown in Table 3-6, have high yields and moderate to low HCN levels in root parenchyma. Most of these clones are improved materials that indicate compatibility of selection and breeding for high yield with low HCN. Álvarez and Llano (2008) have suggested that the bread-making quality of bitter cultivars is different and possibly better than that of sweet cultivars. This might be a reason why the Indians grow bitter cultivars, that is, for culinary, not agronomic, purposes. More research is needed to uncover other possible reasons why bitter cassava is chosen in the Amazon Basin and elsewhere.

Photosynthesis and the C_3-C_4 Intermediate Characteristics of Cassava

Previous research on cassava photosynthesis shows that several cassava cultivars and wild species exhibit activity of the C_4 enzyme PEPC, ranging from 1.5 to >5 μmol per mg Chl/min. This is 15% to 25% of activities of C_4 species such as maize and sorghum. The research also demonstrated the importance of elevated PEPC activity, which may partly underlie cassava's high photosynthetic capacity and which correlates with productivity across environments and genotypes (Table 3-7; Cock et al. 1987; El-Sharkawy and Cock 1987a, 1990; CIAT Reports 1990 to 1994; El-Sharkawy et al. 1990, 1992a, 1993, 2008; Bernal 1991; López et al. 1993; Pellet and El-Sharkawy 1993a; de Tafur et al. 1997b; El-Sharkawy 2004).

The PEPC activity observed in cassava and its wild relatives are much higher than those observed in C_3 species such as field bean. Instead, they are comparable with activities found in several C_3-C_4 intermediate *Flaveria* species, which have a limited functional C_4 cycle. They are also two to three times higher than in C_3-C_4 plants with a C_4-like kranz anatomy, as found in *Panicum milioides* (Ku et al. 1983; Brown and Bouton 1993).

Table 3-7. Activity of C_4 phospho*enol*pyruvate carboxylase (PEPC) carboxylase in leaf extracts. Values are means of four leaves; ± are standard deviations. Note the much higher activity in cassava, compared with beans, a C_3 species, and the very high activity in wild *Manihot* (about 30% to 40% of activity in maize, a C_4 species). In a group of field-grown cultivars under prolonged water stress, P_n was significantly correlated with the PEPC activity measured in the same leaves (El-Sharkawy 2004), indicating the importance of selecting and breeding for elevated PEPC activity. Note that wild *Manihot* also possesses an additional short-palisade layer beneath the lower leaf surface and numerous stomata on both leaf surfaces—two traits advantageous for enhancing photosynthesis (El-Sharkawy 2004).

Species	PEPC activity (μmol NADH)	
	gfw/min	mg Chl/min
Maize (cv. CIMMYT 346)	15.0 ± 1.8	7.0 ± 3.6
Common beans (cv. Calima G 4494)	0.2 ± 0.07	0.3 ± 0.1
Cassava cultivars:		
M Mex 59	3.2 ± 0.6	2.2 ± 1.0
M Nga 2	1.3 ± 0.1	0.4 ± 1.0
Wild *Manihot* species:		
M. grahamii	4.0 ± 0.9	2.8 ± 1.2
M. rubricaulis	5.8 ± 0.6	3.4 ± 1.3

SOURCES: El-Sharkawy and Cock (1990); El-Sharkawy (2004); MA El-Sharkawy, L Bernal, and Y López (1988, unpublished).

The presence of a C_4 PEPC protein in cassava was further determined immunologically (Figure 3-10; CIAT Report 1991). In cassava, PEPC appears to be of at least two different forms (isoenzymes), compared with PEPC from maize. The presence of the enzyme, however, does not necessarily mean it is active. When we used the stain Fast Violet BB, which is relatively specific for oxaloacetate (i.e., the initial C_4 product), we could demonstrate that the PEPC is, indeed, active in cassava (Figure 3-10, at left, lanes 2 and 3 for cassava cultivar M Col 22, lane 1 for maize, and lane 4 for beans). Thus, we quantitatively confirmed activity in centrifuged leaf extracts (Table 3-7).

More recent research on the biochemical and molecular characteristics of cassava photosynthetic enzymes showed that a maize PEPC-specific antiserum (maize *ppc* probe, received from T. Nelson, Yale University, USA) cross-reacted with

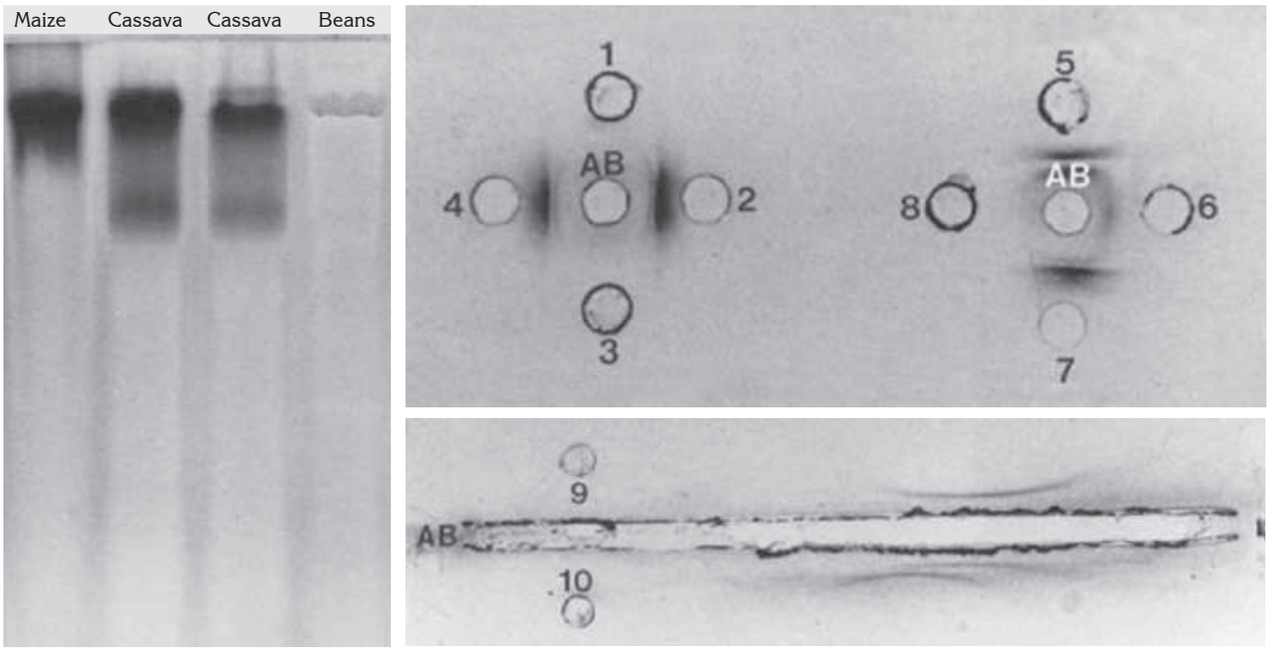


Figure 3-10. At right, immunological detection of phospho*enol*pyruvate carboxylase (PEPC) in leaf extracts: *upper right*, shows a double immunodiffusion, with wells 1, 3, and 8 for beans; wells 2, 4, and 5, for purified maize PEPC; well 6 for cassava cultivar M Col 22; well 7 for maize; AB = antiserum containing anti-PEPC. *Lower right*, shows immunoelectrophoresis in 1.2% agarose gel, where well 9 is for purified maize PEPC; well 10 is for cassava; AB = antiserum containing anti-PEPC. At left, simple PAGE patterns for PEPC in maize, cassava, and beans; the two forms of PEPC (isoenzymes) in cassava are apparent (Y López, MA El-Sharkawy, JH Cock, and H Ramírez 1987, unpublished; CIAT 1991; El-Sharkawy 2006).

cassava PEPC. The reaction indicated the presence of homologous antigenic determinants (CIAT Report 1993; López et al. 1993). This was also shown at the DNA level in Southern blot hybridization with a maize *ppc* probe and total, enzyme-digested, cassava-genomic DNA (Figure 3-11; CIAT Report 1993; López et al. 1993; Tenjo et al. 1993). These studies were repeated with about 60 more accessions, and included *me* (malic enzyme; Figure 3-12) and *mdh* (malate dehydrogenase) maize probes.

No polymorphisms were found that would have related the elevated activity of cassava PEPC to a higher copy number of the genes involved. Moreover, the corresponding gene sequences in cassava appeared similar to the maize probes used, as shown by good hybridization signals at high stringency (CIAT Report 1993).

So far, preliminary studies on the compartmentalization of PEPC in cassava have indicated the location of *ppc* transcripts between the upper epidermis and the top end of the long-palisade layer (CIAT Report 1993). The location tends to support the hypothesis that, over a range of photon flux densities and temperatures, the palisade cells are capable of refixing and/or recycling all respiratory CO_2 in light and in CO_2-free air (Figure 3-13; El-Sharkawy and Cock 1987a). Complete or partial apparent refixation and/or recycling in light of respiratory CO_2 (both photorespiration and mitochondrial dark respiration) was recognized earlier in different C_3 and C_4 species (Meidner 1962; Moss 1962; Tregunna et al. 1964; El-Sharkawy and Hesketh 1965, 1986; Forrester et al. 1966; El-Sharkawy et al. 1967, 1968; Jackson and Volk, 1969; Volk and Jackson 1972) and in C_3-C_4 intermediates (Devi and Raghavendra 1993).

However, more studies are needed, using *in situ* hybridization and immunofluorescent techniques, to elucidate the spatial distribution of the photosynthetic key enzymes within the cassava mesophyll (CIAT Report 1993; López et al. 1993; Tenjo et al. 1993). Cassava and wild relatives show low photorespiration (CO_2 compensation concentration was 20–30 ppm), relative to C_3 species (Figure 3-14; El-Sharkawy and Cock 1987a; CIAT Reports 1992, 1995; El-Sharkawy et al. 1992a; El-Sharkawy 2004); high percentage (40%–60%) of leaf-fed ^{14}C incorporated into C_4 acids after 5–10 s under light; and elevated PEPC activity (Cock et al. 1987; El-Sharkawy and Cock 1987a, 1990). However, they lack the typical C_4 kranz leaf anatomy that is

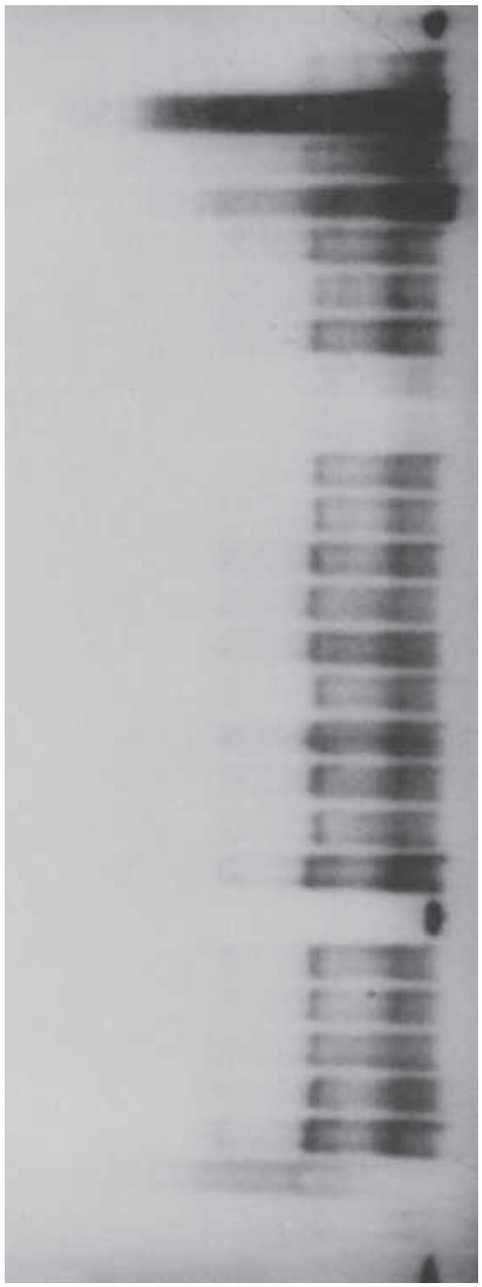


Figure 3-11. Southern hybridization of BamHI-digested cassava DNA, hybridized with a maize *ppc* probe (CIAT Reports 1993, 1994; JE Mayer, MA El-Sharkawy, RM de Estefano, and FA Tenjo 1993, unpublished). Note the variable degrees of hybridization with the maize *ppc* probe within cassava germplasm and wild *Manihot grahamii*.

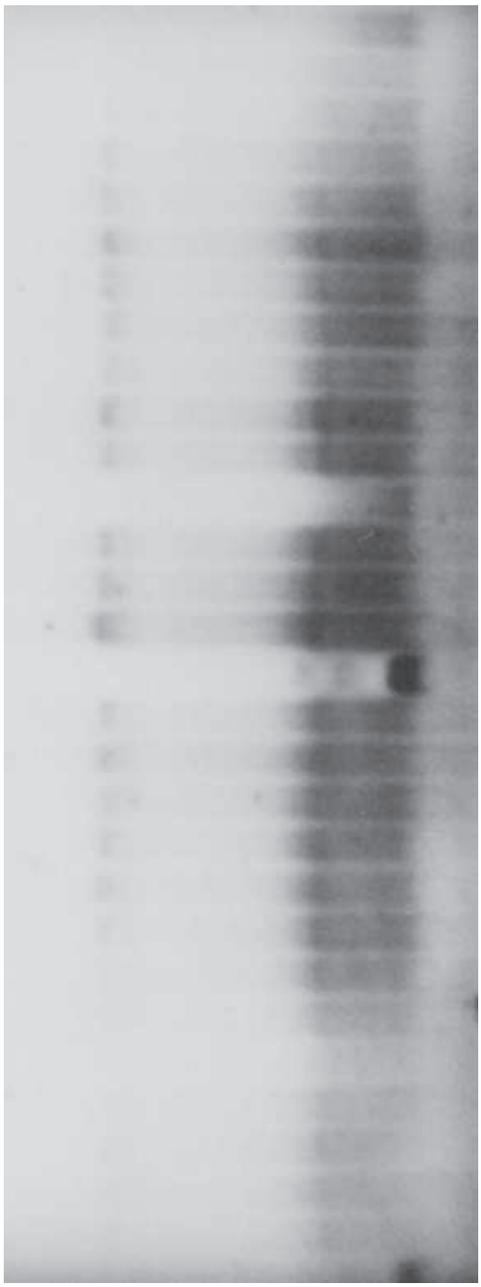


Figure 3-12. Southern hybridization of BamHI-digested cassava DNA, hybridized with a maize *me* probe (CIAT Reports 1993, 1994; JE Mayer, MA El-Sharkawy, RM de Estefano, and FA Tenjo 1993, unpublished). Note the variable degrees of hybridization with the maize *me* probe within cassava germplasm.

required to compartmentalize the key C_3 rubisco and C_4 PEPC enzymes (El-Sharkawy and Hesketh 1965, 1986; Laetsch 1974; Hatch 1977, 1987). We suggest that cassava and *Manihot* species are probably evolving biochemically towards a C_4 photosynthetic pathway and therefore demonstrate C_3-C_4 intermediate photosynthetic behavior (Cock et al. 1987; El-Sharkawy and Cock 1987a, 1990; El-Sharkawy 2004, 2005).

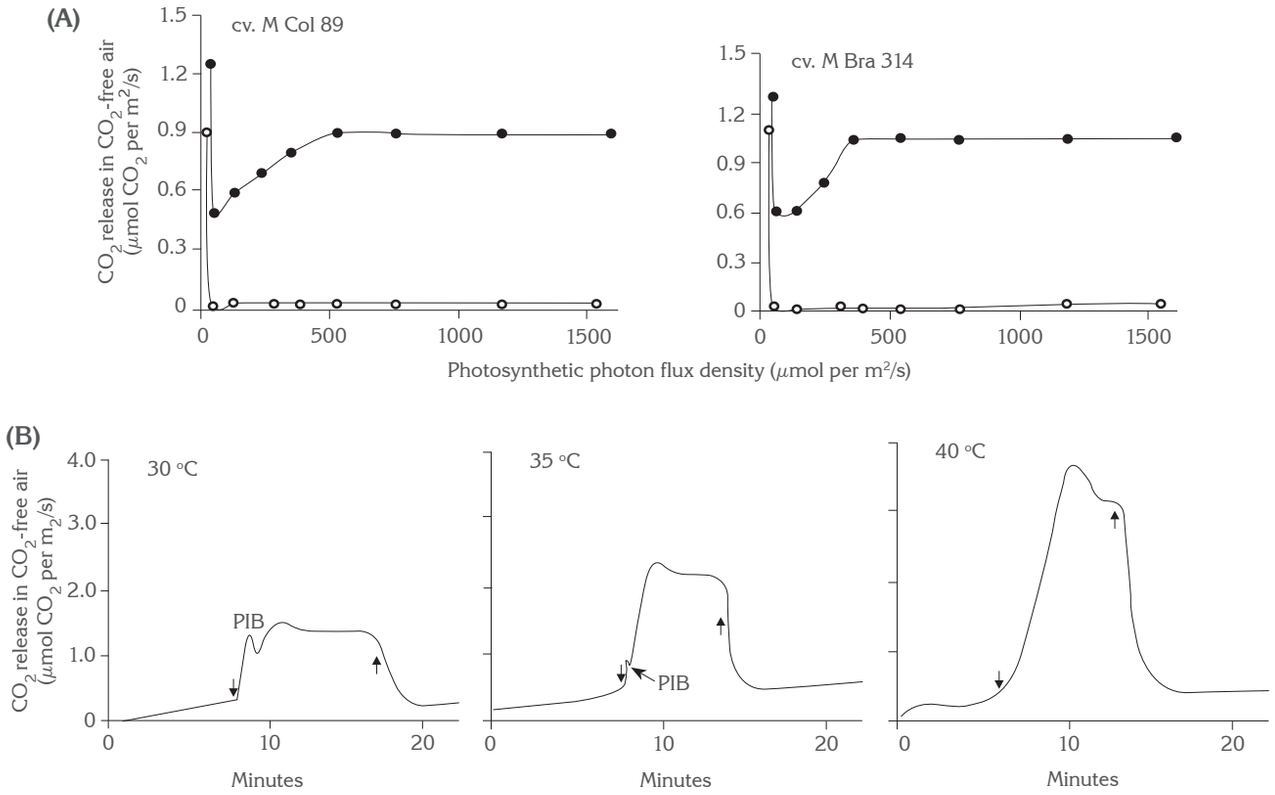


Figure 3-13. **(A)** Differential CO_2 releases in CO_2-free air from the upper (o) and lower (●) surfaces of amphistomatous cassava leaves (cvs. M Col 89 and M Bra 314) as a function of photon flux density at a constant leaf temperature of 27 °C. Note the consistent lack of CO_2 release from the upper surface of leaves of both cultivars when the abaxial stomata were blocked versus release from the lower surface. This indicates the complete refixation/recycling of respiratory carbon dioxide (both photorespiration and dark mitochondrial) within the long-palisade layer, which occupies more than 60% of leaf thickness. **(B)** Recorder's traces of CO_2 releases in CO_2-free air under light and dark from the upper surface of amphistomatous cassava leaves (cv. M Bra 314) at 30, 35, and 40 °C leaf temperatures. Photon flux density was 1200 μmol per m^2/s (↓ refers to light off; ↑ refers to light on; PIB to post-illumination burst of CO_2). Note the lack of carbon dioxide release under light, which was observed in several light–dark cycles over a longer period (>1 h); the decrease in PIB magnitude with rising leaf temperature and eventual disappearance at 40 °C; and the pronounced surge of carbon dioxide within 3 min of darkness. The lack of carbon dioxide release under light was attributed mostly to an efficient refixation/recycling system in the palisade cells (El-Sharkawy and Cock 1987a).

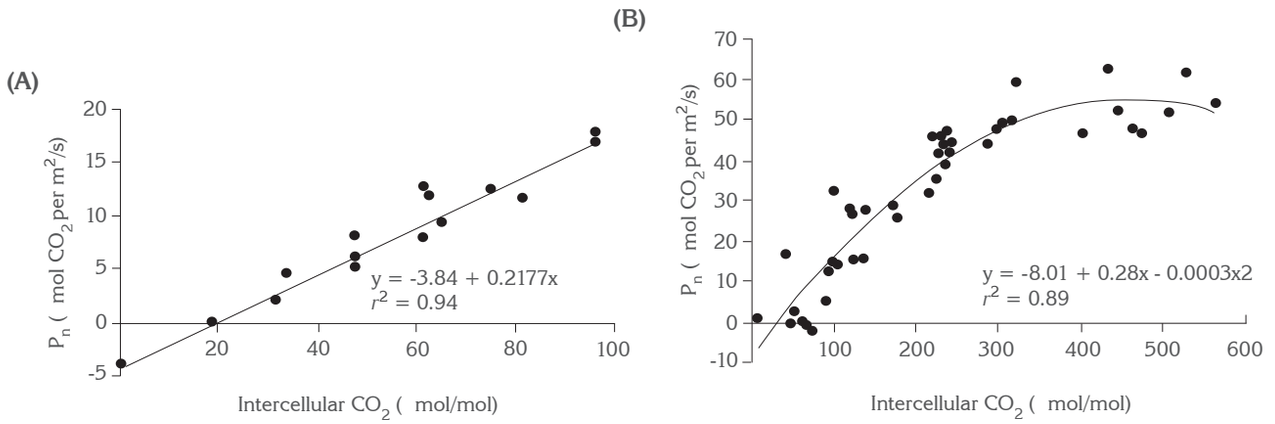


Figure 3-14. Relationship between leaf photosynthesis (P_n) and intercellular CO_2 concentration in cassava cultivar M Col 1684 **(A)** (CIAT Report 1992; El-Sharkawy et al. 1992a) and in wild *Manihot rubricaulis* **(B)** (CIAT Report 1995; SM de Tafur and MA El-Sharkawy 1995, unpublished). Note the linear response and the low photorespiration where the CO_2 compensation point was about 20 in **(A)** and 28–30 μmol/mol in **(B)**; a saturated P_n in *M. rubricaulis* at 400–500 μmol/mol intercellular CO_2 is apparent.

Effects of Water Stress

Photosynthetic enzymes

Three-month-old cassava plants were exposed to water stress for 3 and 8 weeks in the field. After 3 weeks of water stress, activities of PEPC, rubisco, and the C_4 decarboxylase NAD-ME were observed, overall, to have declined, particularly rubisco, in leaf extracts (Table 3-8; CIAT Report 1993). The average PEPC-to-rubisco ratio, indicating the relative importance of these two enzymes, was also reduced by stress.

However, after 8 weeks of stress, PEPC activity, averaged across all clones, was 13% higher than in unstressed crops, with differences among accessions (Table 3-9; CIAT Report 1993). However, rubisco activity was 42% less in the stressed crops. This differential effect of stress on the activities of these two key photosynthetic enzymes resulted in a much higher PEPC-to-rubisco ratio in the stressed crops than in the unstressed ones. These data indicate that, under prolonged water deficit, the relative importance of the C_4 PEPC versus the C_3 rubisco becomes more pronounced, lending support to the hypothesis that the C_4 PEPC enzyme may play a significant role in photosynthetic activity under drought with high air temperatures (CIAT Report 1993; El-Sharkawy 2004), probably by reducing both photorespiratory and mitochondrial dark CO_2 losses and by increasing net carbon uptake and hence productivity.

Moreover, recent evidence suggests that PEPC is possibly located in the upper end of the long-palisade parenchyma. This further supports the role of PEPC involvement in refixing or recycling respiratory CO_2 when highly dense abaxial stomata are partly closed under conditions of drought, high solar irradiance, and high temperatures with dry air, particularly in hypostomatous leaves, which normally possess >400 stomata/mm^2 (El-Sharkawy et al. 1984b). Besides increasing carbon uptake, such a mechanism for CO_2 recycling protects the leaves from photoinhibition by dissipating excess absorbed photons (Osmond et al. 1980; Osmond and Grace 1995). In the field, leaves of over 100 cassava cultivars remained photosynthetically active, although at much reduced rates, under prolonged drought with hot dry air and intense solar radiation (El-Sharkawy et al. 1990, 1992b; El-Sharkawy 1993; de Tafur et al. 1997a, 1997b).

Ueno and Agarie (1997) examined the mitochondria of palisade and spongy mesophyll cells in leaves from cassava plants cultivated in growth chambers and developed under brief water deficits. The palisade cells demonstrated a higher density of immunogold labeling of the P-protein subunit of the photorespiratory enzyme glycine decarboxylase (or GDC). These findings may add another dimension to the C_3-C_4 intermediate hypothesis in cassava and to the essential role of PEPC in recycling respiratory CO_2 within palisade cells (Figure 3-13; El-Sharkawy and Cock 1987a, 1990).

Even so, Ueno and Agarie (1997) concluded that the chamber-grown cassava cultivars were C_3 and not C_3-C_4 intermediates. This conclusion, however, is questionable on the basis of two important aspects: first, the patterns of distribution and confinement of GDC observed in some C_3-C_4 intermediate species with kranz-like leaf anatomy are not necessarily applicable to other C_3-C_4 intermediates lacking such anatomy. Second, the observed GDC labeling patterns in chamber-grown plants are not, however, incompatible with the role of PEPC in the refixing or recycling of respiratory CO_2 in cassava leaves. Moreover, the degree of expression and distribution of GDC within leaf tissues are probably affected by the developmental stages of leaves and by the environmental conditions during growth (Rylott et al. 1998).

Our hypothesis of C_3-C_4 intermediate cassava does not exclude the presence of rubisco and the enzymes associated with the photorespiratory cycle in the palisade cells. Nor does it restrict them to spongy or bundle-sheath cells in the absence of a perfect C_4 kranz leaf anatomy and lack of complete separation and compartmentalization of the key C_4 and C_3 enzymes in palisade, spongy, and bundle-sheath chlorenchyma cells (El-Sharkawy and Cock 1987a; El-Sharkawy 2004).

Possibly, a limited CO_2-concentrating mechanism (via cytosolic PEPC) in palisade cells may operate, as indicated by the disappearance at high temperatures of the post-illumination burst (PIB) of CO_2 in CO_2-free air and the pronounced CO_2 surge within a short period in darkness via the upper leaf surface (Figure 3-13B; El-Sharkawy and Cock 1987a). Under these conditions, the oxygenase reaction by rubisco (in palisade-cell chloroplasts) might be suppressed. When adaxial (upper leaf surface) stomata were blocked, CO_2 releases through lower leaf surfaces in light and CO_2-free air were substantial over a wide range of photon flux density (Figure 3-13A; El-Sharkawy and Cock 1987a).

Table 3-8. Activities of selected photosynthetic enzymes in leaf extracts from clones of field-grown cassava, comparing well-watered plants with those affected by 3 weeks of water stress, starting 92 days after planting at Santander de Quilichao, Colombia. Values are means ± SD; activities are expressed in μmol per mg Chl/min. Note the much higher reduction in C_3 rubisco activity, compared with C_4 PEPC activity in leaves that developed before stress was initiated.

Clone	Unstressed[a]				Stressed[a]			
	PEPC	Rubisco	NAD-ME	PEPC/ rubisco	PEPC	Rubisco	NAD-ME	PEPC/ rubisco
CM 4013-1	0.37 ± 0.60	0.31 ± 0.05	0.40 ± 0.06	1.19	0.31 ± 0.03	0.41 ± 0.09	0.19 ± 0.05	0.76
CM 4063-6	0.57 ± 0.06	3.72 ± 0.11	0.39 ± 0.06	0.15	0.41 ± 0.04	1.69 ± 0.10	0.17 ± 0.09	0.24
SG 536-1	0.67 ± 0.05	0.39 ± 0.20	0.55 ± 0.18	1.72	0.57 ± 0.12	0.81 ± 0.20	0.39 ± 0.50	0.70
M Col 1505	0.45 ± 0.01	1.18 ± 0.08	0.16 ± 0.02	0.38	0.49 ± 0.10	0.49 ± 0.12	0.29 ± 0.06	1.00
Average	0.51	1.4	0.38	0.86	0.45	0.85	0.26	0.68
% change due to stress					-12	-39	-32	-21

a. PEPC refers to phospho*enol*pyruvate carboxylase; rubisco to ribulose bisphosphate carboxylase; NAD-ME to the C_4 photosynthetic pathway, subtype nicotinamide adenine dinucleotide malic enzyme.

SOURCES: CIAT Report (1993); Y López and MA El-Sharkawy (1992, unpublished).

Table 3-9. Activities of selected photosynthetic enzymes in leaf extracts from clones of field-grown cassava, comparing well-watered plants with those affected by 8 weeks of water stress, starting at 92 days after planting at Santander de Quilichao, Colombia. Values are means ± SD; activities are expressed in μmol per mg Chl/min. Note the large reductions in C_3 rubisco activity, compared with the C_4 PEPC, in leaves that developed under stress, resulting in a higher PEPC/rubisco ratio. This photosynthesis-based biochemical assay is useful in selecting for tolerance of prolonged drought (Tables 3-10 and 3-11).

Clone	Unstressed[a]			Stressed[a]		
	PEPC	Rubisco	PEPC/ rubisco	PEPC	Rubisco	PEPC/ rubisco
CM 4013-1	0.86 ± 0.12	0.28 ± 0.10	3.10	1.18 ± 0.17	0.30 ± 0.01	3.9
CM 4063-6	0.89 ± 0.05	2.30 ± 0.03	0.39	1.42 ± 0.26	0.62 ± 0.02	2.3
SG 536-1	1.46 ± 0.42	0.44 ± 0.12	3.30	1.33 ± 0.22	0.25 ± 0.08	5.3
M Col 1505	1.09 ± 0.10	0.57 ± 0.13	1.90	0.96 ± 0.16	0.89 ± 0.14	1.1
Average	1.08	0.9	2.2	1.22	0.52	3.2
% change due to stress				+13	-42	+45

a. PEPC refers to phospho*enol*pyruvate carboxylase; rubisco to ribulose bisphosphate carboxylase.

SOURCES: CIAT Report (1993); Y López and MA El-Sharkawy (1992, unpublished).

In cultivars with amphistomatous leaves, exchange (measured at saturating photon flux density and normal air) of both CO_2 gas and H_2O vapor via either leaf surface was substantial. It was also proportionate to stomatal densities and stomatal conductance on both sides (El-Sharkawy et al. 1984b). Only in some uncultivated C_3-C_4 intermediate species such as those found in the genera *Flaveria*, *Panicum*, and *Diplotaxis,* did a kranz-like leaf anatomy with developed bundle sheaths appear (Ku et al. 1983; Brown et al. 1985; Brown and Hattersley 1989; Araus et al. 1990; Ueno et al. 2003). The GDC is probably confined to this anatomy (Hylton et al. 1988).

C4 photosynthesis in the absence of the typical kranz leaf anatomy in some uncultivated plants, and implications for understanding the origin of the C4 syndrome

Bienertia cycloptera, an uncultivated species of the Chenopodiaceae family, grows in salty depressions in Central Asia. Recent findings indicated that this plant has a functional C4 pathway but lacks the typical kranz anatomy where key C4 and C3 enzymes are presumably located and compartmentalized within the cytosol or chloroplasts of the same mesophyll cell (Voznesenskaya et al. 2001, 2002).

Likewise, the submersed monocot *Hydrilla verticillata,* which also lacks the kranz anatomy, was found to possess a functional C4 pathway with PEPC and rubisco being, respectively, present in the cytosol and chloroplasts of all cells. That is, the enzymes were not segregated into special and separate cell types, as is common in terrestrial C4 species (Salvucci and Bowes 1983; Magnin et al. 1997; Reiskind et al. 1997). Shifts from C3 to C4 photosynthesis can also occur under specific environmental conditions. In this submersed species, a CO_2-concentrating mechanism apparently operates in the chloroplasts where rubisco and decarboxylation enzymes are located. The mechanism may represent an ancient form of C_4 photosynthesis that evolved long before the kranz anatomy-dependent C_4 syndrome appeared in terrestrial species (Magnin et al. 1997; Reiskind et al. 1997).

If this is indeed an ancient mechanism, then an important question arises on the first induction step of C_4 photosynthesis on earth: was the CO_2-concentrating mechanism first induced and then did it evolve in unicellular aquatic organisms in response to limiting supplies of CO_2 in the water? Did this happen before C_4 plants evolved onto land in response to much reduced atmospheric CO_2, higher O_2, and stressful environments, as believed so far? Reinfelder et al. (2000, 2004) found functional C_4 photosynthesis in the unicellular marine diatom, thus possibly providing evidence to support the hypothesis.

Moreover, in some amphibious sedges such as *Eleocharis vivipara*, different culms on the same plant can have C_3, kranz-less, photosynthetic characteristics when they develop under water but C_4, kranz-type characteristics when formed in air (Ueno 2001). In this case, C_4 photosynthesis was apparently linked to kranz-type anatomy, but with the incomplete compartmentalization of rubisco, which was located in both mesophyll and bundle-sheath cells (Ueno 1996).

Hibberd and Quick (2002) also reported on the biochemical characteristics of C_4 photosynthesis, that is, high C_4 enzyme activity and the respective controlling genes. These were found to already exist and be expressed in the stem and petiole photosynthetic cells that surround vascular tissues of C_3 flowering plants. These features therefore indicate a possible first step in the induction and evolution of the C_4 syndrome.

The induction and evolution of the biochemical components of the C_4 syndrome in the plant kingdom perhaps took place long before the more complex structural and anatomical components had evolved in terrestrial plants. Extensive research has recently been conducted on the molecular mechanisms underlying the C_4 syndrome; its multiple families of genes and isogenes encoding different isoforms of PEPC in C_3, C_4, C_3-C_4 intermediate, and the crassulacean acid metabolism (CAM) systems; and the expression patterns of the respective controlling genes in different plant species, organs, tissues, and subcellular organelles (Hermans and Westhoff 1990, 1992; Rajagopalan et al. 1994; Westhoff et al. 1997; Sheen 1999; Westhoff and Gowik 2004). Such gene-level studies increase understanding of how C_4 photosynthesis evolved and is controlled. They may also pave the way for possible bioengineering of more efficient leaves in economically important crops.

In light of these advances and discoveries, the re-evaluation and revision of classification systems, previously used in the past to identify C_3, C_4, or C_3-C_4 intermediate plants, is therefore warranted. These classifications were based on only a few given criteria of leaf anatomy, subcellular structure and organization, physiology, and biochemistry. Cassava is a case in point, where its photosynthetic characteristics

comprise perhaps the only discovery so far of C_3-C_4 intermediate photosynthesis in cultivated plants. The case therefore points to the need for more comprehensive classification systems.

In cassava and its wild relatives, wide genetic variations exist for C_4 PEPC activity, correlating with leaf photosynthesis and yield under extended water stress in the field (Calatayud et al. 2002; El-Sharkawy 2004; El-Sharkawy et al. 2008). These attributes should be exploited when selecting and breeding for enhanced photosynthetic capacity, at least when identifying parental materials (Tables 3-7 to 3-10; CIAT Reports 1990 to 1994; El-Sharkawy and Cock 1990; López et al. 1993; El-Sharkawy 2004). Also notable are the C_4 decarboxylation enzymes NAD-ME and NADP-ME showing activity in cassava, with differences among cultivars (Table 3-10), and comparable with those observed in C_4 and C_3-C_4 species.

Wild species such as *Manihot rubricaulis* and *M. grahamii* represent good genetic sources for elevated PEPC activity. They also show more efficient leaf anatomy, having developed a second palisade layer, albeit short, on the lower side of their amphistomatous leaves (Table 3-7; Calatayud et al. 2002; El-Sharkawy 2004). The existence of two palisade layers and the distribution of stomata on both leaf sides may provide an adaptive advantage in terms of carbon uptake (Parkhurst 1978; Solárová and Pospisilová 1979; Pospisilová and Solárová 1980; Tichá 1982; El-Sharkawy et al. 1984b; Gutschick 1984; Mott and O'Leary 1984). For similar reasons, known genetic diversity in rubisco characteristics should also be recorded (Paul and Yeoh 1987, 1988).

Because biochemical assays are often expensive and difficult to use in screening large breeding populations, molecular biology techniques, genetic markers, and mapping tools would be useful for identifying desirable genetic traits (Beeching et al. 1993).

Leaf water status, canopy light interception, and leaf photosynthesis

Trials showed that pre-dawn leaf-water potential (Figure 3-15A; CIAT Report 1992) remain at about -0.5 MPa for all cultivars throughout most of a 3-month stress period, with virtually no differences between stressed and unstressed crops. Mid-day leaf water potential (Figure 3-15B) in all cultivars in both stressed and unstressed crops fluctuated between -0.6 MPa (during wet periods when, presumably, leaf-to-air VPD was lower) and -1.6 MPa (during dry or sunny periods when VPD was much higher), with stressed crops often showing slight reductions. These values fall in the ranges previously reported for cassava under extended periods of soil water shortages in the field (Connor and Palta 1981; Porto 1983; Cock et al. 1985; El-Sharkawy et al. 1992b; Cayón et al. 1997; de Tafur et al. 1997a). They are higher than those normally observed in other field crops under stress. These findings indicate that cassava conserves water and prevents extreme leaf dehydration through stomatal sensitivity to stress, that is, the crop uses stress avoidance mechanisms.

The phenomenon of osmotic adjustment (OA) in mature leaves therefore appears to have developed under water and edaphic stresses, as has been observed in several other field crops (Hsiao 1973; Hsiao et al. 1976; Jones and Turner 1978; Turner et al. 1978; Ackerson and Hebert 1981; Morgan 1984). It does not operate in field-grown cassava, because pre-dawn and mid-day, bulk, leaf-water potential always remains above -0.8 MPa and -2.0 MPa, respectively, during prolonged water deficits. Hence, OA is of little importance as a possible mechanism underlying cassava's tolerance of drought. Recent studies with potted cassava grown in the greenhouse showed that, after few days of water deficit, the largest increases in solutes occurred in the youngest and not yet fully expanded leaves (Alves 1998, 2002). The smallest increases occurred in mature ones, confirming the lack of importance of OA to mature leaves. Even so, further study on field-grown plants is needed if results are to be extrapolated to field conditions and to obviate acclimation problems (El-Sharkawy 2005).

Osmoregulation requires the investment and accumulation of solutes and assimilates for its development under stress. McCree (1986) examined the relative carbon costs involved in OA in sorghum grown under either water deficit or salinity. He concluded that the metabolic costs of storing photosynthates and using them for OA were less than those of converting photosynthates to new biomass, although costs did increase slightly under salinity. Under drought, changes occur in the biosynthesis, contents, and distribution of plant growth regulators such as ABA within plant organs and tissues (particularly roots, leaves, and buds). Changes in regulators may be important for the plant's sensing changes in both soil water and atmospheric humidity. They may also enable the plant to control stomatal movements, leaf formation and extension, root growth, bud dormancy, and other biological functions such as

Table 3-10. Activities of selected photosynthetic enzymes in leaf extracts from cassava clones grown in the field at Santander de Quilichao, Colombia, 1992. Values are means ± SD. Note the wide range of genetic variation for enzyme activity that could be used to select and breed for enhanced photosynthesis and, hence, productivity. Also note that cultivar CMC 40 (also known as M Col 1468) had the highest rubisco and PEPC activities, and the highest root yield under prolonged terminal water stress (Table 3-11).

Clone	Activities (μmol per mg Chl/min)[a]				
	PEPC	Rubisco	NAD-ME	NADP-ME	PEPC/rubisco
CM 523-7	1.57 ± 0.10	3.62 ± 0.62	1.84 ± 0.1	0.41 ± 0.04	0.43
CM 507-37	1.91 ± 0.10	6.84 ± 0.66	1.37 ± 0.4	0.46 ± 0.18	0.28
M Col 1684	2.90 ± 0.19	6.96 ± 1.18	2.05 ± 0.6	0.36 ± 0.03	0.42
CMC 40	3.07 ± 0.27	8.16 ± 0.71	1.84 ± 0.6	0.24 ± 0.05	0.38

a. PEPC refers to phospho*enol*pyruvate carboxylase; rubisco to ribulose bisphosphate carboxylase; NAD-ME to the C_4 photosynthetic pathway, subtype nicotinamide adenine dinucleotide malic enzyme; NADP-ME to the C_4 photosynthetic pathway, subtype nicotinamide adenine dinucleotide phosphate malic enzyme.

SOURCES: CIAT Report (1992); López et al. (1993).

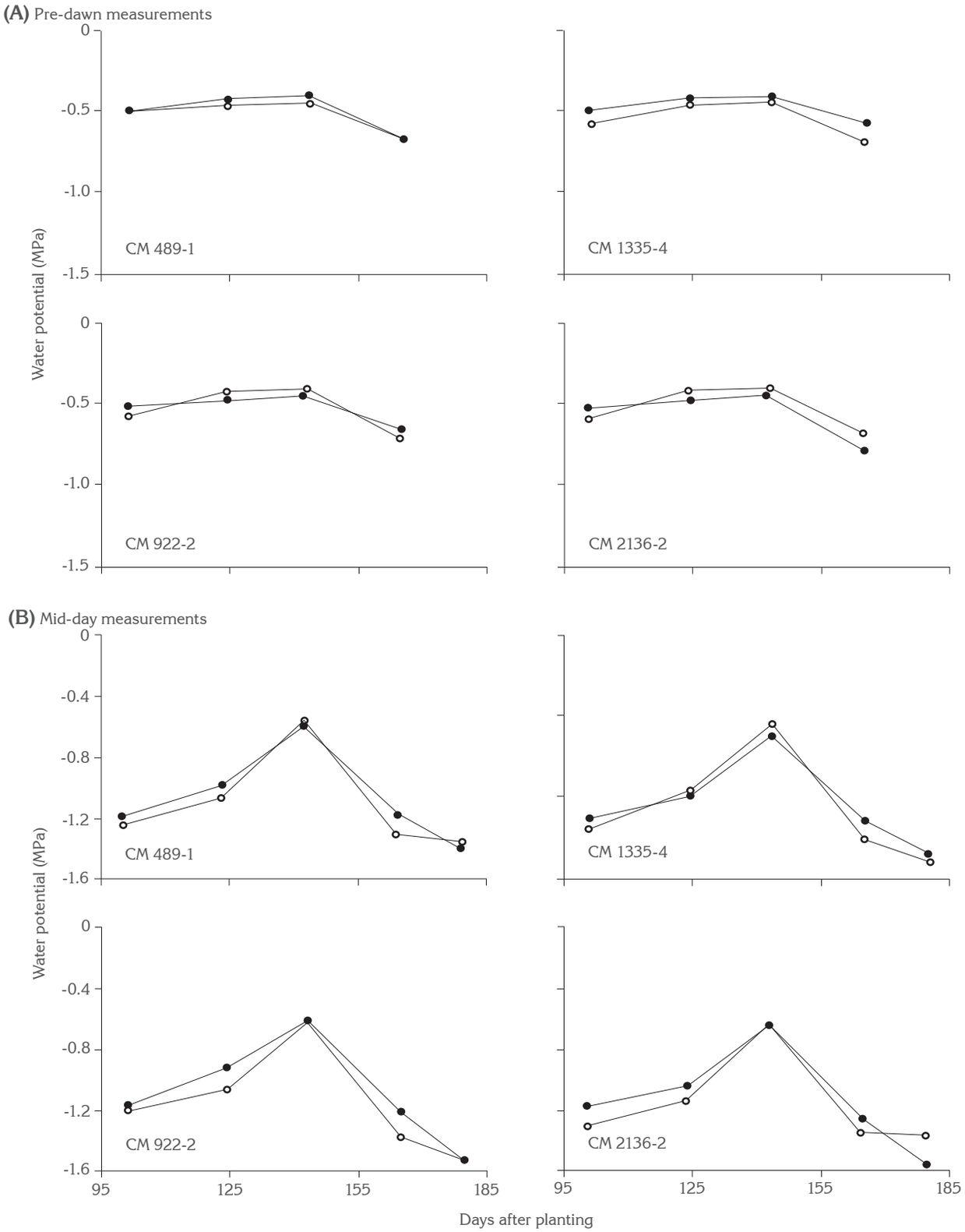


Figure 3-15. Leaf-water potential in water-stressed (○) and well-watered (●) cassava crops during stress, starting 90 days after planting. Values are means of 5 to 10 leaves from the upper canopy and taken at pre-dawn **(A)** and mid-day **(B)**. Note the small differences between the two water regimes and the four crops' pre-dawn and mid-day water potentials, and the increases in water potential during high ambient humidity. The pre-dawn and mid-day levels were more than -0.8 and -2.0 MPa, respectively, indicating the striking stomatal control in cassava, regardless of soil-water status (CIAT Report 1991; El-Sharkawy 1993).

PEPC activation and expression, and possibly the switching or induction from C_3 to CAM or C_4 photosynthesis in some species (Jones and Mansfield 1972; Huber and Sankhla 1976; Ackerson 1980; Walton 1980; Radin et al. 1982; Zeiger 1983; Henson 1984; Radin 1984; Davies et al. 1986; Schulze 1986; Turner 1986; Jones et al. 1987; Zeevaart and Creelman 1988; Zhang and Davies 1989; Chu et al. 1990; Chapin, III, 1991; Taybi and Cushman 1999; Alves and Setter 2000; Ueno 2001).

The adaptive "stress avoidance mechanism in cassava" that operates via stomatal sensitivity to both soil and atmospheric water deficits is of paramount importance for the crop's tolerance of prolonged drought (>3 months) and hot dry air in seasonally dry and semi-arid zones (El-Sharkawy 1993; de Tafur 1997a, 1997b). Coupled with this mechanism is a deep rooting system (reaching soil layers more than 2 m deep) that allows the crop to extract available stored water (Connor et al. 1981; CIAT Reports 1983 to 1994; Porto 1983; El-Sharkawy and Cock 1987b; El-Sharkawy et al. 1992b; de Tafur et al. 1997a; Cadavid et al. 1998).

Another important mechanism for conserving water under extended stress is to significantly reduce light interception (Figure 3-16; CIAT Reports 1991 to 1995). The leaf canopy is reduced, mostly through restricted new leaf formation, smaller leaf size, and leaf drop (Connor and Cock 1981; Porto 1983; Palta 1984; El-Sharkawy and Cock 1987b; El-Sharkawy et al. 1992b)—this factor is also essential for reducing water consumption. Although reduced leaf area would conserve water, it would also reduce total biomass and yield (Figure 3-9; Table 3-6; Connor and Cock 1981; Connor et al. 1981; Porto 1983; El-Sharkawy and Cock 1987b; CIAT Reports 1991 to 1995; El-Sharkawy et al. 1992b, 1998b; El-Sharkawy and Cadavid 2002). Nevertheless, once released from stress, cassava recovers rapidly by forming new leaves, which increase light interception and canopy photosynthesis. Thus, previous losses in biomass, particularly root yield, are compensated (Figure 3-16; El-Sharkawy and Cock 1987b; CIAT Reports 1991 to 1995; El-Sharkawy et al. 1992b, 1998b; El-Sharkawy 1993; El-Sharkawy and Cadavid 2002).

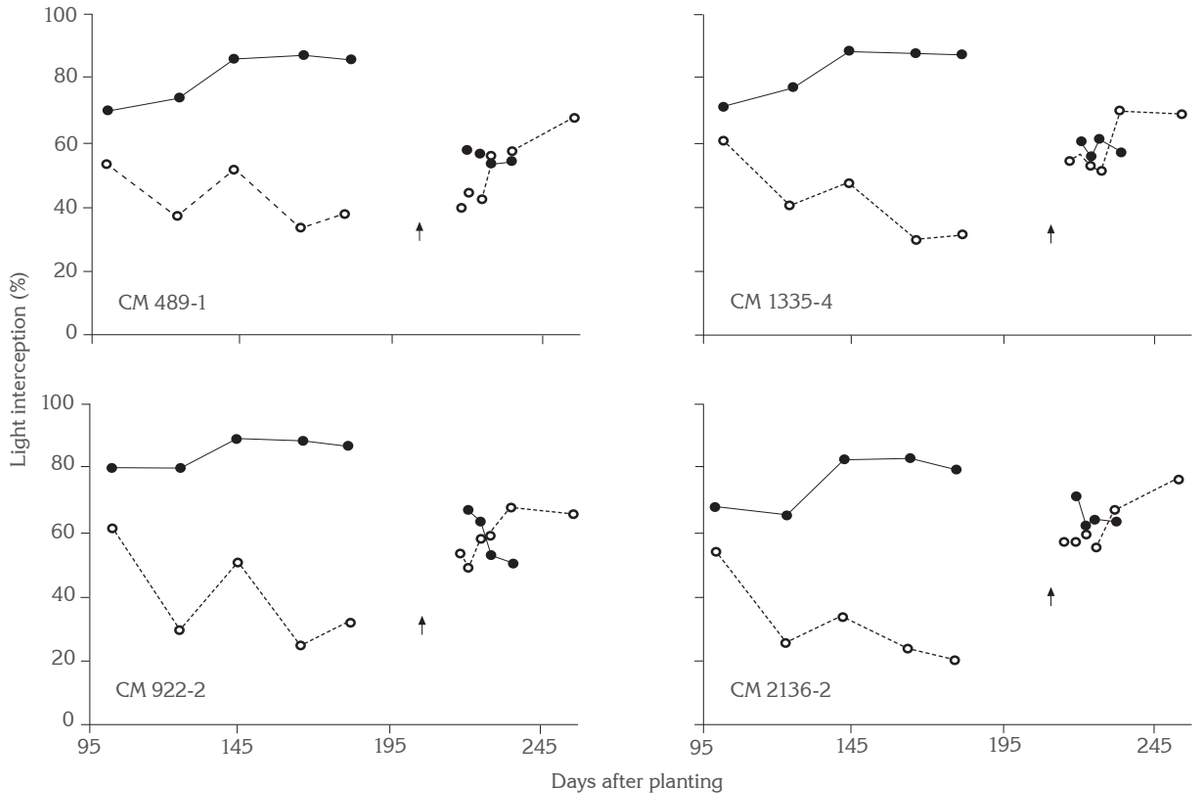


Figure 3-16. Light interception in water-stressed (o) and well-watered (●) cassava crops. Note the large reductions in light interception over time in the stressed crops because of a lack of leaf formation, the small size of new leaves, and the dropping of old leaves. Note also the increases after recovery (↑) from stress as new leaves formed (CIAT Report 1991; El-Sharkawy 1993).

Cassava leaves also remain adequately active during water shortages in the field (Figure 3-17). Stressed leaves can maintain a photosynthetic rate that is 40%–60% that of unstressed leaves over a 3-month stress period. Cultivars show differences, for example, hybrid CM 489-1 demonstrates smaller reductions than others. Once recovered from stress, previously stressed leaves can approach the rates of unstressed ones. Furthermore, newly formed leaves of previously stressed crops show even higher photosynthetic rates than those of the unstressed crops (Figure 3-17). These higher photosynthetic rates in new leaves coincide with higher stomatal conductance to water vapor; higher mesophyll conductance to CO_2 diffusion; and higher N, P, Ca, and Mg in leaves than unstressed crops (CIAT Report 1990; El-Sharkawy 1993; Cayón et al. 1997).

Moreover, Cayón et al. (1997) reported greater mobilization of potassium (an average of 0.79% K) in newly developed leaves of previously stressed crops, whereas new leaves from unstressed crops averaged 0.96% K. This finding suggests a higher demand for assimilates in storage roots, as K is normally translocated, together with sugars, to sinks (Giaquinta 1983). Thus, leaf photosynthesis is also controlled, in this case, by sink demand and strength (Burt 1964; Thorne and Evans 1964; Nösberger and Humphries 1965; Humphries 1967; Herold 1980; Ho 1988; Wardlaw 1990; Pellet and El-Sharkawy 1994; El-Sharkawy 2004). The dynamics of K in leaves of field-grown cassava may therefore be used as an indicator of root sink strength and source–sink relationships.

These remarkable physiological responses to mid-season water stress point to cassava's potential to tolerate prolonged drought, and its resilience and ability to recover from stress when water becomes available, as in subhumid zones with intermittent dry spells or in seasonally dry zones with well-marked bimodal rainfall distribution. Under these conditions, longer leaf life, that is, increased leaf retention, coupled with resistance to pests and diseases (Byrne et al. 1982; El-Sharkawy 1993), is advantageous in saving dry matter invested in leaves and in allowing partitioning of excess photosynthates towards storage roots.

The crop can also survive, but with higher losses of leaf canopy and less dry matter in storage roots, in semi-arid zones with an annual rainfall of less than 600 mm and with periods of water deficits of more than 4–5 months (e.g., Northeast Brazil, northeastern Colombia, and sub-Saharan Africa; El-Sharkawy 1993; de Tafur et al. 1997b; El-Sharkawy 2004). In this ecosystem, a second wet cycle is needed to allow recovery of growth and complete root bulking.

Evaluating Germplasm for Tolerance of Water Stress

Cassava germplasm can be evaluated for different traits while grown under different levels of water stress. The studies described in the next three sections were conducted under prolonged early water stress (occurring 2–6 months after planting); mid-season stress (4–8 months after planting), and terminal (i.e., end-of-season) stress (6–12 months after planting).

Productivity, nutrient-use efficiency, photosynthesis, and water uptake

Three-year field trials were conducted at CIAT–Quilichao experiment station to study the effects of prolonged water stress imposed at different growth stages on cassava productivity, nutrient uptake and use efficiency, leaf photosynthesis, and patterns of water uptake (CIAT Reports 1992, 1993; Caicedo 1993; El-Sharkawy et al. 1998b; El-Sharkawy and Cadavid 2002). Figure 3-18 illustrates the dynamics of dry matter accumulation in storage roots over the growth cycle of four contrasting clones. Under early stress (initiated at 2 months after planting and terminated at 6 months), root yield at 6 months was significantly smaller than the control for all clones in both growth cycles.

The same trends were observed in shoot biomass but with greater reductions than those observed for roots (CIAT Reports 1992, 1993; Caicedo 1993; El-Sharkawy et al. 1998b; El-Sharkawy and Cadavid 2002). Under mid-season stress (initiated 4 months after planting and terminated at 8 months), yield at 8 months was also significantly lower than for the well-watered control in both cycles, except for CMC 40 (also known as 'M Col 1468' in Colombia). Reductions in shoot biomass were less pronounced than those under early stress (Caicedo 1993; El-Sharkawy et al. 1998b; El-Sharkawy and Cadavid 2002).

Under both early and mid-season stress, leaf area, as determined from periodic harvests, was also significantly smaller than for controls, resulting in a much reduced canopy light interception (Figure 3-19; CIAT Report 1992; El-Sharkawy and Cadavid 2002). Once the cassava crops were allowed to recover, new

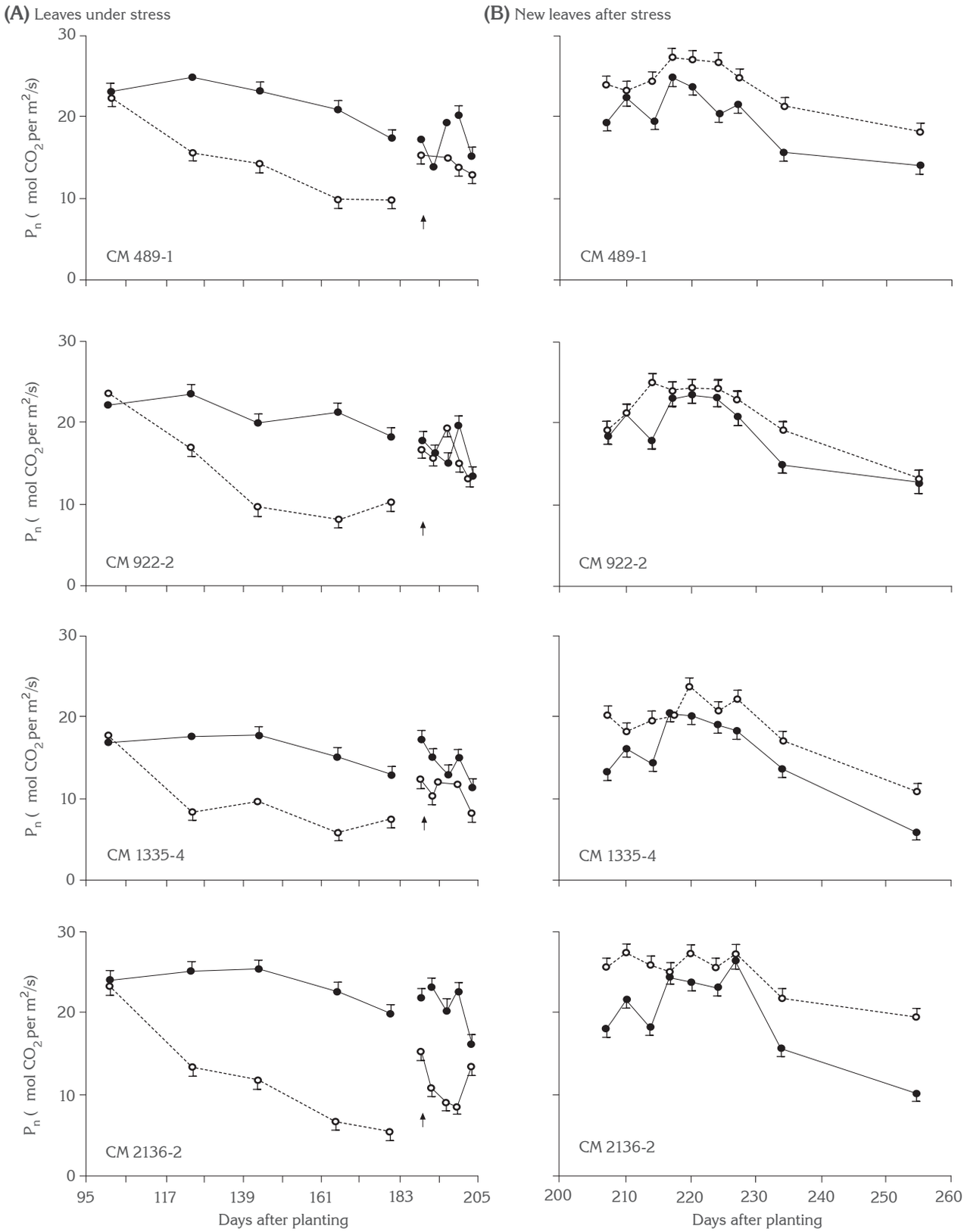


Figure 3-17. Leaf photosynthesis (P_n) in the upper canopy when affected by mid-season water stress (CIAT Report 1991; El-Sharkawy 2006). **(A)** Leaves under water stress; ↑ refers to recovery. **(B)** New leaves after stress period. ○ refers to leaves under stress; ● to control.

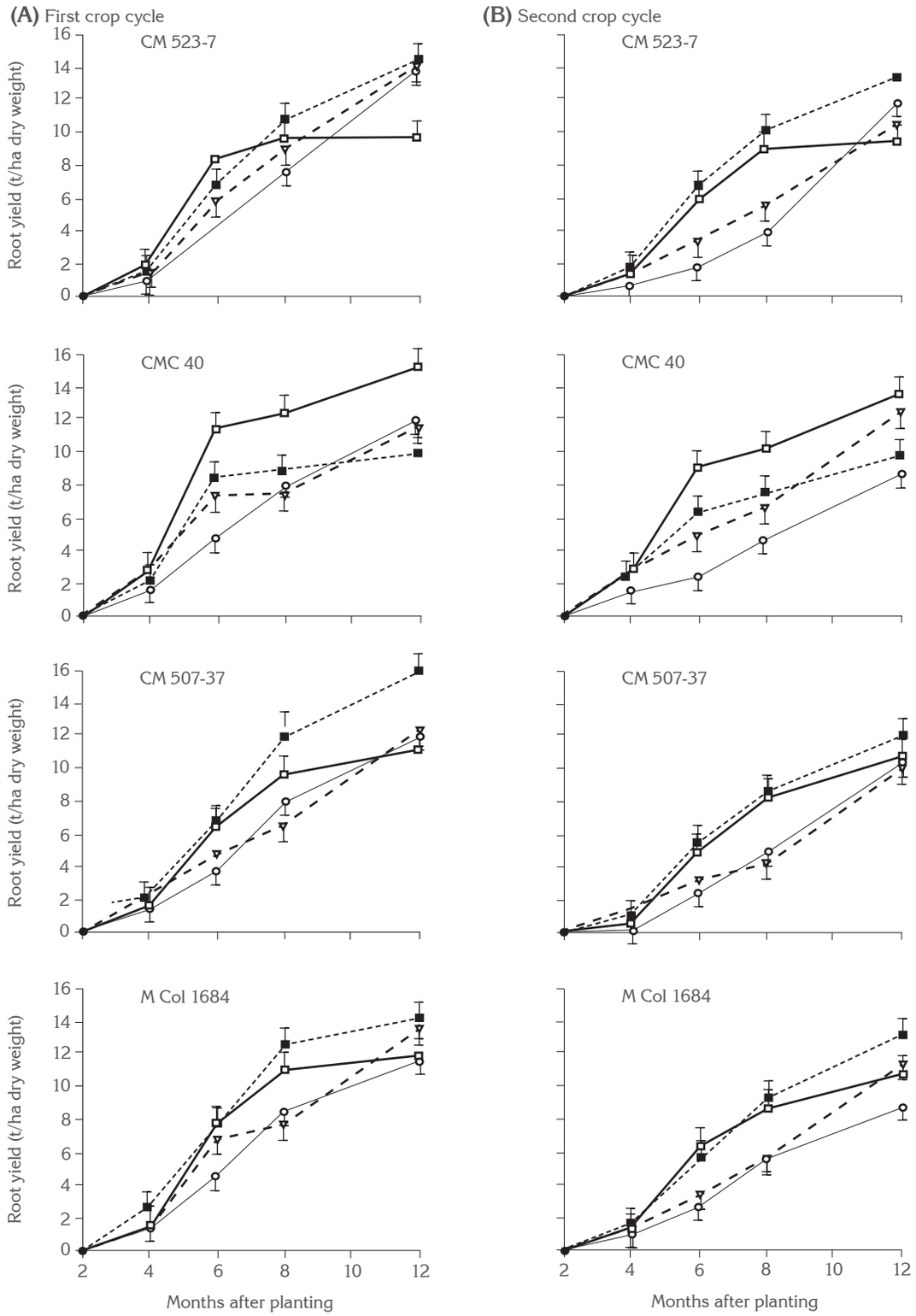


Figure 3-18. Storage root dry matter yield over time in response to prolonged water stress imposed at different growth stages (early, i.e., 2–6 months; mid-season, 4–8 months; terminal, 6–12 months after planting) and the control in four cassava cultivars. Vertical bars = ± SE (n = 4); **(A)** first crop cycle; **(B)** second crop cycle. ■ refers to control; ○ to early stress; ▽ to mid-season stress; □ to terminal stress. Note the reduction in yields during stress and recovery at final harvest from early and mid-season stress. Cultivars differed, with cv. CMC 40 (also known as M Col 1468) having the highest yield under stress. (El-Sharkawy and Cadavid 2002.)

leaf area formed rapidly, developing values similar to or higher than those of the controls, thus resulting in increased light interception (Figure 3-19). In the early stressed crops, increases in shoot biomass were lower, and remained lower, than under other water regimes. This indicated adverse effects of early stress on shoot biomass recovery (Caicedo 1993; El-Sharkawy et al. 1998b; El-Sharkawy and Cadavid 2002).

Under terminal stress (initiated 6 months after planting until final harvest at 12 months), final root yield at 12 months was less than the control. The largest reductions occurred in clone CM 523-7 (also known as 'ICA Catumare' in Colombia). An exception was CMC 40, whose yield was higher under stress. Genotype × water regime interaction was significant ($P < 0.01$), indicating the soundness of the strategy of breeding and selecting for specific edaphoclimatic zones. Similar findings were recently reported in the Sudanian savanna of Nigeria, using variations in the soil-water table as a variable for testing responses of cassava cultivars to water stress (Okogbenin et al. 2003).

Final yields of several clones across 2 years were not significantly different among water regimes (Table 3-11), indicating cassava's capacity to tolerate extended water deficit in subhumid and seasonally dry warm climates with bimodal precipitation patterns. Compared with clone CM 523-7, CMC 40 had the higher yield and shoot biomass under terminal stress, and the smaller leaf area, probably because of the high leaf photosynthesis observed in the field under diverse environments (El-Sharkawy et al. 1990; El-Sharkawy et al. 1992a; Pellet and El-Sharkawy 1993a).

Moreover, the upper-canopy leaves of CMC 40 showed greater activity for both C_3 and C_4 main enzymes than did the leaves of CM 523-7. In μmol per mg Chl/min, values were 8.2 for rubisco and 3.1 for PEPC in CMC 40 versus 3.6 and 1.6 in CM 523-7 (Table 3-10; CIAT Report 1992; López et al. 1993). These findings indicate the importance of selecting and breeding for high leaf photosynthesis, particularly under stress. Variations among clones for leaf photosynthesis, as measured in the field, were observed (Figure 3-20).

Nutrient uptake and use efficiency

Plant nutrient contents at final harvest were much less in stressed crops, particularly at early stages (El-Sharkawy et al. 1998b; El-Sharkawy and Cadavid 2002). The resulting higher nutrient-use efficiencies for all elements in both root and total biomass were caused mainly by increased reductions in shoot biomass and stable root yields, and higher HI (Table 3-12). Across clones, increases in nutrient-use efficiency due to early stress were >35% and >10% in roots and total biomass, respectively. However, among nutrient elements, the lowest percentage increases were for nitrogen-use efficiency and the highest for magnesium.

Similar trends were observed for mid-season stressed crops, but with lower values than for early stress. Under terminal stress, which started after peak crop growth at 6 months and after the bulk of nutrient uptake took place between 2 and 5 months (Howeler and Cadavid 1983; Howeler 2002), nutrient-use efficiency increased minimally in terms of root production, except for magnesium, which showed a 25% increase.

These findings clearly illustrate the beneficial effect of responses to water stress on conserving soil fertility, as well as on nutrient-use efficiency. Cassava is known for its high levels of tolerance of both water stress and poor soils (CIAT Reports 1990 to 1995; Howeler and Cadavid 1990; El-Sharkawy 1993; Pellet and El-Sharkawy 1993a, 1993b, 1997; Cadavid et al. 1998; Howeler 2002; El-Sharkawy 2004). Its capacity to accumulate more dry matter per unit of water and nutrient absorbed than most other food crops points to its inherent advantage in marginal edaphoclimatic conditions.

Furthermore, these data have important implications for a breeding strategy for low-input, agricultural production systems (Hershey and Jennings 1992). Selection and breeding for plant types that demand less water and fewer nutrient resources (e.g., medium-statured to short cultivars) may help stabilize and sustain adequate productivity in resource-limited environments. In 2-year field trials held at CIAT–Quilichao, a group of clones that were tall (high top biomass), medium-statured (medium top biomass), and short (low top biomass) were evaluated for productivity and nutrient-use efficiency (CIAT Report 1996, 1997; El-Sharkawy et al. 1998a). Differences in root yields among this group of clones (planted at 10,000 plants/ha) were small because of higher HI in the medium-statured and short cassava than in tall cassava, with early root bulking tending to occur in both medium-statured and short clones (Table 3-13).

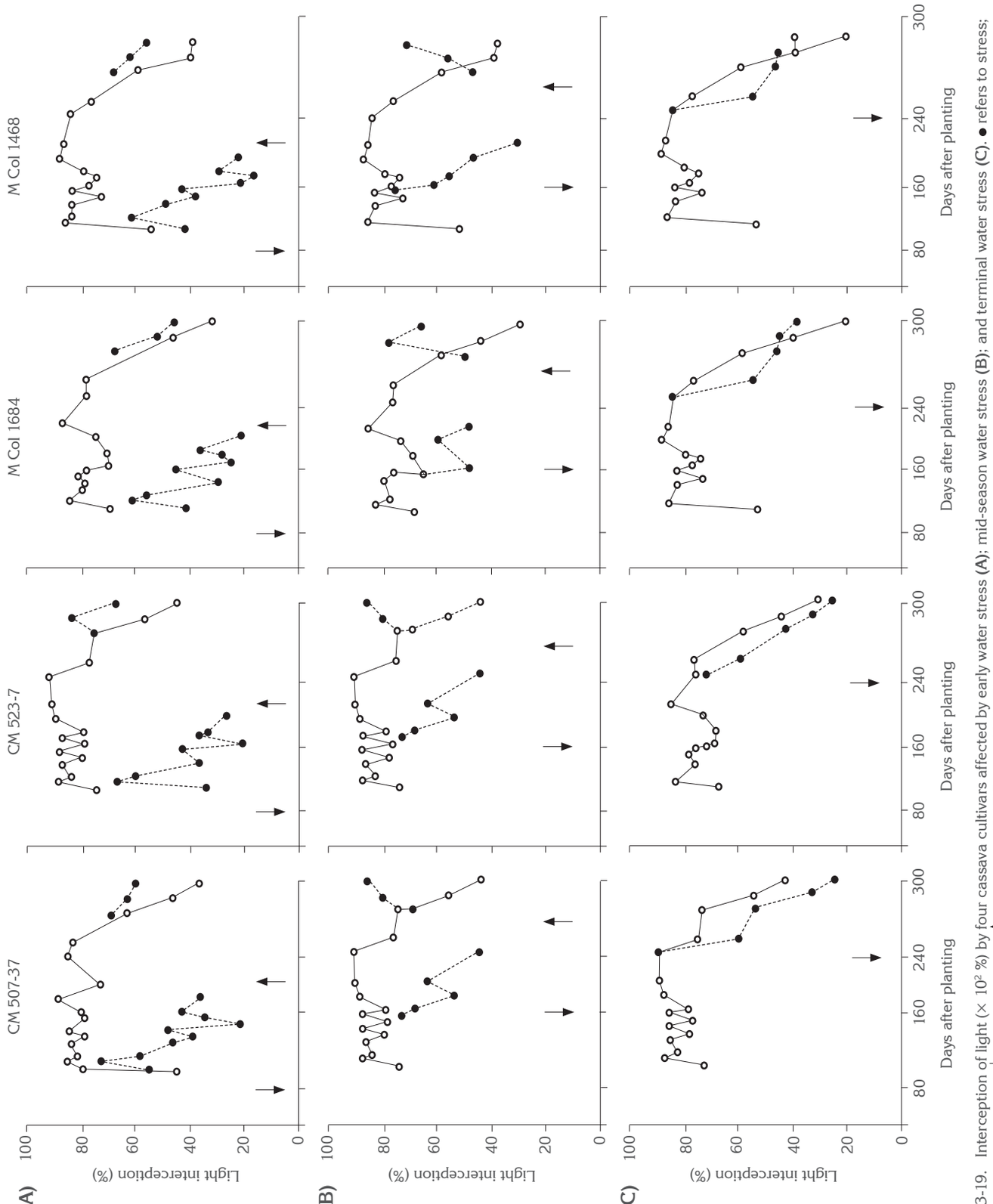


Figure 3-19. Interception of light ($\times 10^2$ %) by four cassava cultivars affected by early water stress **(A)**; mid-season water stress **(B)**; and terminal water stress **(C)**. ● refers to stress; ○ to control; ▼ to stress starting; ◀ to recovery. (CIAT Report 1992; El-Sharkawy 2006.)

Table 3-11. Effect of prolonged water stress imposed on four cassava cultivars at different growth stages, Santander de Quilichao, Department of Cauca, Colombia, over the 1990/91, 1991/92, and 1992/93 seasons. Parameters evaluated were storage root yield and shoot biomass at 12 months after planting, and mean leaf area index (mean LAI) over the growth cycle. The data given below are from the 1991/92 and 1992/93 seasons. Note that cv. CMC 40 (also known as M Col 1468) had the highest root yield under prolonged terminal water stress and the highest activities for phospho*enol*pyruvate carboxylase (PEPC) and rubisco activities (Table 3-10).

Cultivar	Stress treatment (root yield at t/ha, dry weight)				Stress treatment (shoot biomass at t/ha, dry weight)				Stress treatment (mean LAI)			
	Control	Early	Mid-season	Terminal	Control	Early	Mid-season	Terminal	Control	Early	Mid-season	Terminal
CM 507-37	14.0	11.1	11.3	11.1	6.0	2.7	5.6	5.3	2.3	1.3	1.8	2.3
CM 523-7	13.8	12.8	12.1	9.7	5.3	4.2	5.2	4.5	2.3	1.4	1.3	2.0
CMC 40	10.0	10.4	12.1	14.6	7.8	3.9	5.7	6.7	1.7	1.1	1.1	1.7
M Col 1684	13.6	10.3	12.5	11.5	5.0	2.2	4.0	4.3	1.8	1.1	1.3	1.8
Average	12.9	11.2	12.9	11.7	6.0	3.3	5.1	5.2	2.0	1.2	1.4	2.0
$LSD_{0.05}$	NS*				0.8				0.3			
Treatment × cultivar	2.7				1.4				0.5			

* NS = not significant at 5%.

SOURCES: Caicedo (1993); El-Sharkawy et al. (1998b); El-Sharkawy and Cadavid (2002).

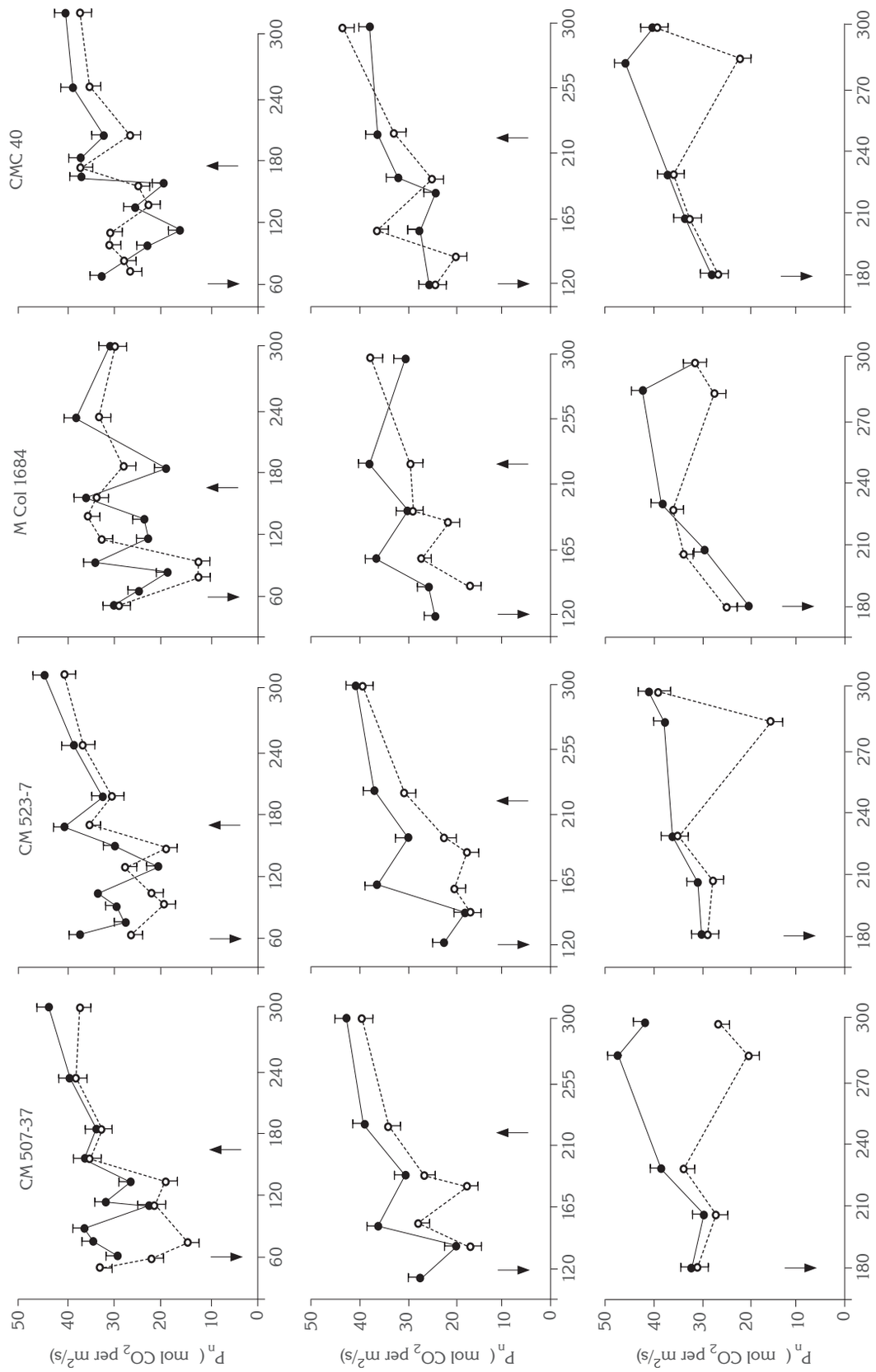


Figure 3-20. Photosynthetic rate (P_n) of upper-canopy leaves of four cassava cultivars affected by early water stress **(A)**; mid-season water stress **(B)**; and terminal water stress **(C)**. ● refers to stress; ○ to control; ▼ to stress starting; ▲ to recovery. Values are averages of four leaves ± SD. (CIAT Report 1992; El-Sharkawy 2006.)

Table 3-12. Effect of prolonged water stress on cassava at different growth stages on dry root yield, total harvestable biomass (t/ha), and nutrient-use efficiency (kg dry matter/kg total nutrient uptake) at final harvest, using an average of four clones. Note the higher nutrient-use efficiency under prolonged early and mid-season water stresses, compared with well-watered crops. The higher nutrient-use efficiency was mainly due to larger reductions in top biomass (and hence less nutrient uptake), compared with the smaller reductions in storage roots (and hence higher harvest indices).

Trait[a]	Stress treatment[b]							
	Control		Early (2–6 MAP)		Mid-season (4–8 MAP)		Terminal (6–11 MAP)	
	Roots	Total biomass	Roots	Total biomass	Roots	Total biomass	Roots	Total biomass
Root yield	11.5	—	11.9	—	13.1	—	11.0	—
Total biomass	—	15.8	—	15.5	—	18.2	—	14.5
N-UE	93	144	126	159	97	139	85	127
P-UE	615	947	971	1232	777	1109	645	966
K-UE	112	172	173	219	146	210	115	173
Ca-UE	270	414	408	519	300	433	274	413
Mg-UE	379	577	616	780	504	722	473	712
% change due to stress								
Root yield			+3		+14		-4	
Total biomass				-2		+15		-8
N-UE			+35	+10	+4	-3	-9	-12
P-UE			+58	+30	+26	+17	+5	+2
K-UE			+54	+27	+30	+22	+3	0
Ca-UE			+51	+25	+11	+5	+1	0
Mg-UE			+63	+35	+33	+25	+25	+23

a. N-UE, P-UE, K-UE, Ca-UE, and Mg-UE refer to use efficiency of nitrogen, phosphorus, potassium, calcium, and magnesium, respectively.
b. MAP refers to months after planting.

\SOURCES: CIAT Report (1993); El-Sharkawy et al. (1998b); El-Sharkawy and Cadavid (2002).

Table 3-13. Dry root yield and top biomass (t/ha) for 15 cassava clones of differing biomass weights (higher, intermediate, and lower) grown at Santander de Quilichao, Colombia. Data are from the first cycle (1994/95). Note the early bulking (i.e., storage root-filling capacity) trends within the first 5 months in clones with medium or short stature, a trait advantageous for selecting and breeding improved materials for semi-arid ecosystems.

Biomass weight	Root yield at days after planting			Tops at 303 days after planting
	126	182	303	
Higher (mean of 5 clones)	1.63	2.64	11.32	6.6
Intermediate (mean of 5 clones)	2.32	2.80	10.90	3.7
Lower (mean of 5 clones)	2.21	3.02	10.39	2.6
$LSD_{0.05}$	0.55	NS	NS	0.95

SOURCE: El-Sharkawy et al. (1998a).

The higher shoot biomass of tall cultivars meant higher nutrient uptake and less nutrient-use efficiency in terms of root production. In contrast, the total plant nutrient uptake in medium-statured and short cultivars was 15% to 30% less (Table 3-14; El-Sharkawy et al. 1998a). Furthermore, short cultivars had 12% higher leaf photosynthesis than tall ones (El-Sharkawy and de Tafur 2010). These data support the strategy of breeding and selecting for medium to short plant architecture, which would be advantageous for higher efficiency in the use of both native soil nutrients and applied fertilizers, particularly if crop residues are not recycled to the soil.

Short cassava would be furthermore beneficial for both increasing productivity and reducing soil erosion if it is planted at higher densities than normally used for mono- or intercropping. Current farming practices use about 5000 and 10,000 plants/ha in intercropped and monocropped cassava, respectively. The more rapidly the canopy closes during early growth, the less likely soils are prone to erosion. This breeding objective should be combined with greater leaf photosynthesis, longer leaf life, and host-plant resistance or tolerance of pests and diseases (i.e., improved leaf retention; Figure 3-21; Lenis et al. 2006), particularly for developing improved germplasm targeted to seasonally dry and semi-arid zones (Byrne et al. 1982; Cock and El-Sharkawy 1988a, 1988b; El-Sharkawy et al. 1990, 1992b; Hershey and Jennings 1992; El-Sharkawy 1993, 2004).

Table 3-14. Nutrient-use efficiency for root production at 10 months after planting (kg dry root/kg total nutrient uptake) for tall, medium-statured, or short cassava. Note the significantly higher nutrient-use efficiency in both medium-statured and short clones, compared with the tall ones. The higher values were mainly a result of both much smaller top biomass (and hence smaller nutrient uptake), as root yields were comparable, regardless of plant heights (Table 3-13). The medium-statured and short clones with higher nutrient-use efficiency are advantageous for sustainable production in low-input production systems and in low-fertility soils. Values are averages of 2 years (1994–1996).

Group of 5 cultivars	Nutrient				
	N	P	K	Ca	Mg
Tall	110	715	132	347	589
Medium-statured	133	837	149	439	686
Short	131	885	161	430	669
$LSD_{0.05}$	17	85	22	77	91

SOURCE: El-Sharkawy et al. (1998a).

The short cultivar M Col 2215 was selected in 1987–1989 for its high drought tolerance, high dry matter content in storage roots, and high PEPC activity in leaf extracts (El-Sharkawy et al. 1990, 2008). It was introduced to Ecuador and evaluated for several years in the semi-arid western coast, where it yielded better than local varieties. Farmers participated in field trials and quickly accepted it, which led to its official release under the name 'Portoviejo 650' in 1992.

Water uptake and use efficiency

Patterns of water uptake in various clones during extended water stress imposed at different stages of growth are shown in Figure 3-22. In all stress treatments, cassava withdrew more water from the deep soil layer (at 2 m deep), after the upper layer was almost depleted. Moreover, the water uptake from this deep layer increased as stress progressed, particularly in the terminal stress treatment, indicating deep rooting behavior, as previously reported (Connor et al. 1981; El-Sharkawy and Cock 1987b; CIAT Reports 1991 to 1994; El-Sharkawy et al. 1992b; de Tafur et al. 1997a; Cadavid et al. 1998).

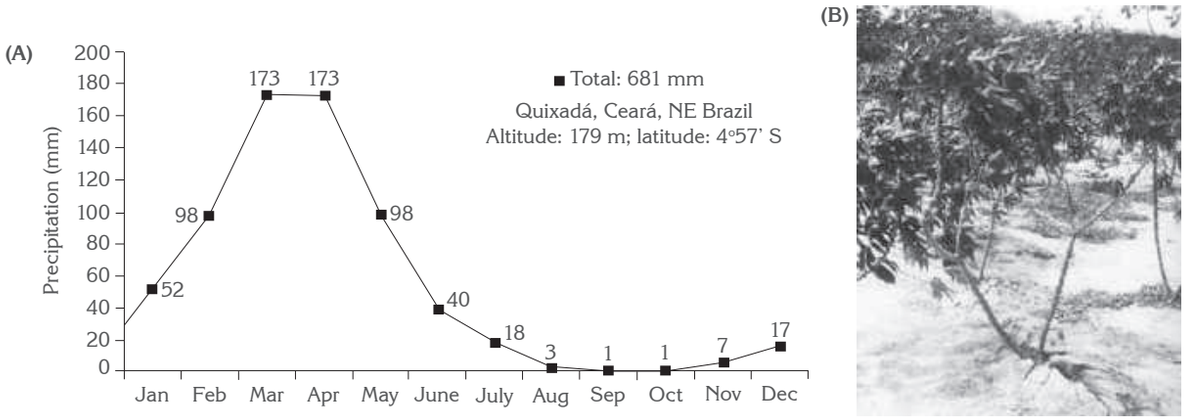


Figure 3-21. Screening for drought tolerance for the semi-arid ecosystem at Quixadá, Ceará, Northeast Brazil. **(A)** Long-term (30 years) annual precipitation; 80% occurs over 4 months and the rest of the growing season is dry, with high air temperatures, high evapotranspiration, and high solar radiation. Soils are sandy, with low water-holding capacity, and very low in nutrients. **(B)** Cassava germplasm at 8 months, showing good leaf retention and sustainable canopy. Several clones were selected with high yield potential, tolerance of drought, low HCN, and tolerance of major pests and diseases. Yield was >12 t/ha fresh root at 12 months with a dry matter content of >25% that could be greatly enhanced with a second wet cycle.
References: El-Sharkawy 1993; de Tafur et al. 1997b.

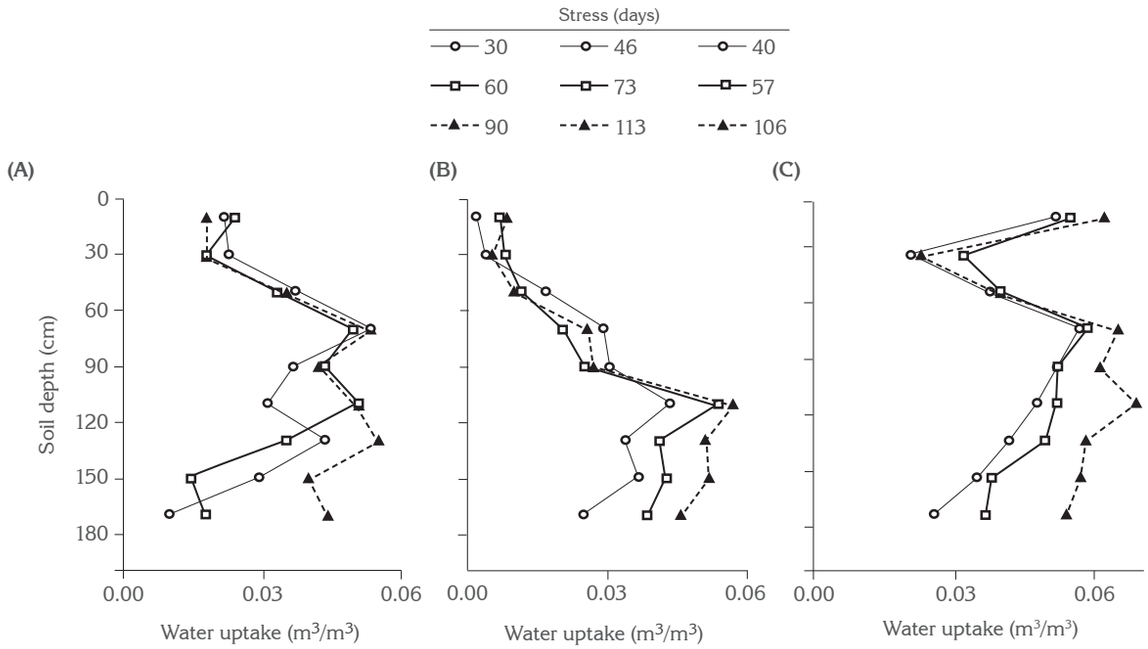


Figure 3-22. Patterns of water uptake by cassava (averages of four cultivars) during water deficits of differing lengths, Santander de Quilichao, Department of Cauca, Colombia. **(A)** Stress at 2 months after planting; **(B)** stress at 4 months after planting; and **(C)** stress at 6 months after planting. Note the greater water extraction from deeper soil layers that increased as water stress progressed over time, particularly in terminally stressed crops **(C)** (El- Sharkawy et al. 1992b; CIAT Report 1993; de Tafur et al. 1997a; El-Sharkawy 2006).

By volume, the soil water available in the first 2 m of soil ranges from 8% to 12% (Connor et al. 1981; El-Sharkawy et al. 1992b). Hence, water uptake under any of these prolonged stress treatments would probably not exceed about 200 mm (i.e., the total available water at 2 m deep). This indicates cassava's capacity to conserve and deplete deep soil water slowly over extended stress. For two cultivars (M Col 1684 and its hybrid CM 507-37) subjected to a 3-month mid-season water shortage, El-Sharkawy et al. (1992b) reported that total water uptake, as estimated from periodic sampling of soil cores at 2 m deep, was

around 100 and 160 mm during 35 and 96 days of stress, respectively. The latter value was equivalent to 70%–75% of the plant-available water at a depth of 2 m in this soil, and much less than the rate of pan evaporation of about 4.4 mm/day at the trial site.

In recent studies in Ghana, Oguntunde (2005) used the sap flow method to estimate daily cassava canopy transpiration under prolonged natural stress, which he estimated as 0.8–1.2 mm. This is equivalent to 24% of potential evapotranspiration. El-Sharkawy et al. (1992b) found that, over 43 days of peak canopy growth (117 to 160 days after planting), estimated crop water-use efficiency values were 4.4–4.8 g/kg of water in stressed crops and 3.7–4.9 g/kg in unstressed crops (clone M Col 1684 and its hybrid CM 507-37, and using total oven-dried biomass).

Because cassava has a long growth cycle and a low LAI during a significant portion of its growing season, seasonal crop water-use efficiency is reduced. A cassava crop grown in a field lysimeter was estimated as having a seasonal water-use efficiency of about 2.9 g total dry biomass/kg water. This value compares favorably with the value found for grain sorghum (C_4), which is about 3.1 g/kg, and is much higher than that found for field bean (C_3), which is about 1.7 g/kg (El-Sharkawy and Cock 1986; El-Sharkawy 2004). Because cassava has a higher HI (0.6–0.7), water-use efficiency in terms of economic yield would be even higher than for either sorghum or field bean, which have lower HI values.

A large field trial on yield, involving 16 improved cassava cultivars, was established in a seasonally dry zone (Patia Valley, Cauca, Colombia) that had less than 1000 mm of precipitation in 10 months. Average harvestable total dry biomass, excluding dropped leaves and fine roots, was more than 30 t/ha (El-Sharkawy et al. 1990). In this trial, the mean oven-dried root yield ranged among cultivars from 15 to 27.4 t/ha, with an overall mean of 20 t/ha. About 60% of rainfall occurred in months 6 and 7 of the growth cycle, with perhaps some water runoff and deep percolation into the clayey soil occurring.

However, if we assume all rainfall to have been effectively used by the crops and lost only through evapotranspiration (i.e., through plant transpiration and evaporation from exposed soils), then an evapotranspiration ratio of 270–300 is obtained. This ratio is water loss per unit of total dry matter produced. Such a ratio is comparable with values (excluding soil evaporation) observed in tropical C_4 crop species such as maize, millet, sorghum, and sudangrass. It is also much smaller than the values obtained in C_3 species that were grown in large weighable containers in a semi-arid climate almost a century ago by L.J. Briggs and H.L. Shantz at Akron, Colorado, USA (Stanhill 1986).

The actual evapotranspiration ratio of cassava might have been even lower than the estimated values here, as dropped leaves may account for 2–6 t/ha (El-Sharkawy and Cock 1987b; El-Sharkawy et al. 1992b; Pellet and El-Sharkawy 1997). In terms of economic yield, the estimated evapotranspiration ratio for cassava of about 500 in this trial is much less than the values for grain sorghum (868), proso millet (567), and maize (1405) obtained in the Briggs and Shantz trials (Stanhill 1986). If adjusted for moisture content in the grains of these cereals, the values would be much greater than in cassava. These findings indicate cassava's potentially high water-use efficiency and further strengthen its comparative advantage in water-limited zones. Under non-limiting rainfall or with irrigation, however, cassava would be more efficient in terms of annual calories production per unit land area and water consumption than most tropical C_4 grain crops (El-Sharkawy 1993, 2004).

El-Sharkawy (2005) predicted that cassava productivity would probably be enhanced further by rises in atmospheric CO_2 and temperature (i.e., as a result of global climate change), which should result in much higher water-use efficiency. This prediction was corroborated by recent findings that leaf photosynthesis and root yield of field-grown cassava under elevated levels of CO_2 in the tropics (i.e., 680 cm^3/m^3 in open-top chambers) had higher values than plants grown under ambient CO_2 (Fernández et al. 2002). These findings indicated an absence of photosynthetic down-regulation often observed in other plant species (Kramer 1981; Mooney et al. 1991; Pettersson and McDonald 1994; Webber et al. 1994; Woodrow 1994).

The absence of photosynthetic down-regulation in cassava grown under elevated CO_2 was apparently associated with the higher carboxylation efficiency of the C_3 rubisco, despite reductions in soluble protein and N contents in leaves. Thus, higher nitrogen-use efficiency in terms of CO_2 uptake is indicated. El-Sharkawy (2004) reported significant positive correlations between dry root yield and photosynthetic N-use efficiency across a wide range of field-grown cassava cultivars with no CO_2 enrichment. (Photosynthetic N-use efficiency is defined as CO_2 uptake per unit of total leaf N, as measured in normal air and with high solar irradiance in upper-canopy leaves.)

Furthermore, soluble sugars and starch contents in leaves of plants grown under elevated levels of CO_2 were reduced. These findings suggest that higher demands are made by strong sinks for assimilates, as indicated by the concomitant increases in both shoot biomass and storage root yield (Fernández et al. 2002). Ziska et al. (1991) also reported 56% increases in leaf photosynthesis of cassava plants grown for long periods under elevated levels of CO_2 under controlled conditions (at 300 cm^3/m^3 more than ambient CO_2), indicating an absence of down-regulation.

In contrast to the above findings, Gleadow et al. (2009) reported lower leaf photosynthetic rates in plants grown at higher than ambient CO_2, particularly in those grown at the highest level. They also found significant reductions in shoot and storage root biomass. However, we point out that the authors studied potted cassava grown under greenhouse conditions at different levels of CO_2, that is, at 360, 550, and 710 ppm CO_2. Obviously, these findings indicated a feedback inhibition due to the rooting systems being confined by the growth media used. Cassava is a tropical shrub that requires large volumes of soil. When grown under inappropriate conditions, it will not express either its leaf photosynthetic capacity or its potential productivity. Thus, as warned earlier in the chapter, such findings are invalid and any resulting conclusions must be questioned. In contrast, field research conducted in CIAT's sunny, hot, humid, and tropical environment, demonstrated cassava's high photosynthetic capacity and productivity.

These photosynthetic attributes, combined with a high optimal temperature for leaf photosynthesis (Figure 3-4) and elevated activity of the C_4 PEPC in cassava leaves (Tables 3-7 to 3-10), may confer adaptive advantages for cassava growth and productivity in a globally warming climate.

In seasonally dry tropical ecosystems, excess rains often recharge deeper soil layers. Cassava's deep-rooting characteristics are of paramount importance, particularly where the crop must endure several months' of prolonged drought. These characteristics, combined with partial stomatal closure in response to both soil and atmospheric water deficits; reduced leaf canopy and light interception; and adequate leaf photosynthesis make cassava a highly drought-resistant crop.

This pattern of conserved water use results in optimizing seasonal crop water-use efficiency (El-Sharkawy and Cock 1986; El-Sharkawy 2004). Boyer (1996) reviewed and discussed advances in drought tolerance in field crops and the possible mechanisms underlying enhanced crop water-use efficiencies. Deep-rooting characteristics account for many differences in drought tolerance among species. These inherent mechanisms may partly explain why stressed cassava is still able to produce more adequately than cereals and grain-legume food crops. They also further strengthen the relevance of the strategy to expand cassava cultivation into drought-prone areas where severe food shortages may occur (Hershey and Jennings 1992; El-Sharkawy 1993, 2004; de Tafur et al. 1997a; Okogbenin et al. 2003).

Selecting for Tolerance of Low-Fertility Soils

To alleviate pressures on natural resources, particularly in marginal soils where most cassava is produced with few or no inputs, selecting for tolerance of low-fertility soil is warranted (Hershey and Jennings 1992; El-Sharkawy 1993, 2004). Potassium (K) and phosphorus (P) are the two most limiting nutrients, mainly because harvested roots remove large quantities of K (>60%) and most acidic soils in the tropics have low levels of P (Howeler 1985; CIAT Reports 1988 to 1997; Howeler and Cadavid 1990; Pellet and El-Sharkawy 1993a, 1993b, 1997; El-Sharkawy and Cadavid 2000; Howeler 2002). Large screening trials of cassava germplasm were conducted in low-fertility soils at CIAT–Quilichao over 10 years to evaluate tolerance of low soil-P levels (CIAT Reports 1986 to 1996; Hershey and Jennings 1992; Pellet and El-Sharkawy 1993a, 1993b; El-Sharkawy 2004) and, more recently, for low K levels (CIAT Reports 1992 to 1996; El-Sharkawy and Cadavid 2000).

Table 3-15 presents data on yield and root dry matter content, with and without applied K fertilizer, for a group of the screened accessions. Low levels of K in these soils were indicated by the strong responses to K applications of all clones tested. The average dry root yield for accessions receiving K applications was 10.3 t/ha. In contrast, yield for accessions not receiving K fertilizer was 5.9 t/ha. Dry matter content was, respectively, 38.1% and 36.2%. However, genetic differences were wide for yield and for tolerance levels, as estimated by the calculated low-K adaptation index (i.e., the product of yields at K levels relative to the overall mean in the trial).

Two accessions (CM 2777-2 and CM 3372-4) had high tolerance levels with an adaptation index that was 50% higher than the overall mean index (1.0). They

Table 3-15. Dry root yield (t/ha), root dry matter (DM; %), and low-K adaptation index for 15 cassava clones grown at Santander de Quilichao, Colombia. Data are from the second cycle (1994/95). Clones with high adaptation indices are good genetic sources for selecting and breeding for tolerance of low soil-fertility (El-Sharkawy and Cadavid 2000).

Clones	Zero K		100 kg K/ha		Low-K adaptation index[a]	
	Dry root	Root DM	Dry root	Root DM		
CM 2777-2	7.9	31.8	13.3	35.8	1.73	HA
CM 3372-4	7.8	38.9	12.8	40.8	1.64	
CG 402-11	7.6	22.9	11.5	27.3	1.44	
CG 1141-1	6.9	40.4	12.0	42.2	1.36	
CG 165-7	6.2	35.2	12.1	37.8	1.23	IA
CM 4777-2	5.6	40.5	13.4	42.1	1.23	
CM 4729-4	7.5	39.9	9.8	38.8	1.21	
CM 4574-7	5.7	35.9	9.8	36.9	0.92	LA
CM 3311-3	6.0	38.6	9.2	37.5	0.91	
SG 107-35	5.6	41.3	9.7	40.1	0.89	
CM 5286-3	4.9	30.6	10.7	35.9	0.86	
CM 2177-2	6.5	34.9	7.0	36.9	0.75	
CM 3306-4	3.8	41.9	10.3	43.4	0.64	
CM 2766-5	3.5	32.1	8.1	35.2	0.47	
CM 3299-4	3.3	37.9	5.1	41.2	0.28	
Mean of all clones	5.9	36.2	10.3	38.1	1.00	
$LSD_{0.05}$	1.8	3.7	2.5	2.6		

a.
$$\text{Low-K adaptation index} = \frac{\text{(yield with zero K) (yield with 100 kg K/ha)}}{\text{(mean yield with zero K) (mean yield with 100 kg K/ha)}}$$

Index of adaptation to low soil K: H = high; I = intermediate; L = low.

SOURCE: CIAT Report (1995).

therefore represent suitable genetic sources for breeding improved germplasm. Pellet and El-Sharkawy (1997) identified clones that had high yields, whether with or without fertilizer, indicating that selecting these clones, instead of landraces or other varieties, for high yield would not be detrimental to soil fertility. El-Sharkawy and Cadavid (2000) also reported on the existence of genetic variation in clones responding to K in a 5-year trial. These clones also showed high yield potential, whether with or without K application, and high K-use efficiency in terms of root production.

One clone (CM 507-37) had good levels of leaf retention and a deep fine-root system (El-Sharkawy and Cock 1987b; El-Sharkawy et al. 1992b), indicating the importance of these traits. Moreover, clone CMC 40 (i.e., M Col 1468) showed the highest nutrient-use efficiency under extended water stress at different growth stages. It had higher biomass and yield (El-Sharkawy et al. 1998b; El-Sharkawy and Cadavid 2002), but low efficiency under wet conditions (Pellet and El-Sharkawy 1997; El-Sharkawy and Cadavid 2000), highlighting that the genotype × environment interaction is important in this case.

Figure 3-23 presents data on yields, whether with or without P application, of a group of 33 accessions. Some clones had high yields, with or without P fertilizer, indicating high tolerance of low soil-P, as shown by their enhanced low-P adaptation indices. Cassava relies on vesicular arbuscular mycorrhizae (VAM) for P uptake (Howeler et al. 1982; Howeler and Sieverding 1983). However, Pellet and El-Sharkawy (1993b) reported that cultivar differences in P uptake were related more to differences in fine-root-length density than to VAM infection rates. Uptake efficiency (estimated as uptake per unit root length) did not differ among cultivars. This finding again indicates the importance of the fine-root system in cassava plant–soil relationships.

Furthermore, these authors concluded that yield response to P was regulated by the balance between the potential for shoot growth and for storage roots. Adaptation to low-P could be improved by selecting for high fine-root-length density, moderate shoot growth, and stable high HI. This conclusion was further corroborated by

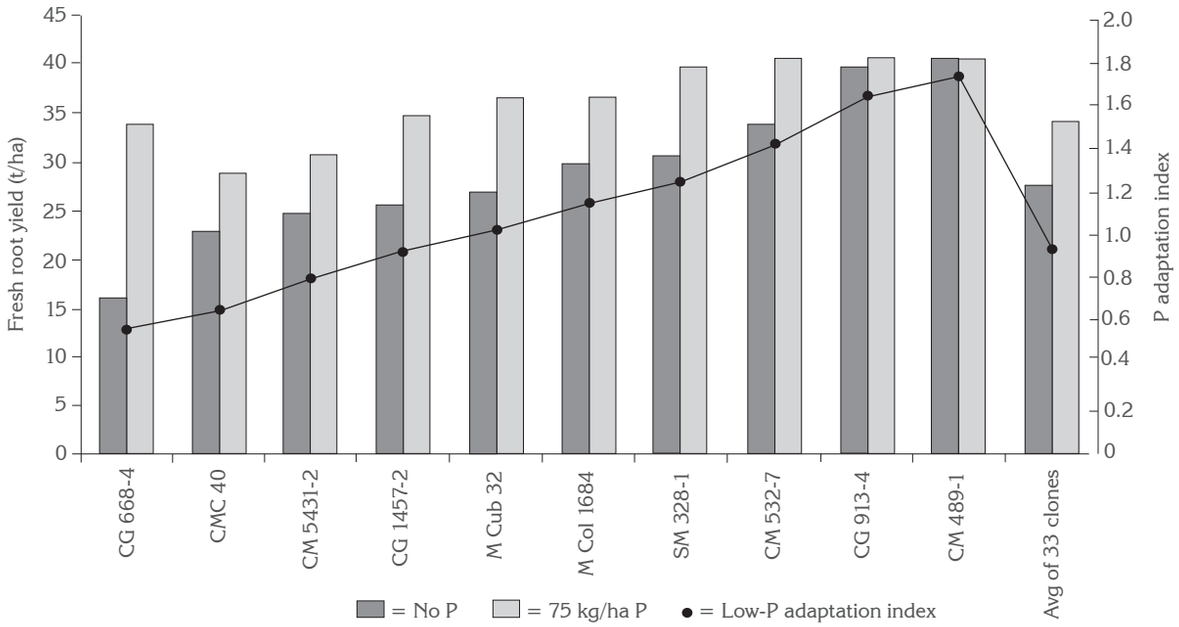


Figure 3-23. Screening cassava germplasm for tolerance of low-phosphorus soils. Note that some clones had good yield potential at low and high levels. More than 1600 accessions were screened, and clones selected for the breeding program. Low-P adaptation index was calculated as in Table 3-15. (CIAT Report 1992; El-Sharkawy 2006; Borrell 2010.)

enhanced nutrient-use efficiency under stress through higher reductions in shoot biomass than in roots (i.e., higher HI) and in terms of plant architecture (medium-statured and short versus tall cultivars) (Table 3-12; El-Sharkawy et al. 1998a, 1998b; El-Sharkawy and Cadavid 2002).

Moreover, in another group of accessions, low-P adaptation indices were correlated with standing shoot biomass at harvest (not including dropped leaves), number of harvested roots per plant, and seasonal average, upper-canopy-leaf photosynthesis (CIAT Report 1990; El-Sharkawy 2004). This finding indicated the importance of both carbon assimilation source and capacity, and of root sink capacity in selecting and breeding for tolerance of low-fertility soils. Notably, clone CM 489-1, with a high adaptation index to low-P (Figure 3-23), had the following characteristics: high photosynthetic rate at different levels of P; high efficiency in the use of nutrients and solar radiation (Pellet and El-Sharkawy 1993a, 1993b, 1997); high yields, with or without mid-season extended water deficits (Table 3-6; Figure 3-9; El-Sharkawy 1993); less reduction in leaf photosynthesis during water stress (Figure 3-17); and high PEPC activity in leaves under field conditions that correlate with photosynthesis (El-Sharkawy 2004).

These findings indicate that selecting for and assembling several desirable plant traits in one genotype is possible. Complementary multidisciplinary or, even better, multi-institutional research is crucial in this case, as it would enhance research efficiency and the benefit-to-cost ratio (El-Sharkawy 2005).

Highlights and Conclusions

The research reviewed here on cassava productivity, physiology and/or ecophysiology, and responses to environmental stresses was conducted in collaboration with a multidisciplinary team at CIAT. The Center also holds a diverse germplasm bank of the crop, which has been assembled over 40 years. The research objectives revolved around the strategy adopted for developing new technologies to enhance crop productivity in most of the edaphoclimatic zones under which cassava is cultivated, particularly stressful environments.

Under favorable environments in lowland and mid-altitude tropical zones with near-optimal climatic and edaphic conditions for the crop to realize its inherent potential, cassava is highly productive in terms of root yield and total biological biomass. For example, under trial conditions, improved germplasm

can, after 10–12 months' growth, attain >15 t/ha of oven-dried roots, containing 85% starch. The physiological mechanisms underlying such high potential productivity are:

1. High leaf photosynthetic potential, comparable with those in efficient C_4 crops (assuming the following conditions are common: high humidity, adequate soil moisture, high leaf temperature, high solar radiation, and a Pn rate that exceeds 40 μmol CO2 per m^2/s);

2. Long leaf life (>60 days), with the leaves remaining active for most of their life spans;

3. Sustainable leaf canopy that optimizes light interception during a significant portion of the growth cycle; and

4. High harvest index (>0.5), coupled with strong root sink (i.e., larger number of storage roots/plant).

Under stressful environments in seasonally dry and semi-arid tropics, productivity is reduced, with more reduction in aboveground parts (shoots) than in storage roots (i.e., higher HI). Under these conditions, the crop possesses some inherent adaptive mechanisms for tolerance. The most important one is the remarkable stomatal sensitivity to changes in atmospheric humidity, as well as in soil water. By closing stomata under water stress, the leaf remains hydrated and photosynthetically active, although at reduced rates, over most of its life span.

Together with this "stress avoidance mechanism" is a capacity for deep rooting that enables the plant to slowly extract water from as deep as 2 m. The crop therefore not only survives dry periods of up to 3 months long, but also produces a reasonable yield through its efficient use of water and nutrients. Moreover, leaf canopy is much reduced under prolonged stress, contributing to lower crop water consumption. When it recovers from stress, cassava rapidly forms new leaves with higher photosynthetic capacity, which compensates for yield reductions from the previous prolonged stress.

Productivity over a wide range of germplasm and in different environments correlates with upper canopy leaf photosynthesis, as measured in the field. The relationship stems mostly from non-stomatal factors, that is, from biochemical and anatomical leaf traits. Among these leaf traits is the elevated activity of the C_4 PEPC enzyme. Breeding programs could exploit the genetic variations found within cassava germplasm and wild *Manihot* for both leaf photosynthesis and enzyme activity. Leaf area duration under stress, together with host-plant resistance or tolerance of pests and diseases, is a critical trait because yield correlates with leaf retention capacity (Lenis et al. 2006). Deep rooting capacity is another important trait for selecting and breeding improved germplasm for drier zones.

In cooler zones such as higher altitudes in the tropics and lowland subtropics, cassava growth is slower and the crop stays in the ground for longer to achieve adequate yields. Under these conditions, leaf formation is slower, leaf photosynthesis is much reduced, but leaf life is longer (Irikura et al. 1979; El-Sharkawy et al. 1992a, 1993). Wide genetic variations exist for photosynthesis that may be valuable for selecting and breeding for genotypes that better tolerate cool climates. Combining enhanced leaf photosynthesis with the normally longer leaf life in cool climates may improve productivity.

Selecting for medium-statured and short cassava instead of tall cassava is advantageous for saving on nutrient uptake and ensuring higher nutrient-use efficiency for root production without sacrificing potential yield. Germplasm from the core collection was screened for tolerance of soils low in P and K, resulting in the identification of several accessions with good levels of tolerance.

Results also point to the importance of field research versus greenhouse or growth-chamber studies that do not calibrate for representative environments to account for acclimation factors (El-Sharkawy 2005). Calibration becomes even more critical when data from indoor-grown plants are used to extrapolate to the field or to develop crop models.

Much remains to be done to further improve productivity while conserving dwindling natural resources such as water and land. Developing countries, in particular, need more support to continue with maintenance research, which aims to upgrade previous findings and technologies; contribute to sustainable agricultural, economic, and social developments; and enhance food supply to meet increasing demands.

Basic research can be cost-effective, with high returns, even if slower. It can be especially successful

when conducted in collaboration with multidisciplinary and/or multi-institutional teams that follow well-planned strategies and are focused towards fulfilling a set of high priority goals and objectives.

International research and development organizations, donor agencies, and private sectors should take leading roles in financing and supporting basic research efforts, particularly those oriented towards serving the technological needs of resource-poor developing countries. Without the steady funding by only a few international donors during the 1940s and 1950s, the Green Revolution of the 1960s, which had saved many developing countries from famine, would probably never have happened. The current CGIAR policy of conducting short-term research projects, instead of team-oriented core research, is counterproductive and should be reversed.

Acknowledgments

The authors are indebted to the many colleagues, associates, students, workers, and secretaries at CIAT whose dedication and support were crucial in realizing the research achievements highlighted in this chapter.

We most appreciated the many useful reprints received from G. Bowes, V. Gutschick, P. Jarvis, Ch. Körner, R. Lösch, F. Meinzer, O. Ueno, and P. Westhoff. We thank M.B. Kirkham for the copy of her invaluable textbook on *Principles of Soil and Plant Water Relations*. Useful comments on an original version were received from D. Laing, former deputy director for research at CIAT; J.D. Hesketh, USDA/ARS and the University of Illinois, Urbana, USA; and three anonymous reviewers. Many constructive editorial changes were made by Elizabeth L. McAdam, Melbourne, Australia.

We are grateful to Farah El-Sharkawy Navarro for her highly needed help in searching the Internet for pertinent information, assembling the numerous data in tables and figures scattered in various published and unpublished documents, and typing the manuscript.

Crucial in conducting this research was the logistic and financial support from various governments and research-funding organizations, including Australia, Brazil, Colombia, Germany, Switzerland, and USA. This support allowed us to target the research towards answering the needs of some of the poorest farmers and consumers living in developing countries.

References

To save space, the acronym "CIAT" is used instead of "Centro Internaccional de Agricultura tropical".

Ackerson RC. 1980. Stomatal response of cotton to water stress and abscisic acid as affected by water stress history. Plant Physiol 65:455–459.

Ackerson RC; Hebert RR. 1981. Osmoregulation in cotton in response to water stress. Plant Physiol 67:484–488.

Allem AC. 2002. The origins and taxonomy of cassava. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 1–16.

Álvarez E; Llano GA; with the collaboration of EL McAdam. 2008. Controlling cassava root rots with the participation of Tukano communities in the Mitú area of the Colombian Amazon. Gene Conserve [online] 7(28):446–475. Available at www.geneconserve.pro.br/artigos08.htm

Alves AAC. 1998. Physiological and developmental changes in cassava (*Manihot esculenta* Crantz) under water deficit. Dissertation. Cornell University, Ithaca, NY, USA.

Alves AAC. 2002. Cassava botany and physiology. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK.

Alves AAC; Setter TL. 2000. Response of cassava to water deficit: leaf area growth and abscisic acid. Crop Sci 40:131–137.

Angelov MN; Sun J; Byrd GT; Brown RH; Black CC. 1993. Novel characteristics of cassava, *Manihot esculenta* Crantz, a reputed C_3-C_4 intermediate photosynthesis species. Photosynth Res 38:61–72.

Appleby RF; Davies WJ. 1983. The structure and orientation of guard cells in plants showing stomatal responses to changing vapour pressure difference. Ann Bot 52:459–468.

Araus JL; Brown RH; Bouton JH; Serret MD. 1990. Leaf anatomical characteristics in *Flaveria trinervia* (C_4), *Flaveria brownii* (C_4-like), and their F_1 hybrid. Photosynth Res 26:49–57.

Aslam M; Lowe SB; Hunt LA. 1977. Effect of leaf age on photosynthesis and transpiration of cassava (*Manihot esculenta*). Can J Bot 55:2288–2295.

Aston MJ. 1976. Variation of stomatal diffusion resistance with ambient humidity in sunflower (*Helianthus annuus*). Aust J Plant Physiol 3:489–501.

Balagopalan C. 2002. Cassava utilization in food, feed and industry. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 301–318.

Beeching JR; Marmey P; Gavalda MC; Noirot M; Hayson HR; Hughes MA; Charrier A. 1993. An assessment of genetic diversity within a collection of cassava (*Manihot esculenta* Crantz) germplasm using molecular markers. Ann Bot 72:515–520.

Bellotti AC. 2002. Arthropod pests. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 209–235.

Bellotti AC; Arias V, B. 1993. The possible role of HCN in the biology and feeding behavior of the cassava burrowing bug (*Cyrtomenus bergi* Froeschner: Cydnidae: Hemiptera). In: Roca WM; Thro AM, eds. Proc First International Scientific Meeting of the Cassava Biotechnology Network. CIAT, Cali, Colombia. p 406–409.

Bellotti AC; Riis L. 1994. Cassava cyanogenic potential and resistance to pests and diseases. Acta Hortic 375:141–151.

Bellotti AC; Vargas OH; Arias B; Castaño O; García C. 1988. *Cyrtomenus bergi* Froeschner, a new pest of cassava: biology, ecology and control. In: Degras LM, ed. Proc 7th Symposium of the International Society for Tropical Root and Tuber Crops, held in Gosier (Guadeloupe), 1–6 July 1985. Institut National de la Recherche Agronomique (INRA), Paris, France. p 551–561.

Berg VS; El-Sharkawy MA; Hernández ADP; Cock JH. 1986. Leaf orientation and water relations in cassava. In: Annual Meeting of the American Society of Plant Physiologists, 8–12 June. Louisiana State University, Baton Rouge, LA, USA. p 186.

Bernal LM. 1991. Estudios sobre la actividad fosfo*enol*piruvato carboxilasa en cultivares de yuca (*Manihot esculenta* Crantz). BSc thesis. Pontificia Universidad Javeriana, Bogotá, Colombia.

Berry J; Björkman O. 1980. Photosynthetic response to temperature in higher plants. Annu Rev Plant Physiol 31:491–543.

Björkman O; Badger MR; Armond PA. 1980. Response and adaptation of photosynthesis to high temperature. In: Turner NC; Kramer PJ, eds. Adaptation of plants to water and high temperature stress. John Wiley & Sons, New York, USA. p 233–249.

Boardman NK. 1977. Comparative photosynthesis of sun and shade plants. Annu Rev Plant Physiol 28:355–377.

Bongi G; Mencuccini M; Fontanazza G. 1987. Photosynthesis of olive leaves: effect of light flux density, leaf age, temperature, peltates, and H_2O vapour pressure deficit on gas exchange. J Am Hortic Sci 112:143–148.

Borrell B. 2010. Elemental shortage. The Scientist [on line] 24(11):46. Available at www.the-scientist.com/2010/11/1/46/1/.

Boyer JS. 1996. Advances in drought tolerance in plants. Adv Agron 56:187–218.

Brekelbaum T; Bellotti A; Lozano JC, eds. 1978. Proc Cassava Protection Workshop. CIAT, Cali, Colombia.

Brown RH; Bouton JH. 1993. Physiology and genetics of interspecific hybrids between photosynthetic types. Annu Rev Plant Physiol Plant Mol Biol 44:435–456.

Brown RH; Hattersley PW. 1989. Leaf anatomy of C_3-C_4 species as related to evolution of C_4 photosynthesis. Plant Physiol 91:1543–1550.

Brown RH; Bouton JH; Evans PT; Malter HE; Rigsby LL. 1985. Photosynthesis, morphology, leaf anatomy, and cytogenetics of hybrids between C_3 and C_3/C_4 *Panicum* species. Plant Physiol 77:653–658.

Bunce JA. 1981. Comparative responses of leaf conductance to humidity in single attached leaves. J Exp Bot 32:629–634.

Bunce JA. 1982. Photosynthesis at ambient and elevated humidity over a growing season in soybean. Photosynth Res 3:307–311.

Bunce JA. 1984. Identifying soybean lines differing in gas exchange sensitivity to humidity. Ann Appl Biol 105:313–318.

Bunce JA. 1985. Effect of boundary layer conductance on the response of stomata to humidity. Plant, Cell Environ 8:55–57.

Bunce JA. 1986. Measurements and modelling of photosynthesis in field crops. CRC Crit Rev Plant Sci 4:47–77.

Burt RL. 1964. Carbohydrate utilization as a factor in plant growth. Aust J Biol Sci 17:867–877.

Byrne DH; Guerrero JM; Bellotti AC; Gracen VE. 1982. Yield and plant growth responses of *Mononychellus* mite resistant and susceptible cassava cultivars under protected vs. infested conditions. Crop Sci 22: 486–490.

Cadavid L, LF; El-Sharkawy MA; Acosta A; Sánchez T. 1998. Long-term effects of mulch fertilization and tillage on cassava grown in sandy soils in northern Colombia. Field Crops Res 57:45–56.

Caicedo JA. 1993. Respuesta de cuatro cultivares de yuca (*Manihot esculenta* Crantz) a la modificación del estado hídrico del suelo. BSc thesis. Universidad Nacional de Colombia, Palmira, Colombia.

Calatayud P-A; Barón CH; Velásquez H; Arroyave JA; Lamaze T. 2002. Wild *Manihot* species do not possess C_4 photosynthesis. Ann Bot 89:125–127.

Calvert LA; Thresh JM. 2002. The viruses and virus diseases of cassava. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 237–260.

Cayón MG; El-Sharkawy MA; Cadavid L, LF. 1997. Leaf gas exchange of cassava as affected by quality of planting material and water stress. Photosynthetica 34:409–418.

Chabot BF; Hicks DJ. 1982. The ecology of leaf life span. Ann Rev Ecol Syst 13:229–259.

Chapin III, FS. 1991. Integrated responses of plants to stress. BioScience 41:29–36.

Chu C; Dai Z; Ku MSB; Edwards GE. 1990. Induction of Crassulacean acid metabolism in the facultative halophyte *Mesembryanthemum crystallinum* by abscisic acid. Plant Physiol 93:1253–1260.

CIAT Reports. 1983 to 1998. Cassava Program annual reports. CIAT, Cali, Colombia.

Cock JH. 1985. Cassava: new potential for a neglected crop. Westview Press, Boulder, CO, USA.

Cock JH; El-Sharkawy MA. 1988a. Physiological characteristics for cassava selection. Exp Agric 24:443–448.

Cock JH; El-Sharkawy MA. 1988b. The physiological response of cassava to stress. In: Degras LM, ed. Proc 7th Symposium of the International Society for Tropical Root and Tuber Crops, held in Gosier (Guadeloupe), 1–6 July 1985. Institut National de la Recherche Agronomique (INRA), Paris, France. p 451–462.

Cock JH; Franklin D; Sandoval G; Juri P. 1979. The ideal cassava plant for maximum yield. Crop Sci 19: 271–279.

Cock JH; Porto MCM; El-Sharkawy MA. 1985. Water use efficiency of cassava, III: Influence of air humidity and water stress on gas exchange of field grown cassava. Crop Sci 25:265–272.

Cock JH; Riaño NM; El-Sharkawy MA; López Y; Bastidas G. 1987. C_3-C_4 intermediate photosynthetic characteristics of cassava (*Manihot esculenta* Crantz), II: Initial products of $^{14}CO_2$ fixation. Photosynth Res 12:237–241.

Connor DJ; Cock JH. 1981. Response of cassava to water shortage, II: Canopy dynamics. Field Crops Res 4:285–296.

Connor DJ; Palta J. 1981. Response of cassava to water shortage, III: Stomatal control of plant water status. Field Crops Res 4:285–296.

Connor DJ; Cock JH; Parra GE. 1981. Response of cassava to water shortage, I: Growth and yield. Field Crops Res 4:181–200.

Cours G. 1951. Le manioc a Madagascar. In: Memoires, 3B. l'Institute Scientifique de Madagascar, Tananarive, Madagascar. p 203–400.

Cowan IR. 1977. Stomatal behaviour and environment. Adv Bot Res 4:117–228.

Davies WJ; Kozlowski TT. 1974. Stomatal responses of 5 woody angiosperms to light intensity and humidity. Can J Bot 52:1525–1535.

Davies WJ; Metcalfe J; Lodge TA; da Costa AR. 1986. Plant growth substances and the regulation of growth under drought. Aust J Plant Physiol 13:105–125.

de Tafur SM. 2002. Fisiología de la yuca (*Manihot esculenta* Crantz). In: Ospina B; Ceballos H, eds. Cultivo de la yuca en el tercer milenio: Sistemas modernos de producción, procesamiento, utilización y comercialización. CIAT; Consorcio Latinoamericano y del Caribe de Apoyo a la Investigación y al Desarrollo de la Yuca (CLAYUCA), Cali, Colombia. p 34–45.

de Tafur SM; El-Sharkawy MA; Cadavid LF. 1997a. Response of cassava (*Manihot esculenta* Crantz) to water stress and fertilization. Photosynthetica 34:233–239.

de Tafur SM; El-Sharkawy MA; Calle F. 1997b. Photosynthesis and yield performance of cassava in seasonally dry and semiarid environments. Photosynthetica 33:249–257.

Devi MT; Raghavendra AS. 1993. Photorespiration in C_3-C_4 intermediate species of *Alternanthera* and *Parthenium*: reduced ammonia production and increased capacity of CO_2 refixation in the light. Photosynth Res 38: 177–184.

Dufour DL. 1988. Cyanide content of cassava (*Manihot esculenta*: Euphorbiaceae) cultivars used by Tukanoan Indians in Northwest Amazonia. Econ Bot 42:255–266.

Edwards GE; Sheta E; Moore Bi; Dai Z; Franceschi VR; Cheng SH; Lin CH; Ku MSB. 1990. Photosynthetic characteristics of cassava (*Manihot esculenta* Crantz), a C_3 species with chlorenchymatous bundle sheath cells. Plant, Cell Physiol 31:1199–1206.

Ekanayake IJ; Dixon AGO; Kasele IN; Noah AND. 2007. Plant water relations and photosynthetic properties of polyploidy cassava grown in the Nigerian Savanna. In: Kapinga R; Kingamkono R; Msabaha M; Ndunguru J; Lemaga B; Tusiime G, eds. Proc 13th Triennial Symposium of the International Society for Tropical Root Crops (ISTRC). ISTRC, Arusha, Tanzania. p 210–217.

El-Sharkawy MA. 1990. Effect of humidity and wind on leaf conductance of field grown cassava. Rev Bras Fisiol Veg 2:17–22.

El-Sharkawy MA. 1993. Drought-tolerant cassava for Africa, Asia, and Latin America. BioScience 43:441–451.

El-Sharkawy MA. 2004. Cassava biology and physiology. Plant Mol Biol 56:481–501.

El-Sharkawy MA. 2005. How can calibrated research-based models be improved for use as a tool in identifying genes controlling crop tolerance to environmental stresses in the era of genomics—from an experimentalist's perspective. Photosynthetica 43:161–176.

El-Sharkawy MA. 2006. International research on cassava photosynthesis, productivity, eco-physiology, and responses to environmental stresses in the tropics. Photosynthetica 44:481–512.

El-Sharkawy MA. 2010. Cassava: physiological mechanisms and plant traits underlying tolerance to prolonged drought and their application for breeding cultivars in the seasonally dry and semiarid tropics. In: da Matta FM, ed. Ecophysiology of tropical tree crops. Nova Science Publishers, Hauppauge, NY, USA. p 71–110.

El-Sharkawy MA; Cadavid L, LF. 2000. Genetic variation within cassava germplasm in response to potassium. Exp Agric 36:323–334.

El-Sharkawy MA; Cadavid L, LF. 2002. Response of cassava to prolonged water stress imposed at different stages of growth. Exp Agric 38:333–350.

El-Sharkawy MA; Cock JH. 1984. Water use efficiency of cassava, I: Effects of air humidity and water stress on stomatal conductance and gas exchange. Crop Sci 24:497–502.

El-Sharkawy MA; Cock JH. 1986. The humidity factor in stomatal control and its effect on crop productivity. In: Marcelle R; Clijsters H; Van Poucke M, eds. Biological control of photosynthesis. Martinus Nijhoff Publishers, Dordrecht, Netherlands. p 187–198.

El-Sharkawy MA; Cock JH. 1987a. C_3-C_4 intermediate photosynthetic characteristics of cassava (*Manihot esculenta* Crantz), I: Gas exchange. Photosynth Res 12:219–235.

El-Sharkawy MA; Cock JH. 1987b. Response of cassava to water stress. Plant Soil 100:345–360.

El-Sharkawy MA; Cock JH. 1990. Photosynthesis of cassava (*Manihot esculenta* Crantz). Exp Agric 26:325–340.

El-Sharkawy MA; de Tafur SM. 2007. Genotypic and within canopy variation in leaf carbon isotope discrimination and its relation to short-term leaf gas exchange characteristics in cassava grown under rain-fed conditions in the tropics. Photosynthetica 45:515–526.

El-Sharkawy MA; de Tafur SM. 2010. Comparative photosynthesis, growth, productivity, and nutrient use efficiency among tall- and short-stemmed rain-fed cassava cultivars. Photosynthetica 48:173–188.

El-Sharkawy MA: Hesketh J. 1965. Photosynthesis among species in relation to characteristics of leaf anatomy and CO_2 diffusion resistances. Crop Sci 5:517–521.

El-Sharkawy MA; Hesketh JD. 1986. Citation classic—Photosynthesis among species in relation to characteristics of leaf anatomy and CO_2 diffusion resistances. Curr Cont/Agric Biol Environ 27:14.

El-Sharkawy MA; Cadavid L, LF; de Tafur SM. 1998a. Nutrient use efficiency of cassava differs with genotype architecture. Acta Agron Univ Nac–Palmira Colombia 48:23–32.

El-Sharkawy MA; Cadavid L, LF; de Tafur SM; Caicedo JA. 1998b. Genotypic differences in productivity and nutrient uptake and use efficiency of cassava as influenced by prolonged water stress. Acta Agron Univ Nac–Palmira Colombia 48:9–22.

El-Sharkawy MA; Cock JH; de Cadena G. 1984a. Influence of differences in leaf anatomy on net photosynthetic rates of some cultivars of cassava. Photosynth Res 5:235–242.

El-Sharkawy MA; Cock JH; de Cadena G. 1984b. Stomatal characteristics among cassava cultivars and their relation to gas exchange. Exp Agric 20:67–76.

El-Sharkawy MA; Cock JH; Held K, AA. 1984c. Photosynthetic responses of cassava cultivars (*Manihot esculenta* Crantz) from different habitats to temperature. Photosynth Res 5:243–250.

El-Sharkawy MA; Cock JH; Held K, AA. 1984d. Water use efficiency of cassava, II: Differing sensitivity of stomata to air humidity in cassava and other warm-climate species. Crop Sci 24:503–507.

El-Sharkawy MA; Cock JH; Hernández ADP. 1985. Stomatal response to air humidity and its relation to stomatal density in a wide range of warm climate species. Photosynth Res 7:137–149.

El-Sharkawy MA; Cock JH; Lynam JK; Hernández ADP; Cadavid LF. 1990. Relationships between biomass, root-yield and single-leaf photosynthesis in field-grown cassava. Field Crops Res 25:183–201.

El-Sharkawy MA; de Tafur SM; Cadavid L, LF. 1992a. Potential photosynthesis of cassava as affected by growth conditions. Crop Sci 32:1336–1342.

El-Sharkawy MA; de Tafur SM; Cadavid L, LF. 1993. Photosynthesis of cassava and its relation to crop productivity. Photosynthetica 28:431–438.

El-Sharkawy MA; Hernández ADP; Hershey C. 1992b. Yield stability of cassava during prolonged mid-season water stress. Exp Agric 28:165–174.

El-Sharkawy MA; Loomis RS; Williams WA. 1967. Apparent reassimilation of respiratory carbon dioxide by different plant species. Physiol Plant 20:171–186.

El-Sharkawy MA; Loomis RS; Williams WA. 1968. Photosynthetic and respiratory exchanges of carbon dioxide by leaves of grain amaranth. J Appl Ecol 5:243–251.

El-Sharkawy MA; López Y; Bernal LM. 2008. Genotypic variations in activities of phospho*enol*pyruvate carboxylase (PEPC) and correlations with leaf photosynthetic characteristics and crop productivity of cassava grown in lowland seasonally dry tropics. Photosynthetica 46:238–247.

Essers AJA. 1995. Removal of cyanogens from cassava roots: studies on domestic sun-drying and solid-substrate fermentation in rural Africa. Dissertation. Wageningen Agricultural University, Wageningen, Netherlands.

Evans LT. 1993. Crop evolution, adaptation and yield. Cambridge University Press, Cambridge, UK.

Fanjul L; Jones HG. 1982. Rapid stomatal response to humidity. Planta 154:135–138.

Farquhar GD. 1978. Feed-forward responses of stomata to humidity. Aust Plant Physiol 5:787–800.

Farquhar GD; Schulze E-D; Kuppers M. 1980. Response to humidity by stomata of *Nicotiana glauca* L. and *Corylus avellana* L. are consistent with the optimization of carbon dioxide uptake with respect to water loss. Aust J Plant Physiol 7:315–327.

Fermont AM. 2009. Cassava and soil fertility in intensifying smallholder farming systems of East Africa. Dissertation. Wageningen Agricultural University, Wageningen, Netherlands.

Fernández MD; Tezara W; Rengifo E; Herrera A. 2002. Lack of down-regulation of photosynthesis in a tropical root crop, cassava, grown under an elevated CO_2 concentration. Funct Plant Biol 29:805–814.

Flörchinger FA; Leihner DE; Steinmüller N; Müller-Sämann K; El-Sharkawy MA. 2000. Effects of artificial topsoil removal on sorghum, peanut and cassava yield. J Soil Water Conserv 55:334–339.

Forrester ML; Krotkov G; Nelson CD. 1966. Effect of oxygen on photosynthesis, photorespiration and respiration in detached leaves, II: Corn and other monocotyledons. Plant Physiol 41:428–431.

Giaquinta RT. 1983. Phloem loading of sucrose. Annu Rev Plant Physiol 34:347–387.

Gleadow RM; Evans JR; McCaffery S; Cavagnaro TR. 2009. Growth and nutritive value of cassava (*Manihot esculenta* Crantz) are reduced when grown in elevated CO_2. Plant Biol 11(S1):76–82. DOI:10.1111/j.1438-8677.2009.00238.x

Gollan T; Turner NC; Schulze E-D. 1985. The responses of stomata and leaf gas exchange to vapour pressure deficits and soil water content, III: In the sclerophyllous woody species *Nerium oleander*. Oecologia 65:356–362.

Gutschick VP. 1984. Photosynthesis model for C_3 leaves incorporating CO_2 transport, propagation of radiation, and biochemistry, 2: Ecological and agricultural utility. Photosynthetica 18:569–595.

Guzmán G. 1989. Aspectos ecofisiológicos en cultivares anfiestomáticos de yuca (*Manihot esculenta* Crantz). BSc thesis. Pontificia Universidad Javeriana, Bogotá, Colombia.

Haberlandt G. 1914. Physiological plant anatomy. McMillan and Co., London.

Hall AE; Hoffman GJ. 1976. Leaf conductance response to humidity and water transport in plants. Agron J 68:876–881.

Hall AE; Schulze E-D. 1980. Stomatal response to environment and a possible interrelation between stomatal effects on transpiration and CO_2 assimilation. Plant, Cell Environ 3:467–474.

Hatch MD. 1977. C_4 pathway photosynthesis: mechanism and physiological function. Trends Biochem Sci 2:199–202.

Hatch MD. 1987. C_4 photosynthesis: a unique blend of modified biochemistry, anatomy and ultrastructure. Biochim Biophys Acta 895:81–106.

Held K, AA. 1991. Control of canopy photosynthesis and water-use efficiency in well-watered field crops. Dissertation. University of California–Davis, USA.

Henson IE. 1984. Effects of atmospheric humidity on abscisic acid accumulation and water stress in leaves of rice (*Oryza sativa* L.). Ann Bot 54:569–582.

Hermans J; Westhoff P. 1990. Analysis of expression and evolutionary relationships of phospho*enol*pyruvate carboxylase genes in *Flaveria trinervia* (C_4) and *F. pringlei* (C_3). Mol Gen Genet 224:459–468.

Hermans J; Westhoff P. 1992. Homologous genes for the C_4 isoform of phospho*enol*pyruvate carboxylase in a C_3 and C_4 *Flaveria* species. Mol Gen Genet 234:275–284.

Herold A. 1980. Regulation of photosynthesis by sink activity—the missing link. New Phytol 86:131–144.

Hershey CH. 1984. Breeding cassava for adaptation to stress conditions: development of a methodology. Proc 6th Symposium of the International Society for Tropical Root Crops, held in Lima, Peru, 20–25 Feb 1983. Centro Internacional de la Papa (CIP), Lima, Peru. p 303–314.

Hershey CH; Jennings DL. 1992. Progress in breeding cassava for adaptation to stress. Plant Breed Abstr 62:823–831.

Hershey CH; Kawano K; Lozano JC . 1988. Breeding cassava for adaptation to a new ecosystem: a case study from the Colombian llanos. In: Degras LM, ed. Proc 7th Symposium of the International Society for Tropical Root Crops, held in Gosier (Guadeloupe), 1–6 July 1985. Institut National de la Recherche Agronomique (INRA), Paris, France. p 525–540.

Hibberd JM; Quick WP. 2002. Characteristics of C_4 photosynthesis in stems and petioles of C_3 flowering plants. Nature 415:451–454.

Hillocks RJ; Wydra K. 2002. Bacterial, fungal and nematode diseases. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. 2002. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 261–280.

Hillocks RJ; Thresh JM; Bellotti AC, eds. 2002. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK.

Hirasawa T; Iida Y; Ishihara K. 1988. Effect of leaf water potential and air humidity on photosynthetic rate and diffusive conductance in rice plants. Jpn J Crop Sci 57:112–118.

Ho LC. 1988. Metabolism and compartmentation of imported sugars in sink organs in relation to sink strength. Annu Rev Plant Physiol 39:355–378.

Hoffman GJ; Rawlins SL. 1971. Growth and water potential of root crops as influenced by salinity and relative humidity. Agron J 63:877–881.

Hoffman GJ; Rawlins SL; Garber MJ; Cullen EM. 1971. Water relations and growth of cotton as influenced by salinity and relative humidity. Agron J 63:822–826.

Howeler RH. 1985. Potassium nutrition of cassava. In: Munson RD, ed. Potassium in agriculture. ASA; CSSA; SSSA, Madison, WI, USA. p 819–841.

Howeler RH. 2002. Cassava mineral nutrition and fertilization. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 115–147.

Howeler RH; Cadavid L, LF. 1983. Accumulation and distribution of dry matter and nutrients during a 12-month growth cycle of cassava. Field Crops Res 7:123–139.

Howeler RH; Cadavid L, LF. 1990. Short- and long-term fertility trials in Colombia to determine the nutrient requirements of cassava. Fertiliz Res 26:61–80.

Howeler RH; Sieverding E. 1983. Potential and limitation of mycorrhizal inoculation illustrated by experiments with field grown cassava. Plant Soil 75:245–261.

Howeler RH; Cadavid L, LF; Burckhardt E. 1982. Response of cassava to VA mycorrhizal inoculation and phosphorus application in greenhouse and field experiments. Plant Soil 69:327–339.

Hsiao TC. 1973. Plant responses to water stress. Annu Rev Plant Physiol 24:519–570.

Hsiao TC; Acevedo E; Fereres E; Henderson DW. 1976. Water stress, growth, and osmotic adjustment. Philos Trans R Soc Lond Ser B 273:479–500.

Huber W; Sankhla N. 1976. C_4 pathway and regulation of the balance between C_4 and C_3 metabolism. In: Lange OL; Kappen L; Schulze E-D, eds. 1976. Water and plant life: problems and modern approaches. Springer-Verlag, New York, USA. p 335–386.

Humphries EC. 1967. The dependence of photosynthesis on carbohydrate sinks: current concepts. In: Proc 1st Symposium of the International Society for Tropical Root Crops, held in St. Augustine, Trinidad, 2–8 April 1967. University of the West Indies, St. Augustine, Trinidad and Tobago. p 34-45.

Hunt LA; Wholey DW; Cock JH. 1977. Growth physiology of cassava. Field Crop Abstr 30:77–91.

Hylton CM; Rawsthorne S; Smith AM; Jones DA; Woolhouse HW. 1988. Glycine decarboxylase is confined to bundle-sheath cells of leaves of C_3-C_4 intermediate species. Planta 175:452–459.

Irikura Y; Cock JH; Kawano K. 1979. The physiological basis of genotype-temperature interactions in cassava. Field Crops Res 2:227–239.

Jackson WA; Volk RJ. 1969. Oxygen uptake by illuminated maize leaves. Nature 222:269–271.

James WO. 1959. Manioc in Africa. Stanford University Press, Stanford, CA, USA.

Jarvis PG. 1980. Stomatal response to water stress in conifers. In: Turner NC; Kramer PJ, eds. Adaptation of plants to water and high temperatures stress. John Wiley & Sons, New York, USA. p 105–122.

Jarvis PG; McNaughton KG. 1986. Stomatal control of transpiration: scaling up from leaf to region. Adv Ecol Res 15:1–49.

Jennings DL; Iglesias C. 2002. Breeding for crop improvement. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 149–166.

Jones H; Leigh RA; Tomos AD; Jones RGW. 1987. The effect of abscisic acid on cell turgor pressures, solute content and growth of wheat roots. Planta 170:257–262. DOI:10.1007/BF00397896

Jones MM; Turner NC. 1978. Osmotic adjustment in leaves of sorghum in response to water deficits. Plant Physiol 61:122–126.

Jones RJ; Mansfield TA. 1972. Effects of abscisic acid and its esters on stomatal aperture and the transpiration ratio. Physiol Plant 26:321–327.

Jørgensen K; Bak S; Busk PK; Sørensen C; Olsen CK; Puonti-Kaerlas J; Møller BL. 2005. Cassava plants with a depleted cyanogenic glucoside content in leaves and tubers: distribution of cyanogenic glucosides, their site of synthesis and transport, and blockage of the biosynthesis by RNA interference technology. Plant Physiol 139:363–374. (Also available at www.plantphysiol.org)

Kappen L; Haeger S. 1991. Stomatal responses of *Tradescantia albiflora* to changing air humidity and in darkness. J Exp Bot 42:979–986.

Kaufmann MR. 1982. Leaf conductance as a function of photosynthetic photon flux density and absolute humidity difference from leaf to air. Plant Physiol 69:1018–1022.

Kawano K. 1990. Harvest index and evolution of major food crop cultivars in the tropics. Euphytica 46:195–202.

Kawano K. 2003. Thirty years of cassava breeding for productivity-biological and social factors for success. Crop Sci 43:1325–1335.

Kawano K; Daza P; Amaya A; Rios M; Gonçalves WMF. 1978. Evaluation of cassava germplasm for productivity. Crop Sci 18:377–382.

Kawano K; Narintaraporn K; Narintaraporn P; Sarakarn S; Limsila A; Limsila J; Suparhan D; Sarawat V; Watananonta W. 1998. Yield improvement in a multistage breeding program for cassava. Crop Sci 38:325–332.

Kirkham MB. 2005. Principles of soil and plant water relations. Elsevier Academic Press, Amsterdam, Netherlands.

Körner Ch. 1985. Humidity responses in forest trees: precautions in thermal scanning surveys. Arch Met Geoph Biocl Ser B 36:83–98.

Körner Ch; Bannister P. 1985. Stomatal responses to humidity in Nothofagus menziesii. NZ J Bot 23: 425–429.

Körner Ch; Cochrane PM. 1985. Stomatal responses and water relations of *Eucalyptus pauciflora* in summer along an elevation gradient. Oecologia 66:443–455.

Kramer PJ. 1981. Carbon dioxide concentration, photosynthesis, and dry matter production. BioScience 31:29–33.

Kramer PJ. 1983. Water relations of plants. Academic Press, New York, USA.

Ku MSB; Monson RK; Littlejohn Jr, RO; Nakamoto H; Fisher DB; Edwards GE. 1983. Photosynthetic characteristics of C_3-C_4 intermediate *Flaveria* species. Plant Physiol 71:944–948.

Laetsch WM. 1974. The C_4 syndrome: a structural analysis. Annu Rev Plant Physiol 25:27–52.

Lange OL; Lösch R; Schulze E-D; Kappen L. 1971. Responses of stomata to changes in humidity. Planta 100:76–86.

Lenis JI; Calle F; Jaramillo G; Pérez JC; Ceballos H; Cock JH. 2006. Leaf retention and cassava productivity. Field Crops Res 95:126–134.

Leverenz JW. 1981. Photosynthesis and transpiration in large forest-grown Douglas fir: diurnal variation. Can J Bot 59:349–356.

Long SP; Ainsworth EA; Leakey ADB; Nösberger J; Ort DR. 2006. Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentration. Science 312:1918–1921.

López Y; Vélez W; El-Sharkawy MA; Mayer JE. 1993. Biochemical characterization of PEPC from cassava: a preliminary report. In: Roca WM; Thro AM, eds. Proc First International Scientific Meeting of the Cassava Biotechnology Network. CIAT, Cali, Colombia. p 340–343.

Lösch R. 1977. Responses of stomata to environmental factors: experiments with isolated epidermal strips of *Polypodium vulgare,* I: Temperature and humidity. Oecologia 29:85–97.

Lösch R. 1979. Stomatal responses to changes in air humidity. In: Sen DN; Chawan DD; Bansal RP, eds. Structure, function, and ecology of stomata. Bishen Singh Mahendra Pal Singh (Publishers), Dehra Dun, Uttarakhand, India. p 189–216.

Lösch R; Schenk B. 1978. Humidity responses of stomata and potassium content of guard cells. J Exp Bot 29:781–787.

Lösch R; Tenhunen JD. 1981. Stomatal responses to humidity: phenomenon and mechanism. In: Jarvis PG; Mansfield TA, eds. Stomatal physiology. Cambridge University Press, Cambridge, UK. p 137–161.

Ludlow MM; Ibaraki K. 1979. Stomatal control of water loss in siratro (*Macroptilium atropurpureum* (DC) Urb.), a tropical pasture legume. Ann Bot 43:639–647.

Magnin NC; Cooley BA; Reiskind JB; Bowes G. 1997. Regulation and localization of key enzymes during the induction of kranz-less, C_4-type photosynthesis in *Hydrilla verticillata*. Plant Physiol 115:1681–1689.

Mahon JD; Lowe SB; Hunt LA. 1977a. Variation in the rate of photosynthetic CO_2 uptake in cassava cultivars and related species of *Manihot*. Photosynthetica 11:131–138.

Mahon JD; Lowe SB; Hunt LA; Thiagarajah M. 1977b. Environmental effects on photosynthesis and transpiration in attached leaves of cassava (*Manihot esculenta* Crantz). Photosynthetica 11:121–130.

Maier-Maercker U. 1979a. "Peristomatal transpiration" and stomatal movement: a controversial view, I: Additional proof of peristomatal transpiration by hygrophotography and a comprehensive discussion in the light of recent results. Z Pflanzenphysiol 91:25–43.

Maier-Maercker U. 1979b. "Peristomatal transpiration" and stomatal movement: a controversial view, II: Observation of stomatal movements under different conditions of water supply and demand. Z Pflanzenphysiol 91:157–172.

Maier-Maercker U. 1983. The role of peristomatal transpiration in the mechanism of stomatal movement. Plant, Cell Environ 6:369–380.

McCree KJ. 1986. Whole-plant carbon balance during osmotic adjustment to drought and salinity stress. Aust J Plant Physiol 13:33–43.

Meidner H. 1962. The minimum intercellular-space CO_2-concentration (Γ) of maize leaves and its influence on stomatal movements. J Exp Bot 13:284–293.

Meidner H. 1976. Water vapour loss from a physical model of a substomatal cavity. J Exp Bot 27:691–694.

Meidner H; Mansfield TA. 1968. Physiology of stomata. McGraw-Hill, London.

Meinzer FD. 1982. The effect of vapour pressure on stomatal control of gas exchange in Douglas fir (*Pseudotsuga menziesii*) saplings. Oecologia 54:236–242.

Mooney HA; Drake BG; Luxmoore RJ; Oechel WC; Pitelka LF. 1991. Predicting ecosystem responses to elevated CO_2 concentrations. BioScience 41:96–104.

Morgan JM. 1984. Osmoregulation and water stress in higher plants. Annu Rev Plant Physiol 35:299–319.

Moss DN. 1962. The limiting carbon dioxide concentration for photosynthesis. Nature 193:587.

Moss DN; Musgrave RB. 1971. Photosynthesis and crop production. Adv Agron 23:317–336.

Mott KA; O'Leary JW. 1984. Stomatal behaviour and CO_2 exchange characteristics in amphistomatous leaves. Plant Physiol 74:47–51.

Mott KA; Gibson AC; O'Leary JW. 1982. The adaptive significance of amphistomatic leaves. Plant, Cell Environ 5:455–460.

Nassar NMA. 1986. Genetic variation of wild *Manihot* species native to Brazil and its potential for cassava improvement. Field Crops Res 13:177–184.

Nassar NMA; Ortiz R. 2010. Breeding cassava to feed the poor. Sci Am 302(5):78–84. (Also available at www.ScientificAmerican.com)

Neales TF; Incolls LD. 1968. The control of leaf photosynthesis rate by the level of assimilate concentration in the leaf: a review of the hypothesis. Bot Rev 34:107–125.

Nijholt JA. 1935. Opname van voedingsstoffen uit den bodem bij cassave [*Absorption of nutrients from the soil by a cassava crop*]. Alg Proefstn Landbouw Korte Meded (Buitenzorg, Indonesia) No. 15.

Nobel PS. 1976. Photosynthetic rates of sun versus shade leaves of *Hyptis emoryi* Torr. Plant Physiol 58: 218–223.

Nobel PS. 1980. Leaf anatomy and water use efficiency. In: Turner NC; Kramer PJ, eds. Adaptation of plants to water and high temperature stress. John Wiley & Sons, New York, USA. p 43–55.

Nobel PS; Hartsock TL. 1981. Development of leaf thickness for *Plectranthus parviflorus*: influence of photosynthetically active radiation. Physiol Plant 51:163–166.

North C. 1956. A technique for measuring structural features of plant epidermis using cellulose acetate films. Nature 176:1186–1187.

Nösberger J; Humphries EC. 1965. The influence of removing tubers on dry-matter production and net assimilation rate of potato plants. Ann Bot 29: 579–588.

Oguntunde PG. 2005. Whole-plant water use and canopy conductance of cassava under limited available soil water and varying evaporative demand. Plant Soil 278:371–383.

Oguntunde PG; Alatise MO. 2007. Environmental regulation and modelling of cassava canopy conductance under drying root zone soil water. Meteorol Appl 14:245–252.

Okogbenin E; Ekanayake IJ; Porto MCM. 2003. Genotypic variability in adaptation responses of selected clones of cassava to drought stress in the Sudan Savanna zone of Nigeria. J Agron Crop Sci 189:376–389.

Osmond CB; Grace SC. 1995. Perspectives on photoinhibition and photorespiration in the field: quintessential inefficiencies of the light and dark reactions of photosynthesis? J Exp Bot 46:1351–1362.

Osmond CB; Winter K; Powles SB. 1980. Adaptive significance of carbon dioxide cycling during photosynthesis in water-stressed plants. In: Turner NC; Kramer PJ, eds. Adaptation of plants to water and high temperature stress. John Wiley & Sons, New York, USA. p 139–154.

Palta JA. 1984. Influence of water deficits on gas-exchange and the leaf area development of cassava cultivars. J Exp Bot 35:1441–1449.

Parkhurst DF. 1978. The adaptive significance of stomatal occurrence on one or both surfaces of leaves. J Ecol 66:367–383.

Paul K; Yeoh H-H. 1987. K_m values of ribulose 1,5-bisphosphate carboxylase of cassava cultivars. Phytochemistry 26:1965–1967.

Paul K; Yeoh H-H. 1988. Characteristics of ribulose 1,5-bisphosphate carboxylase from cassava leaves. Plant Physiol Biochem 26:615–618.

Pellet D; El-Sharkawy MA. 1993a. Cassava varietal response to phosphorus fertilization, I: Yield, biomass and gas exchange. Field Crops Res 35:1–11.

Pellet D; El-Sharkawy MA. 1993b. Cassava varietal response to phosphorus fertilization, II: Phosphorus uptake and use efficiency. Field Crops Res 35:13–20.

Pellet D; El-Sharkawy MA. 1994. Sink-source relations in cassava: effects of reciprocal grafting on yield and leaf photosynthesis. Exp Agric 30:359–367.

Pellet D; El-Sharkawy MA. 1997. Cassava varietal response to fertilization: growth dynamics and implications for cropping sustainability. Exp Agric 33:353–365.

Pereira JF. 1977. Fisiología de la yuca (*Manihot esculenta* Crantz). Universidad de Oriente, Jusepin, Monagas, Venezuela.

Pettersson R; McDonald JS. 1994. Effects of nitrogen supply on the acclimation of photosynthesis to elevated CO_2. Photosynth Res 39:389–400.

Pettigrew WT; Hesketh JD; Peters DB; Woolley JT. 1990. A vapor pressure deficit effect on crop canopy photosynthesis. Photosynth Res 24:27–34.

Pieruschka R; Huber G; Berry JA. 2010. Control of transpiration by radiation. PNAS 107(3):13372–13377. (Also available at www.pnas.org/cgi/doi/10.1073/pnas.0913177107.)

Pingali P. 2010. Prepared remarks presented at the World Food Prize Symposium. Bill & Melinda Gates Foundation, Seattle, WA, USA. Available at www.gatesfoundation.org/speeches-commentary/Pages/prabhu-pingali-2010-world-food-prize-symposium.aspx

Porto MCM. 1983. Physiological mechanisms of drought tolerance in cassava (*Manihot esculenta* Crantz). Dissertation. University of Arizona, Tucson, AZ, USA.

Pospisilová J; Solárová J. 1980. Environmental and biological control of diffusive conductances of adaxial and abaxial epidermis. Photosynthetica 14:90–127.

Poulton JE. 1990. Cyanogenesis in plants. Plant Physiol 94:401–405.

Radin JW. 1984. Stomatal responses to water stress and to abscisic acid in phosphorus-deficient cotton plants. Plant Physiol 76:392–394.

Radin JW; Parker LL; Guinn G. 1982. Water relations of cotton plants under nitrogen deficiency, V: Environmental control of abscisic acid accumulation and stomatal sensitivity to abscisic acid. Plant Physiol 70:1066–1070.

Rajagopalan AV; Devi MT; Raghavendra AS. 1994. Molecular biology of C_4 phospho*enol*pyruvate carboxylase: structure, regulation and genetic engineering. Photosynth Res 39:115–135.

Rawson HM; Begg JE; Woodward RG. 1977. The effect of atmospheric humidity on photosynthesis, transpiration and water use efficiency of leaves of several plant species. Planta 134:5–10.

Reinfelder JR; Kraepiel AML; Morel FMM. 2000. Unicellular C_4 photosynthesis in a marine diatom. Nature 407:996–999.

Reinfelder JR; Milligan AJ; Morel FMM. 2004. The role of the C_4 pathway in carbon accumulation and fixation in a marine diatom. Plant Physiol 135:2106–2111.

Reiskind JB; Madsen TV; Van Ginkel LC; Bowes G. 1997. Evidence that inducible C_4-type photosynthesis is a chloroplastic CO_2-concentrating mechanism in *Hydrilla,* a submersed monocot. Plant, Cell Environ 20:211–220.

Riis L. 1990. The subterranean burrowing bug *Cyrtomenus bergi* Froeschner, an increasing pest in tropical Latin America: behavioural studies, population fluctuations, botanical control, with special reference to cassava. MSc thesis. Institute of Ecological and Molecular Biology, Section of Zoology, The Royal Veterinary and Agricultural University, Copenhagen, Denmark.

Riis L. 1997. Behaviour and population growth of the burrower bug, *Cyrtomenus bergi* Froeschner: effects of host plants and abiotic factors. Dissertation. Royal Veterinary Agricultural University, Copenhagen, Denmark.

Riis L; Bellotti AC; Bonierbale M; O'Brien GM. 2003. Cyanogenic potential in cassava and its influence on a generalist insect herbivore *Cyrtomenus bergi* (Hemiptera: Cydnidae). J Econ Entomol 96:1905–1914.

Riis L; Bellotti AC; Vargas O. 1995. The response of a polyphagous pest (*Cyrtomenus bergi* Froeschner) to cassava cultivars with variable HCN content in root parenchyma and peel. In: Proc Second International Scientific Meeting of the Cassava Biotechnology Network. CIAT, Cali, Colombia. p 501–509.

Romanoff S; Lynam J. 1992. Cassava and African food security: some ethnographic examples. Ecol Food Nutr 27:29–41.

Rosling H. 1994. Measuring effects in humans of dietary cyanide exposure from cassava. Acta Hortic 375: 271–283.

Ruppenthal M; Leihner DE; Steinmüller N; El-Sharkawy MA. 1997. Losses of organic matter and nutrients by water erosion in cassava-based cropping systems. Exp Agric 33:487–498.

Rylott EL; Metzlaff K; Rawthorne S. 1998. Developmental and environmental effects on the expression of the C_3-C_4 intermediate phenotypes in *Moricandia arvensis*. Plant Physiol 118:1277–1284.

Salvucci ME; Bowes G. 1983. Two photosynthetic mechanisms mediating the low photorespiratory state in submersed aquatic angiosperms. Plant Physiol 73:488–496.

Schoonhoven A van. 1978. Thrips on cassava: economic importance, sources and mechanisms of resistance. In: Brekelbaum T; Bellotti AC; Lozano JC, eds. Proc Cassava Protection Workshop. CIAT, Cali, Colombia. p 177–180.

Schulze E-D. 1986. Carbon dioxide and water vapour exchange in response to drought in the atmosphere and in the soil. Annu Rev Plant Physiol 37:247–274.

Schulze E-D; Hall AE. 1982. Stomatal responses, water loss and CO_2 assimilation rates of plants in contrasting environments. In: Lange OL; Nobel PS; Osmond CB; Ziegler H, eds. Physiological plant ecology, II: Water relations and carbon assimilation. Encyclopaedia of Plant Physiology, vol 12B. Springer-Verlag, Berlin, Germany. p 181–230.

Schulze E-D; Lange OL; Buschbom U; Kappen L; Evenari M. 1972. Stomatal response to changes in humidity in plants growing in the desert. Planta 108:259–270.

Sesták Z, ed. 1985. Photosynthesis during leaf development. Academia Publishing House of The Czech Academy of Sciences (Praha); Dr. W. Junk N.V. Publishers, Dordrecht, Netherlands.

Seybold WD. 1961/1962. Ergebnisse und probleme pflanzlicher transpirationsanalysen. Jahresh Heidelb Akad Wiss 6:5–8.

Sheen J. 1999. C_4 gene expression. Annu Rev Plant Physiol Plant Mol Biol 50:187–217.

Sheriff DW. 1977. Where is humidity sensed when stomata respond to it directly? Ann Bot 41:1083–1084.

Sheriff DW. 1979. Stomatal aperture and the sensing of the environment by guard cells. Plant, Cell Environ 2:15–22.

Sheriff DW. 1984. Epidermal transpiration and stomatal responses to humidity: some hypotheses explored. Plant, Cell Environ 7:669–677.

Sheriff DW; Kaye PE. 1977. Responses of diffusive conductance to humidity in a drought-avoiding and a drought-resistant (in terms of stomatal response) legume. Ann Bot 41:653–655.

Siritunga D; Sayre RT. 2003. Generation of cyanogen-free transgenic cassava. Planta 217:367–373.

Slávik B. 1971. Determination of stomatal aperture. In: Sesták Z; Cátsky J; Jarvis PG, eds. Plant photosynthetic production: manual of methods. Dr. W. Junk N.V. Publishers, The Hague, Netherlands. p 556–563.

Solárová J; Pospisilová J. 1979. Diffusive conductances of adaxial and abaxial epidermis, 1: Response to photon flux density during development of water stress in primary bean leaves. Biol Plant 21:446–451.

Stanhill G. 1986. Water use efficiency. Adv Agron 39:53–85.

Taybi T; Cushman JC. 1999. Signaling events leading to Crassulacean acid metabolism induction in the common ice plant. Plant Physiol 121:545–555.

Tazaki TK; Ishihara K; Ushijima T. 1980. Influence of water stress on the photosynthesis and productivity of plants in humid areas. In: Turner NC; Kramer PJ, eds. Adaptation of plants to water and high temperature stress. John Wiley & Sons, New York, USA. p 309–321.

Tenjo FA; Mayer JE; El-Sharkawy MA. 1993. Cloning and sequence analysis of PEP-carboxylase from cassava. In: Roca WM; Thro AM, eds. Proc First International Scientific Meeting of the Cassava Biotechnology Network. CIAT, Cali, Colombia. p 331–334.

Thoday D. 1938. Stomatal movement and epidermal water-content. Nature 141:164.

Thorne GN; Evans AF. 1964. Influence of tops and roots on net assimilation rate of sugar-beet and spinach beet and grafts between them. Ann Bot 28:499–508.

Tibbitts TW. 1979. Humidity and plants. BioScience 29:358–363.

Tichá I. 1982. Photosynthetic characteristics during ontogenesis of leaves, 7: Stomata density and size. Photosynthetica 16:375–471.

Tinoco-Ojanguren C; Pearcy RW. 1993. Stomatal dynamics and its importance to carbon gain in two rainforest *Piper* species. Oecologia 94:388–394.

Tregunna EB; Krotkov G; Nelson CD. 1964. Further evidence on the effects of light on respiration during photosynthesis. Can J Bot 42:989–997.

Tscherning K; Leihner DE; Hilger TH; Müller-Sämann KM; El-Sharkawy MA. 1995. Grass barriers in cassava hillside cultivation: rooting patterns and root growth dynamics. Field Crops Res 43:131–140.

Turner NC. 1986. Adaptation to water deficits: a changing perspective. Aust J Plant Physiol 13:175–190.

Turner NC; Begg JE; Tonnet ML. 1978. Osmotic adjustment of sorghum and sunflower crops in response to water deficits and its influence on the water potential at which stomata close. Aust J Plant Physiol 5:597–608.

Tyree MT; Yianoulis P. 1980. The site of water evaporation from sub-stomatal cavities, liquid path resistance and hydroactive stomatal closure. Ann Bot 46:175–193.

Ueno O. 1996. Immunocytochemical localization of enzymes involved in the C_3 and C_4 pathways in the photosynthetic cells of an amphibious sedge, *Eleocharis vivipara*. Planta 199:394–403.

Ueno O. 2001. Environmental regulation of C_3 and C_4 diffferentiation in the amphibious sedge *Eleocharis vivipara*. Plant Physiol 127:1524–1532.

Ueno O; Agarie S. 1997. The intercellular distribution of glycine decarboxylase in leaves of cassava in relation to the photosynthetic mode and leaf anatomy. Jpn J Crop Sci 66:268–278.

Ueno O; Bang SW; Wada Y; Kondo A; Ishihara K; Kaneko Y; Matsuzawa Y. 2003. Structural and biochemical dissection of photorespiration in hybrids differing in genome constitution between *Diplotaxis tenuifolia* (C_3-C_4) and radish (C_3). Plant Physiol 132:1550–1559.

van Oirschot QEA; O'Brien GM; Dufour DL; El-Sharkawy MA; Mesa E. 2000. The effect of pre-harvest pruning of cassava upon root deterioration and quality characteristics. J Sci Food Agric 80:1866–1873.

Veltkamp HJ. 1985. Physiological causes of yield variation in cassava (*Manihot esculenta* Crantz). Dissertation. Wageningen Agricultural University, Wageningen, Netherlands.

Verteuil J de. 1917. Cassava experiments. Bull Dep Agric Trinidad and Tobago 16:18–21.

Verteuil J de. 1918. Cassava experiments 1916–1918. Bull Dep Agric Trinidad and Tobago 17:193–198.

Volk RJ; Jackson WA. 1972. Photorespiratory phenomena in maize: oxygen uptake, isotope discrimination, and carbon dioxide efflux. Plant Physiol 49:218–223.

Voznesenskaya EV; Franceschi VR; Kiirats O; Artyusheva EG; Freitag H; Edwards GE. 2002. Proof of C_4 photosynthesis without kranz anatomy in *Bienertia cycloptera* (Chenopodiaceae). Plant J 31:649–662.

Voznesenskaya EV; Franceschi VR; Kiirats O; Freitag H; Edwards GE. 2001. Kranz anatomy is not essential for terrestrial C_4 plant photosynthesis. Nature 414:543–546.

Walton DC. 1980. Biochemistry and physiology of abscisic acid. Annu Rev Plant Physiol 31:453–489.

Ward DA; Bunce JA. 1986. Novel evidence for lack of water vapour saturation within the intercellular airspace of turgid leaves of mesophytic species. J Exp Bot 37:504–516.

Wardlaw IF. 1990. The control of carbon partitioning in plants. New Phytol 116:341–381.

Webber AN; Nie G-Y; Long SP. 1994. Acclimation of photosynthetic proteins to rising atmospheric CO_2. Photosynth Res 39:413–425.

Westby A. 2002. Cassava utilization, storage and small-scale processing. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 281–300.

Westhoff P; Gowik U. 2004. Evolution of C_4 phospho*enol*pyruvate carboxylase—genes and proteins: a case study with the genus *Flaveria*. Ann Bot 93:13–23.

Westhoff P; Svensson P; Ernst K; Blasing O; Burscheidt J; Stockhaus J. 1997. Molecular evolution of C_4 phospho*enol*pyruvate carboxylase in the genus *Flaveria*. Aust J Plant Physiol 24:429–436.

Wilson WM. 2003. Cassava (*Manihot esculenta* Crantz), cyanogenic potential, and predation in northwestern Amazonia: the Tukanoan perspective. Human Ecol 31:403–416.

Wilson WM; Dufour DL. 2002. Why bitter cassava? Productivity of bitter and sweet cassava in a Tukanoan Indian settlement in Northwest Amazon. J Econ Bot 56:49–57.

Woodrow IE. 1994. Optimal acclimation of the C_3 photosynthetic system under enhanced CO_2. Photosynth Res 39:401–412.

Wortman S. 1981. Beyond the bottom line. The Rockefeller Foundation, New York, USA.

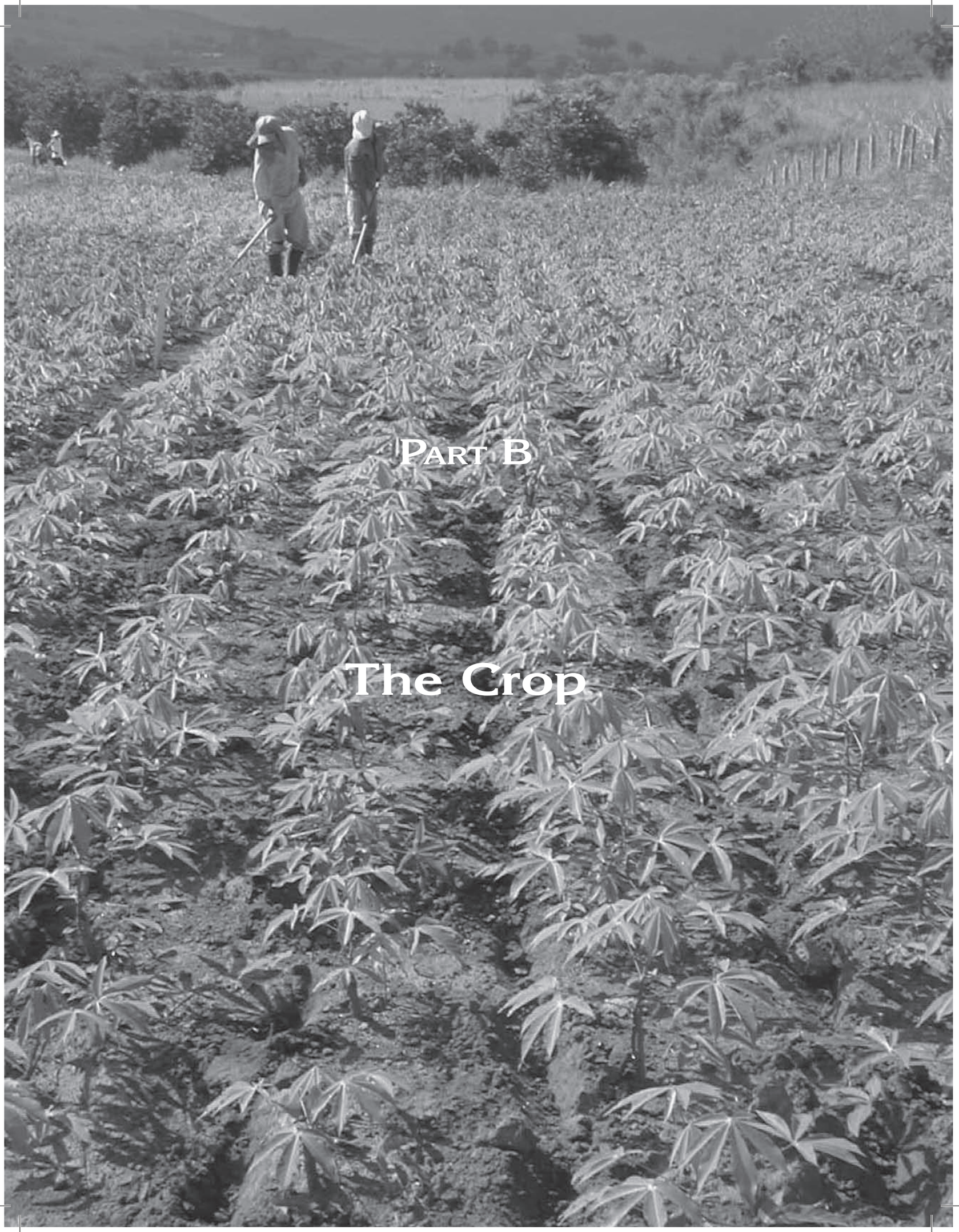
Zeevaart JAD; Creelman RA. 1988. Metabolism and physiology of abscisic acid. Annu Rev Plant Physiol Plant Mol Biol 39:439–473.

Zeiger E. 1983. The biology of stomatal guard cells. Annu Rev Plant Physiol 34:441–475.

Zelitch I. 1962. Biochemical control of stomatal opening in leaves. Proc Natl Acad Sci USA 47:1423–1433.

Zhang J; Davies WJ. 1989. Abscisic acid produced in dehydrating roots may enable the plant to measure the water status of the soil. Plant, Cell Environ 12:73–81.

Ziska LH; Hogan KP; Smith AP; Drake BG. 1991. Growth and photosynthesis response of nine tropical species with long-term exposure to elevated carbon dioxide. Oecologia 86:383–389.



Part B

The Crop

CHAPTER 4

Cassava Planting Materials

Javier López[1]

Introduction

Cassava propagates vegetatively. This enables it to form clones, where all plants of a variety are the same, both externally and in root and foliage production. However, biotic (pests and diseases) and abiotic (climate and soil) environmental factors can considerably modify individual plants, changing, for example, their height, vigor, flowering, branching, root production, and starch and hydrocyanic acid (HCN)[2] contents. One significant feature that the environment can affect is the quality of planting materials, degrading them, even to the point where a given variety may disappear.

Factors that can reduce yields of cassava plants include systemic diseases such as those caused by viruses, bacteria, and phytoplasmas; low soil-fertility; nutritional imbalances; and even moderate levels of soil salinity. These factors can also reduce the capacity of planting materials to express the genotypes' respective yield potential.

The effect of such negative factors during several vegetative propagation cycles of the cassava crop can result in a cumulative reduction of quality in planting materials, leading to their gradual deterioration (Lozano et al. 1984). Introducing the use of good-quality planting stakes as part of the package of "best" farming practices would permit the acquisition of healthy vigorous plantings, with yields that are close to the respective genotypes' potential.

1. Soil Agronomist, formerly of Cassava Program, CIAT, Cali, Colombia.
E-mail: ingjavierlopez@yahoo.es
2. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Situation of Cassava "Seed"

The timely availability of good quality planting materials constitutes a decisive factor for the dissemination and use of new cassava varieties. The lack of improved seed (i.e., planting stakes) is often a feature of crops of simple asexual propagation, but is accentuated in cassava because of its biology, farmers' socioeconomic status, and lack of organized seed-supply systems.

Biological aspects

Cassava is one of the few crops whose planting materials, in themselves, have no economic value. In grain crops (e.g., maize and beans) and even in crops with vegetative propagation such as potato, yam, and sugarcane, planting materials that are not used as seed still have value as food. Even seeds, such as those of horticultural crops, that have no other use, at least have the advantage of occupying very little space, and the potential for being conserved over prolonged periods under good storage conditions. Cassava, in contrast, is planted for its roots, and stems that are not used as seed have no other attribute of value. Cassava also has other characteristics that hamper large or medium-scale seed production.

Low storage potential

Cassava planting materials deteriorate during storage as stems dehydrate, reserves are lost through sprouting, and pests and other pathogens attack. The result is a gradual reduction in the number of usable stakes, as the storage period increases. To date, despite considerable research, no technology is available that solves these problems. However, the potential for storage is known to be a varietal characteristic. Some cultivars such as M Col 1468 (previously called CMC 40) can be stored for as long as 6 months, while others such as M Col 1684 can deteriorate in as quickly as 2 or 3 weeks.

Growth habit is related to such varietal differences. For example, stems from non-branching or late-branching clones can be stored for longer periods than those from early branching clones. The nutritional status of the mother plants may also affect the stems' storage potential.

Low multiplication rate

On the average, a mature cassava plant in good condition produces only 10 or so 20-cm-long commercial stakes. Cropping conditions can reduce this figure to 5 or even fewer stakes. This means that, from 1 ha, over 1 year, only enough stakes to plant 10 new hectares can be obtained. Such figures represent a very low multiplication rate when compared with grain crops (Table 4-1). Such a situation has the following consequences:

1. Expanding the planted area rapidly is very difficult.

2. The costs incurred to produce 1 ha of crop for seed acquisition must be divided among a low number of stakes.

3. The seed producer must dedicate a considerable amount of land to obtain planting materials (Table 4-1).

Weight and volume

The handling and transportation of cassava stakes are wasteful and expensive operations because of the planting materials' considerable weight and volume. A single cassava stake weighs the equivalent of 230 maize seeds. Planting materials for 1 ha (10,000 stakes) weigh about 0.7 t and occupy a volume of about 2 m^3. Hence, many farmers tend to use small stakes. Table 4-2 compares the weight and volume of cassava seed with those of seed of four other species.

Table 4-1. Seed plot area needed to plant 100 ha and multiplication rates for cassava and four other crops.

Crop	Area (ha)	Multiplication rate[c]
Cassava	12.5[a]	10
Bean	6.7[b]	225
Soybean	4.0[b]	600
Rice	2.5[b]	1600
Maize	0.7[b]	22,500

a. Land occupied for 1 year.
b. Land occupied for 1 semester.
c. Number of stakes (or seeds) obtained from one stake (or seed over 1 year.

Table 4-2. Approximate weight and volume of seed of some crops.

Crop	Weight of 100 stakes (g)	Weight of 100 seeds (g)	Seed for 1 ha	
			Weight (kg)	Volume (m^3)
Cassava	7000		700	2.00
Rice		2.4	150	0.26
Soybean		16	90	0.12
Bean		45	80	0.10
Maize		30	20	0.03

Cultivation by small farmers

Most cassava production is carried out by small farmers, who use traditional production systems that result in low, but stable, yields. Cassava-growing areas are characterized as having little infrastructure and usually poor soils that are sometimes marginal for crop production. Poor soil fertility leads to both reduced root production and poor quality planting materials, mainly because of insufficient nutritional reserves. Small farmers use intensive-labor agronomic practices, as they possess few resources to exploit in their work.

Uncertain demand

Cassava farmers habitually produce their own planting materials as, cassava being a crop with vegetative propagation, usually produces seed at the same time that the previous crop is harvested. Farmers who buy cassava seed either:

- Are planting for the first time
- Have stopped planting long enough so that no planting materials are conserved
- Wish to change varieties
- Wish to considerably increase the planting area

The volume of sales of a cassava seed producer depends on variations in the planted area, which, in its turn, depends on how root prices are performing.

Stake Quality

For seed to be a highly productive technological component, it must have quality. Experience has demonstrated that good quality seed will give good results in the field, whereas poor quality seed will lead to unsatisfactory results and failure. *Quality* is that set of genetic, physiological, and health attributes that enable stakes to give rise to productive plants. The presence of high levels of these three essential components of quality indicates that seed is at its maximum integrated quality. In contrast, weakness in

any component introduces a constraint. Thus, perfect genotypes cannot express their true potential if their seed has physiologically deteriorated and shows poor germination.

The qualitative attributes of a variety, generated by genetic improvement, will be transferred to the farmer only where its characteristics do not deteriorate from one generation to the next through seed multiplication.

Genetic quality

Genetic quality is produced through improvement. Crosses, selections, and regional trials are all used to develop materials that contain a genetic program that is appropriate for the conditions found in different agroecological areas. When the selected materials are crystallized into varieties acceptable to users, they are then recommended for mass and commercial use. To be useful to the agricultural community, mass quantities of stakes will be needed for each such variety. It is during multiplication that the need for maintaining genetic identity appears.

Genetic quality can be ensured by planting authentic seed, that is, when planting materials are chosen from crops certified by entities such as the Colombian Institute of Agriculture (ICA, its Spanish acronym). Varietal mixes are avoided, and authenticity is maintained through preventive methodologies such as not planting immediately into land previously planted with different cassava varieties. Inspections are also carried out to rogue out atypical plants.

The genetic factors that most affect the seed production of a cassava variety are general vigor and branching habit. Vigor affects the total growth of a plant's aerial parts and, as a result, the number of branches from which stakes can be obtained. Branching habit influences the availability of primary and secondary stems, which are the parts most used for planting materials.

In general, vigorous varieties produce more stakes than non-vigorous ones. However, the greatest difference lies in the type of branching. Late-branching varieties have a larger proportion of primary and secondary stems than early branching genotypes. Hence, increased branching leads to more and heavier stakes.

Physiological quality

The tangible result of physiological quality is the stake's ability to sprout and give rise to a vigorous plant. Physiological quality involves seed nutrition, seed age, and seed viability:

Seed nutrition. The nutritional status of a stake is fundamental to the initiation of a new plant because, in the 20 days following planting, the stake's growth into a plant is exclusively at the expense of the reserves accumulated in the stem. Three weeks after planting, with the appearance of the first leaves and roots, photosynthesis begins to contribute to plant growth, which, however, continues to use the stake's nutrient reserves until day 40 (Hunt et al. 1977).

Soil fertility markedly affects the growth of aerial parts in cassava and, especially, the nutritional status of the stems used as planting materials. In low-fertility soils, stem length and quality are diminished, but can be considerably improved through fertilizer applications. Such applications increase the level of nutrient reserves in the stems, thus improving their performance when used as planting materials.

Indeed, different levels of N, P, and K have been studied in plots planted with seed. Results showed that both the concentration and contents of N, P, and K in stems vary with levels of N, P, and K in the soil. Thus, cassava plants grown in a low-fertility soil produce stems with low contents of N, P, and K. When that soil is given applications of high levels of fertilizers, the resulting stems present high contents, not only of N, P, and K, but also of starch, reducing sugars, and total sugars (Table 4-3). When such stems are used as planting materials, the percentage of stakes germinating is strongly influenced by K levels and the balance of K with N and P.

Table 4-3. Nutrient contents of stakes according to levels of fertilizer applied to the soil from which they were obtained (mg/stake).

Nutrient	Level of fertilizer application		
	Low	Intermediate	High
N	70	131	139
P	10	23	25
K	19	49	72
Starch	2620	3390	4290
Reducing sugars	330	460	500
Total sugars	390	520	680

We point out that the stakes' capacity for germination is not affected by whether or not they are planted in a soil with fertilizer applications. What is important are the stake's levels of nutrient reserves. If stakes with high nutrient contents are used, then a higher production of stems, suitable for use as planting materials, is possible. This is very important for seed production programs because of cassava's low multiplication rate (Table 4-4).

In addition, an application of fertilizer to the seed plot, emphasizing K, will result in stakes that produce, in their turn, denser foliage—a factor of special interest for sustainable agriculture in hillside regions, where, by increasing soil cover, it reduces hydric erosion.

Finally, the use of stakes with adequate nutrient contents will increase the total production of fresh roots, mainly because roots will be larger and, to a lesser extent, more numerous (Table 4-4).

Figure 4-1 shows two plants of the same variety (M Col 1684) and age (12 months). The plant on the left came from a stake with low nutrient contents ($N_0P_0K_0$), while that on the right came from a stake with high nutrient contents ($N_2P_2K_2$). Both stakes were planted in an acid low-fertility soil with no fertilizer applications. Thus, the difference between these two plants would be exclusively in terms of the quantity of nutrient reserves the stakes had.

Table 4-4. Effect of nutrient contents of stakes on the average production of stems and roots, using cassava variety M Col 1684.

Nutrient contents	Average production (fresh weight)	
	Stems (kg/ha)	Roots (t/ha)
Low	3252	16,260
Intermediate	3611	21,180
High	4658	27,160

Figure 4-1. Differences between a plant developing from well-nourished seed (at right) and that from poorly nourished seed (at left), when both are grown in similar low-fertility soils that did not receive fertilizer applications, as indicated by the sign "SIN" (Spanish for "without").

Hence, the photograph demonstrates that the use of stakes having good nutritional status will likely ensure that the variety's true yield potential is reached. Such a low-cost technological component would enable farmers to increase cassava production, together with adequate soil conservation.

What was described above is highly significant to seed production programs, particularly those directed towards regions with soils classified as acid and of low fertility, namely Oxisols and Ultisols. Such soils are found in the current or potential cassava-growing areas of Bolivia, Brazil, Colombia, and Venezuela.

Seed age. One cassava stake normally forms one to four shoots, which form the primary stems. The appearance of flowers produces branching in these primary stems, with the consequent formation of secondary, tertiary, and other stems, according to that variety's flowering and branching cycle. Consequently, the plant's primary stems represent the oldest tissue, while the secondary, tertiary, and more recent stems represent the youngest tissues.

Increasing tissue age results in increased thickness and lignification of the xylem, together with a proportional reduction of medullary tissue. When this process is sufficiently advanced, the stems are considered mature enough and suitable as seed, as the thickness and lignification provide them with sufficient nutrient reserves and resistance to dehydration.

Indeed, any section of a stem from basal parts to the apical meristem can give rise to new plants. However, commercially, herbaceous parts are discarded because of their low dry matter content and high probability of becoming dehydrated in the field after planting. The rest of the stem, however, can be used as seed. Nevertheless, a direct relationship apparently exists between age of seed and the performance of the new plant. Most researchers believe that stakes taken from primary stems or basal parts give rise to plants with higher yields than those developed from stakes taken from apical parts.

This difference in yields may be attributed to differences in the stakes' nutrient reserves, as their

chemical composition (N, P, K, Ca, and Mg) varies between different sections of the stem. Increases in yield, the older the stakes, may result from a higher concentration of nutrients, mainly N and K, and a higher dry matter content (Table 4-5) (Enyi 1970). Hence, the highest total quantities of N, P, K, starch, and fiber accumulates in the oldest parts of the stems.

Seed viability. Stake viability is directly related to its moisture content. In a 10 to 12-month-old plant, stems have about 70% moisture. The stakes they produce will have a viability of almost 100%. Once the stakes are cut, dehydration starts, and accelerates when they are stored in a place with high temperatures and low relative humidity. The effect can be so severe that a reduction of 20% in moisture content can reduce sprouting of the seed by 50% (Table 4-6).

A visual indicator for estimating moisture content and, thus, stake viability is the speed at which latex, a characteristic of euphorbias, flows from a recently cut stake. If it flows immediately, then the stake has sufficient moisture and, thus, good germination power. As the stake becomes dehydrated, the latex appears more slowly and its quantity is less.

Quality of plant health

In seed production, health problems may arise, induced by pathogens (fungi, bacteria, phytoplasmas, and viruses) and pests (insects and mites). These not only reduce the quantity of stakes that a plant can produce, but also reduce their quality, which is later reflected in low yields. They also pose a risk when introduced into areas free of such problems (Lozano et al. 1986).

Table 4-5. Dry weight of stakes, and root yield in cassava.

Stake section	Dry weight of stakes (g/stake)	Root yield (kg/plant)
1 (basal)	47.2	3.47
2	41.0	2.65
3	36.6	2.35
4	32.6	1.98
5	27.2	1.65
6 (apical)	24.2	1.80

SOURCE: Enyi (1970).

Table 4-6. Influence of moisture loss on the viability of cassava stakes.

Moisture loss (%)	Reduction in shoots (%)
10	10
20	50
60	100

Diseases transmitted by stakes. Cassava can be attacked by several pathogens, either systemic or localized, that are transmitted through planting materials, reducing crop yields by:

- Reducing sprouting in stakes
- Killing stakes after sprouting
- Reducing normal plant vigor
- Reducing the number of bulked roots
- Permanently harboring potential inocula that attack future plantings

Systemic pathogens. These are capable of invading the entire plant. They usually do not produce symptoms in lignified and mature tissues, hindering identification once the diseased material is cut. Symptoms almost always develop in the leaf system, or unlignified young branches, or even in the root system (Lozano and Jayasinghe [1983]). These plants constitute the source of primary inocula in new plantings. The systemic pathogens spread by planting materials include:

Fungi. The most important systemic fungal pathogen of cassava is *Diplodia manihotis,* which produces brown necrotic streaks throughout the affected vascular system. Other less important fungi are *Fusarium solani* and *F. oxysporum*. *Sphaceloma manihoticola*, causal agent of superelongation disease, although not properly systemic, produces a large quantity of spores in epidermal cankers on mature stem tissues. The spores are so tiny that the pathogen is unidentifiable. Their large numbers make them appear systemic (Lozano and Jayasinghe [1983]).

Bacteria. The most important bacterial disease and one of the most serious for the crop is cassava bacterial blight (CBB), caused by *Xanthomonas axonopodis* pv. *manihotis*. The disease can cause economic losses of more than 50%. When cassava stakes are infected with blight, germination losses may be more than 25%. This pathogen is restricted to the xylem tissues of the host's immature stems, as the bacterium cannot degrade the stem's lignified tissues. It is therefore very difficult to detect this bacterium's presence in the lignified stems normally chosen for planting, particularly when they are already cut as seed.

However, the severity of the disease is considerably reduced during dry periods. Hence, during such

periods, visually selecting healthy planting materials from an infected crop is sometimes impossible. Its capacity to disseminate through rain, insects, tools, and infested soil means that the pathogen can disperse relatively quickly from a few diseased plants (Lozano [1983]).

Phytoplasmas. Witches' broom, caused by a phytoplasma, has been found in Brazil, Mexico, the Peruvian Amazon, and Venezuela. Although its incidence is not significant, the disease reduces yield in infected plants by as much as 80% (Lozano [1983]).

Viruses. Leaf symptoms may occur in plants infected by viruses such as the African and American common mosaics, leaf vein mosaic, and the Caribbean mosaic. They can also cause symptoms in roots, such as frogskin disease. Viroses also exist that, in some cultivars (carriers), do not show apparent visible symptoms but gradually and slightly reduce the plants' normal vigor and production.

Although healthy plants can be produced, testing for their health is advisable, using laboratory techniques such as serology, electronmicroscopy, and hybridization of nucleic acids (Lozano and Jayasinghe [1983]).

Localized pathogens. These pathogens' invasive capacity is not systemic, that is, they invade only limited areas or stem parts. Their presence is characterized by the formation of cankers, galls, and necrotic areas.

This category of pathogens includes *Erwinia carotovora* pv. *carotovora* (bacterial stem rot), which causes degradation of the pith, which becomes yellowish, reddish, or dark brown; *Agrobacterium tumefaciens* (bacterial stem gall), which produces galls in stem nodes; and *Colletotrichum* spp. (anthracnose) and *Phoma* spp. (concentric-ring leaf spot), which cause epidermal and cortical lesions (Lozano and Jayasinghe [1983]). Localized pathogens enter the stem through wounds caused by mechanical means or insects, directly through stomata, or through petiole invasion. Attack from these pathogens usually decreases as the stem lignifies.

That part of the stem that is healthy can be used as planting material. Consequently, when selecting stakes, care should be taken to discard those parts of the stem affected by pathogens (CIAT 1987b). As a guideline, cassava planting materials should be collected from plantings that are apparently free of systemic pathogens. This apparent health must be confirmed through crop inspections during climatic conditions that favor disease development. For example, from the middle until the end of the rainy season, symptoms of superelongation disease, bacterial blight, and mosaics caused by viruses are more noticeable than during dry periods. The most vigorous and healthiest plants in the crop should be identified before collection (Lozano and Jayasinghe [1983]).

Pests transmitted through stakes. Damage caused by insects attacking cassava planting materials includes reduced germination and plant establishment. Dissemination of insect and mite eggs is more probable than that of larvae and adults, as the former travel on the stem epidermis. Such a location makes eggs relatively easy to detect. However, stemborers, scale insects, and mite eggs are easily disseminated through planting materials (Lozano [1983]).

The risk of disseminating mites to other regions is higher when a severe outbreak occurs in one area and seed is transported to another. The mite *Mononychellus tanajoa* was possibly introduced into Africa this way. Scale insects and mealybugs also spread this way. According to the degree of infestation, these insects may reduce germination of stakes by 70%. The eggs and larvae of other insects, such as thrips, can also be found in buds on stems and branches, and are spread as infected stakes are transported (CIAT 1987b).

Mites and insects that adhere to stems.

Mites are probably the most serious pest of cassava. They frequently attack the crop during the dry season, and cause severe damage in most cassava-producing regions of the world. The principal species are *M. tanajoa* (green mite), *Tetranychus urticae* (red spider mite), and *Oligonychus peruvianus*. Mite infestations at the Centro Internacional de Agricultura Tropical (CIAT) include these three species and, experimentally, losses in yield have ranged from 20% to 53%, depending on the duration of attack (Bellotti et al. [1983]).

Scale insects. Several species of scale insects have been identified as attacking cassava stems in almost all cassava-producing regions of the world. The most important are white scale *Aonidomytilus albus*, which is spread worldwide, probably through planting materials; and Caribbean black scale *Saissetia miranda*. The most severe damage that these insects cause appear to be loss of planting materials through

bud death. CIAT studies of stakes heavily infected with *A. albus* showed a 50% to 60% loss in germination (Bellotti and Schoonhoven 1978).

Thrips attack plants at their growing points, reducing yield. For eight susceptible cassava varieties in Colombia, average yield loss was 17.27% (Bellotti and Schoonhoven 1978). The production of planting materials can be reduced by as much as 57% (Lozano et al. 1986). The most important species is *Frankliniella williamsi*.

Insects found within stems.

Fruit fly. Two species of fruit fly attack cassava in America: *Anastrepha pickeli* and *A. manihoti*. The larvae of this fly tunnels within the stems of cassava plants, forming brown-colored galleries in the pith area. A bacterial pathogen (*Erwinia carotovora* pv. *carotovora*) is frequently found in association with fruit fly larvae, causing severe stem rot. This secondary rot can reduce germination of stakes by as much as 16%, causing reduced yields and loss of planting materials. Yield of plants from damaged stakes are about 17% lower than that of plants from healthy materials (Bellotti and Schoonhoven 1978).

Stemborers. Planting materials can also suffer from stemborers, mainly larvae of Coleopteras such as *Coleosternus* spp. and *Lagochirus* spp., and of lepidopterans such as *Chilomima* sp. that usually cause sporadic or localized damage. Infestations may occur in growing plants, but also during storage of stems, requiring careful inspection of planting materials before their use (Bellotti et al. [1983]).

Termites. Termites attack cassava, mainly in the lowland tropics. They have been reported as a pest in various regions of the world, but mainly in Africa. In Colombia, *Coptotermes niger* feeds on planting materials; roots; or growing plants with parts that have dried up or become necrotic because of unfavorable climatic conditions, pathogens, or poor quality seed.

In studies conducted at CIAT, termites destroyed almost 50% of stored planting materials, and losses in germination ranged between 25% and 30% (Bellotti and Schoonhoven 1978). On the Colombian Caribbean coast, termites attack stored stems, causing severe loss of planting materials, and also reducing the germination and establishment rates of stakes when these are planted with the insect inside. Stakes free of termites may also be attacked if a dry period comes after planting.

Stake Production

A. Field phase

The principal objective of a multiplication plot is to obtain the largest possible number of stakes per plant. Efforts must be made to avoid those factors or circumstances that will reduce root yield of the plants directly affected; or that will reduce the capacity of planting materials, derived from those plants, to express the yield potential of the genotypes planted.

The agronomic management of multiplication plots implies the use of all farming practices recommended for obtaining high root yields, carrying them out at minimal cost. Hence, with sales of roots, sufficient income would be acquired to cover production costs of both roots and stakes. Usually, a profit margin remains that is significant for commercial seed producers and even for basic seed producers. To achieve these objectives, the management of seed multiplication plots should incorporate the following recommendations:

Selection of land. The land for seed production should, ideally, be isolated from commercial cassava crops to prevent risk of contamination from insects and, especially, pathogens.

Land where cassava has been planted for 3 consecutive years or more should not be used, as, over the long run, with continuous planting, the land's capacity to produce both planting materials and roots becomes notably reduced, regardless of soil fertility. This is probably due to increased numbers of soil pathogens and to reduced numbers of beneficial microorganisms such as mycorrhizae.

For such land, the first recommended step is to reduce the potential inocula load of pathogens present in the soil. Continuous cassava cropping can be interrupted by planting, for at least 2 years, crops such as sorghum and maize, whose pathogens are not usually pathogenic to cassava. Where forest crops are felled, these gramineous crops should be planted for 1 or 2 years before planting cassava.

Soil salinity and stake quality. Traditionally, a normal soil is considered as having an electrical conductivity of less than 4 dS/m and a sodium saturation of less than 15%. However, cassava is affected by much smaller levels. Howeler (1981) points out that the critical levels for this crop are a conductivity of 0.7 dS/m and a sodium saturation of 2.5%.

The performance of planting materials was studied in plots with moderate levels of salinity. Cultivar HCM-1 was planted in two types of soil: one with a conductivity of 0.5 dS/m and sodium saturation of 1.3%, and the other with a conductivity of 0.8 dS/m and saturation of 3.0%. The plants in the plots with the higher level of sodium not only had smaller growth (thus reducing the quantity of stakes produced—see Table 4-7), but also, when they were used as seed source for a new planting in a normal soil, gave rise to plants with a smaller production of both stakes and roots (Table 4-7).

Other desirable characteristics of land destined for seed production are:

1. That they be owned: when land is rented and the completed contract is not extended, there is a risk of having to dig up the cassava in advance and store the stems. Hence, planting materials are lost in proportional to storage time.

2. That they are distant from people and roads to prevent theft of cassava by neighbors and transients, with consequent loss of seed.

3. That they are well fenced to prevent damage from livestock, especially cattle and pigs.

Soil fertility. The seed plot should preferably be located in a soil of good natural fertility. Otherwise, a complete fertilizer application should be carried out, as soil fertility decisively influences both the amount and quality of the seed produced. In poor soils, the production of planting materials is low, but increases in both number and weight of stakes can be obtained by applying fertilizers (Table 4-8).

The study on seed nutrient contents mentioned above found that, compared with seed having low levels, seed with high contents planted in a soil with no fertilizer applications could result in 53% more stems suitable for use as planting materials. However, when such seed was planted on a soil that received fertilizer, the percentage was 100% (Table 4-9).

Planting density. The cassava multiplication rate can be increased notably by increasing planting density in seed plots. According to Villamayor Jr (1983), when the number of plants per hectare is increased beyond the density normally used in commercial crops, each plant tends to maintain a stable number of primary stems. This permits a higher production of stakes, even though they have a slightly smaller weight, as the

Table 4-8. Influence of fertilizer applications (fertil.) on cassava stake production.

Cultivar	No. of stakes/ plant		Average stake weight (g)	
	No fertil.	Fertil.	No fertil.	Fertil.
M Mex 59	6.3	9.4	59	68
M Ven 218	8.9	11.3	67	70
M Col 63	4.9	6.7	46	54
M Col 22	5.2	6.2	58	60
M Col 1684	4.2	8.4	53	63
CM 91-3	4.9	4.4	46	63

SOURCE: Leihner (1986).

Table 4-9. Weight (kg/ha) of stems grown from seed with two levels of nutrient contents, using cassava variety M Col 1684 grown in an acid low-fertility soil.

Nutrient contents	Weight in soil with:		
	Fertilizer	No fertilizer	Difference
High	6222	3095	3127
Low	4487	2017	2470
Difference	1735	1078	

Table 4-7. Characteristics of stakes, and plants derived from those stakes, in two types of soil at the CIAT–Palmira experiment station, using cassava variety HCM-1 at 12 months old.

Characteristic	Performance of:			
	Stakes growing in soil[a]		Plants derived from stakes growing in soil[a]	
	A	B	A	B
Plant height (cm)	340.0	130.0	185.0	182.0
Weight of aerial parts (t/ha)	38.1	7.4	21.6	14.2
Seed produced (stakes/plant)	15.7	2.5		
Root production (t/ha)			35.9	29.1
Weight of seeds (t/ha)	8.7	1.3		
Weight per stake (g)	55.5	51.0		

a. Conductivity is 0.5 dS/m for soil A and 0.8 dS/m for soil B; sodium saturation is 1.3% for soil A and 3.0% for soil B.

SOURCE: López (1990).

stems are slimmer. However, the yield of crops planted with these stakes is not affected.

An increased planting density, however, reduces the average root size. Under the conditions of Valle del Cauca, Colombia, the maximum production of commercial roots (i.e., of a size currently acceptable to the market) is achieved at 5000 plants per hectare in tall branching varieties, and at 10,000 plants per hectare in erect varieties that are either short or tall (CIAT 1975).

Weed control. That weed competition reduces yield is well known, not only for cassava but also for other crops. It is also clear that ineffectual weed control will proportionally affect stake production.

A trial used different levels of weed control over the first 2 months of growth (CIAT 1983). Efficiency of weed control, expressed in terms of different levels of competition between weeds and cassava, was reflected by the weight of aerial plant parts dropping as the percentage of control declined. The number of stakes produced per plant was proportional to the weight of aerial parts.

When weeds were not controlled, the growth of aerial parts was reduced to such low levels that only one in three plants produced a stake of an acceptable size and quality. In contrast, with no competition from weeds, almost six stakes per plant were obtained (Table 4-10). Hence, maintaining good weed control is doubly of interest for optimizing stake and root production.

Weed control is expensive, although costs vary considerably, with direct expenses ranging between 20% and 50%. Costs depend on the class of weeds present, their size at planting, planting density, seed quality, and rain distribution during the crop's first months, among other factors. Under normal conditions, the application of a preemergent herbicide, complemented with one or two passes of manual weeding or applications of postemergent herbicides, should be sufficient to maintain the crop free of weeds throughout its growing period. The labor needed to apply preemergent herbicide, using a back fumigator, is reduced to 1 workday per hectare if planting density is 1×1 m, a TK5 fan nozzle is used, a 2-m-wide path per pass is covered, and the herbicidal volume is 150 L/ha.

Table 4-10. Effect of competition with weeds on the production of cassava stakes.

Control system	Weed control (%) at 59 DAP[a]	Stakes/ plant	Fresh weight (t/ha)	
			Branches	Roots
Continuous manual control	100	5.9	18.8	28.4
Preemergent herbicide[b]	62	4.9	16.7	19.2
No weed control	0	0.3	2.6	3.5

a. DAP = days after planting.
b. Diuron + alachlor at 1 kg and 2 L, respectively, per hectare.
SOURCE: CIAT (1983).

For manual weeding, the number of workdays depends on the class of weeds, their height, and the tools used (machete, shovel, or hoe), but it can be budgeted on an average of 15 workdays per hectare for each weeding. We point out that none of the herbicides recommended for cassava, whether preemergent or postemergent (including glyphosate), damage the stakes, whether planted horizontally or vertically, even when applied 8 days after planting.

Intercropping with maize. The practice of incorporating other species in a cassava crop usually reduces the production of both roots and aerial parts in direct proportion to competition from the other crops. It also reduces the average weight of stakes.

At CIAT, in 1989, an on-farm experiment was carried out with five farmers located in different areas over 2 years. To evaluate the influence of maize as an intercrop on the quality of cassava planting materials, stakes were taken from both a monoculture and an intercrop. These stakes were planted in the following season as a monoculture. Neither plant height nor branch or root production was affected by the origin of the planting materials (Table 4-11).

This finding demonstrated that the quality of planting materials, whether obtained from cassava planted in monoculture or associated with maize, was not significantly different. Although the intercrop led to a reduced number of stakes, this cropping system is currently used in many regions throughout the

Table 4-11. Effect of intercropping with maize on cassava stake quality.[†]

Origin of planting material	Plant height (m)	Weight (t/ha)	
		Branches	Roots
Monoculture	1.79 a	8.20 a	17.32 a
Intercrop	1.73 a	8.00 a	16.56 a

†. Values with the same letters in a column are not significantly different.

world and could also be used in the commercial production of cassava seed. Thus, small artisanal businesses could obtain seed from both cassava and maize.

Irrigation. Cassava has a reputation of being a hardy crop, resistant to drought. Indeed, when the dry season begins, the plant reduces its production of new leaves while continually dropping its old leaves. If the dry period becomes accentuated, more leaves fall, decreasing leaf area to a minimum and growth declines to an extent that the plant practically enters a period of latency. When the rains return, the plant uses its carbohydrate reserves to produce leaves again and thus resumes growth (Cock 1989).

Normally, cassava does not have critical periods in which the absence of rains may cause a total harvest loss. However, if drought is so prolonged that plants die—as in the midyear dry periods of western Colombia—some varieties will drastically reduce the production of both roots and planting materials. For example, a 10-week dry period, beginning 12 weeks after planting, when roots begin storing starch, caused variety M Col 22 to reduce root production by almost 30%, and branch and leaf production by almost 50% (Figures 4-2 and 4-3).

As a result, although cassava has traditionally been cultivated exclusively with rainwater, its full yield potential can only be reached if water management is included as a cultural practice. If irrigation is provided during dry periods, at a rate of 20 mm per week, root yields will increase by almost 60% (Mohankumar et al. 1984).

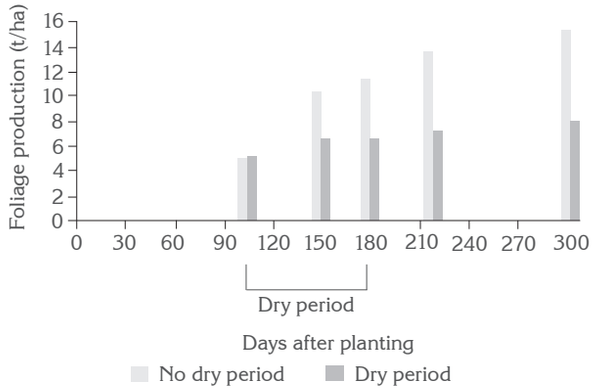


Figure 4-2. Effect of a dry period on the production of branches and leaves in cassava clone M Col 22 (adapted from Connor et al. 1981).

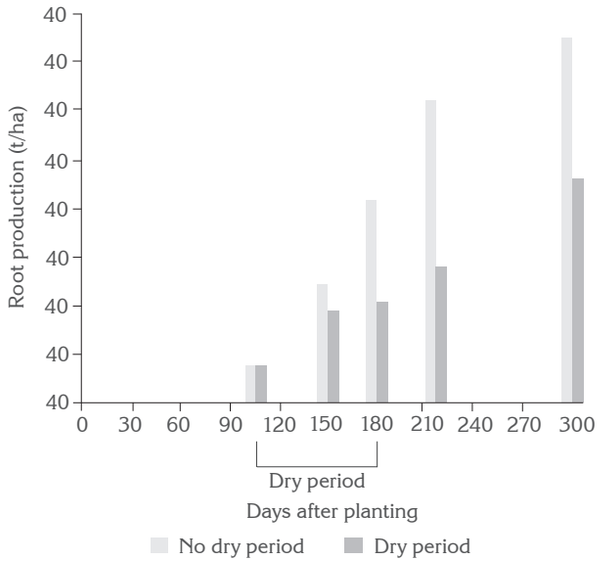


Figure 4-3. Effect of a dry period on root production in cassava clone M Col 22 (adapted from Connor et al. 1981).

B. Harvest and postharvest phases

Maturation and harvest. The quantity of seed that can be produced at any given age is determined by genotype, climatic conditions (higher temperatures lead to faster growth), soil fertility, weed control, and cropping system (competition from an intercrop delays the growth of aerial parts). However, regardless of circumstances, the number of usable stakes per plant is very low, increasing only as tissues lignify. Under CIAT conditions (Palmira), the number of stakes per plant in some varieties increases gradually, even after 12 months, while in other varieties, after this age, the number begins to decline as excessive lignification covers buds, or the buds sprout (Table 4-12).

Storage. If a seed production plot completes 12 months of growth before harvest, the following could be obtained:

- Fresh seed for the establishment of a new planting
- Maximum stake production
- Maximum root production

Table 4-12. Seed production (stakes/plant) in cassava, according to the age of the mother plant. Planting density is 1 × 1 m.

Cultivar	Months after planting					
	7	8	9	10	11	12
M Col 1468	4.6	6.5	10.8	11.1	11.5	11.0
M Col 1505	5.9	6.1	6.5	7.1	8.6	10.5
HMC-1	5.3	6.7	7.0	8.5	11.7	12.0

Given that maximizing income through sales of roots is recommended, then, to fix a reasonable price for stakes, the seed producer must decide on the best time to harvest. Early harvesting to take advantage of high root prices, whether varieties are early or late, tends to result in low stake numbers per plant. That is, the earlier the harvesting, the smaller the possible number of stakes—and the more immature the stems and the longer the storage needed.

The problems that occur during storage are dehydration, loss of reserves by sprouting, and attack by pests and pathogens. These problems gradually reduce the planting materials available, the longer the storage is. Currently, no technology is available that solves these problems. However, some principles help reduce their negative effects:

- The branches to be stored should be cut to lengths that are as long as possible. The longer the storage period, the larger the portions that must be eliminated, because the extremes inevitably dry up, especially apical parts. The usable central parts thus become shorter. Hence, the more cuts a branch is stored as, the smaller the central parts, representing the entire branch, will be.
- Storing branches vertically is preferable to horizontal storage, as fewer planting materials will be lost and reductions in weight of usable stakes will be smaller (Table 4-13).
- Chemical treatment with an insecticide-fungicide solution will, when storage conditions are unfavorable, help prevent deterioration of the seed (Table 4-14).
- In some varieties, plant age at storage affects the proportion of usable planting materials (Table 4-15).
- Branches should be taken to the storage place as soon as the crop is harvested, as exposure to the sun in the field reduces the seed's capacity for storage (Table 4-16).

Table 4-13. Condition of cassava planting materials after 103 days of storage, North Coast Region, Colombia, using variety M Col 2215.

Factor	Before storage	After storage	
		Vertical	Horizontal
Weight/branch (g)	340	307	240
Stakes/branch (no.)	3.4	2.7	2.4
Weight/stake (g)	76	63	54

Storage of stems is facilitated when late-branching varieties are used. The long primary stems (about 1 m) are easy to manage (Figure 4-4), with good yields when cut and facilitating the use of motorized saws. They also store well. Figure 4-5 illustrates vertical storage in a semi-shaded place. The stems are supported upright by a horizontal bar set at 60 cm from the ground.

Before storage, soil should be scuffed and dampened so that each stem makes good contact with the soil. If, in the region, wood-eating insects (e.g., termites) proliferate, an insecticide should be sprinkled over the soil.

About 1 month after storage begins, apical buds start to appear in all the stems, with foliage resuming growth. The stored stems shown in the center of Figure 4-5 have just begun budding, whereas the stored branches at the right have been stored for a longer period and are presenting dense foliage.

Table 4-14. Effect of chemical treatment on stored cassava planting materials, using variety M Col 1684.

Days of storage	Seed loss (%)	
	No treatment	With treatment
30	34	23
60	52	50
90	63	55

SOURCE: Luna (1984).

Table 4-15. Influence of plant age on stored cassava branches over 4 months.

Variety	Age at storage (months)	Seed loss (%)
M Col 22	8	31
	18	8
M Mex 11	8	4
	18	2

Table 4-16. Effect of direct solar exposure on cassava planting materials, using variety M Col 1505, and stored over 2 months.

Time of storage	Seed loss (%)
Immediately after harvest	10
8 days after harvest	23

Figure 4-4. Late-branching variety, with long primary stems that facilitate storage.

Figure 4-5. Storing cassava stems.

Should a prolonged dry season occur, this foliage becomes dry and appears burned. This means that the stems must be irrigated every week. However, if the season becomes rainy, a warm microclimate of high relative humidity is created, favoring the development of diseases. Hence, wide-spectrum fungicides should be applied.

On terminating storage and cutting up the stems, apical extremes that have sprouted should be discarded. This is why stems should be stored vertically because, this way, only two or three apical buds sprout. In contrast, when stems are left in a slanting position, all the buds tend to sprout. Thus, the entire branch is lost.

An environment suitable for storing branches is one where the planting itself will be carried out, especially for late-branching varieties. In addition to the above-mentioned advantages, this type of branching enables workers to move within the crop without becoming entangled in the branches. Hence, part of the crop is left without harvesting, and the branches to be stored are taken into the crop's interior and arranged vertically, as previously described. In this case, the stored stems are supported by a cassava branch held horizontally by tying to plants that are still standing (Figures 4-6 and 4-7). Growing the crop on ridges will facilitate any eventual irrigation for the stored stems.

Selecting planting materials. Because of its long growing cycle, cassava is continually subject to pressure from biotic (pests and diseases) and abiotic (climate and soil) factors. The quality of planting materials is thus reduced. Traditional varieties have been under this type of pressure over considerable

Figure 4-6. Storing stems within the crop.

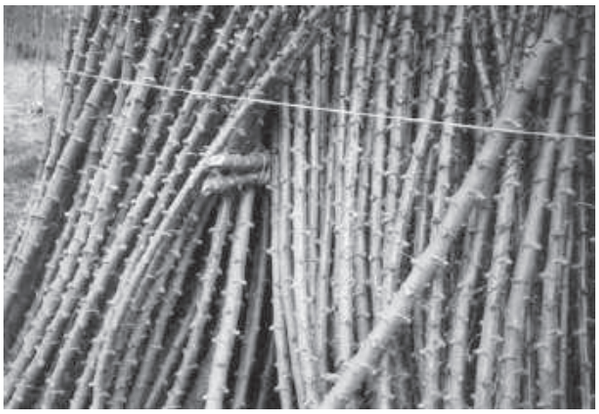


Figure 4-7. Detail of the way in which cassava stems should be supported.

periods and its effect leads to a cumulative decrease in the quality of planting materials after many cycles of vegetative propagation (Lozano et al. 1984). The effect of poor quality seed on production is unpredictable but, sometimes, yields are reduced by much more than 50% (Lozano 1987).

Hence, a positive selection of plants destined as planting materials for seed plots is recommended. According to CIAT (1987a), yields, especially of traditional varieties, may be increased only by using planting materials taken from vigorous and apparently disease-free plants. This selection system is less effective for new clones than for traditional ones (Table 4-17).

However, apparently healthy plants can be infected by latent viruses that do not show visible symptoms or by harmful endophytic fungi (Lozano and Laberry 1993). They may also have suffered disorders that are too recent to show symptoms. Hence, in addition to their external appearance, plants that serve as sources of stakes are also selected for their high root production, on the basis of the simple principle that plants with the highest yields should also be the healthiest (Lozano 1987). This type of selection has proven to be highly successful, and its advantage is more effective for clones that are susceptible to several production constraints (Table 4-18) (CIAT 1987a).

Table 4-17. Yield (t/ha) of two traditional cassava clones and two new hybrids, using visually selected stakes from the healthiest plants in a crop.

Clone	Visual selection	
	No selection	Selection
Traditional		
M Col 22	18	24
M Col 1438	9	13
New		
CM 523-7	26	27
CM 342-170	21	23

SOURCE: CIAT (1987a).

Processing the seed.

Cut. To cut the stakes, two aspects should be taken into account: length and age or stake's location in the plant. Stake length is important in terms of the number of nodes and the amount of nutrient reserves and moisture they contain. Node number is closely related to variety, and age of both plant and stake. A mature plant has a larger number of nodes than a young plant. In addition, in mature plants, nodes in basal parts are shorter than in apical parts.

Theoretically, obtaining a new plant would require planting only a piece of stem that is barely large enough to contain a node. However, the possibility of such a short stake germinating and rooting under field conditions is remote because, to prevent dehydration, the soil must be continually kept moist for the first weeks after planting. In contrast, long stakes of 60 cm or more are highly likely to root and germinate. However, their bulk presents difficulties for handling and transport. Moreover, each mother plant would yield a smaller number of stakes.

The influence that stake length has on yield has been a topic of research in several countries. Results show trends towards slightly increased yields with long stakes, probably because they have a higher nutritional content, which permits a better starting growth in plants and, thus, better bulking in roots. Most researchers believe that 20-cm stakes with at least five nodes would have sufficient nutrient reserves and an adequate number of buds to ensure good establishment and crop yield.

Table 4-18. Yield (t/ha) of three cassava varieties when seed was selected according to yield of mother plants.

Variety	Yield of mother plants		Increase (%)
	Low	High	
M Col 113	17.1	18.7	6
M Col 22	33.9	38.9	17
M Col 1438	18.6	29.5	58

Stakes with fewer than five nodes have fewer bulked roots per plant and a smaller average weight than those from stakes with five or more nodes (Table 4-19) (Gurnah 1974).

Chemical treatment. The stakes, once planted, may be attacked by insects and soil pathogens that usually affect buds first. They may also penetrate fine roots, bases of shoots, extremes of the stakes, and wounds caused by handling.

Practices that help reduce risk of damage caused by disease pathogens and insects include selecting planting materials, avoiding those introduced from regions where diseases or insects, transmissible by stakes, are present; and applying chemical treatment. The last acts in several ways:

- *Eradicates pathogens that are present.* Use of planting materials infected by *Sphaceloma manihoticola* (superelongation disease) or *Diplodia manihotis* (dry rot) is not recommended. However, where this is absolutely necessary, those plants least affected by superelongation should be chosen and treated with captafol or copper-based products. For dry rot, stakes should be treated with benomyl, which is a systemic fungicide. It is also useful in the curative treatment of stakes affected by *Fusarium* spp. and *Scytalidium* spp. (Lozano 1991).

- *Inactivates a present pathogen*. When a planting material is not known to be free of bacterial blight, it should be treated with copper-based fungicides. The copper in these fungicides exerts a bacteriostatic effect that inhibits the proliferation of the bacterium (Lozano 1991).

Table 4-19. Effect of number of nodes in cassava stakes on yield and its components.

Number of nodes	Yield (t/ha)	Roots/ plant	Average root weight (kg)
2	5.10	3.45	0.12
3	6.10	3.80	0.14
4	11.26	4.84	0.19
5	13.71	5.49	0.20
6	13.73	5.29	0.21
7	14.17	5.31	0.21
8	14.26	5.27	0.22

- *Eliminates mites and adhering insects.* Eggs and adults of mites and insects such as scales, mealybugs (*Phenacoccus* sp.), and thrips can be eliminated by immersing the stakes in a solution of an insecticide such as malathion (CIAT 1987b).

- *Protects stakes from pathogens and insects in the planting site*. Table 4-20 illustrates different treatments that can be given to stakes, including two that do not require chemical products.

Differences in production attributed to selection and stake treatment are more noticeable when susceptible or infected clones are used than when resistant clones are used. However, with the selection and treatment of stakes, beneficial effects sometimes cannot be seen, as in the following examples:

- When selecting and treating stems from vigorous plants growing in a region with no or only mild pathological or entomological problems.

- When an incorrect product is used for treatment against a pathogen infecting the stake or infesting the soil where planting will take place.

C. Production costs

Production costs for a crop designed to produce planting materials are much the same as those incurred to produce only roots. Additional protection needs to be given to aerial parts to ensure that the seed is free of pests and pathogens. Disease control is preventive, achieved almost exclusively through the use of healthy seed and treatment with fungicides. In the field, additional costs include roguing contaminated plants and possibly applying insecticides to control insect vectors.

Pest control, in contrast, requires habitual use of inputs, whether biological or chemical. The acquisition of seed free of adults or eggs of insects and mites implies the use of about an extra 10% more of inputs. However, this category represents a very low (<5%) proportion of production costs, so that to establish adult cassava plants destined for seed production, costs would be only slightly more than that of root production.

Table 4-20. Treatment of cassava stakes before planting.

Problem	Product or method	Dosage
Soil pathogens	Derosal + Orthocide®	6 cc + 6 g/L of water[a]
Root rots (*Phytophthora* spp.)	Ridomil® + Orthocide®	3 g/L + 3 g/L[b]
Bacterial blight (*Xanthomonas campestris*)	Kocide® (a bacteriostatic copper fungicide)	3 g/L[a]
Dry rot (*Diplodia manihotis*)	Benlate® + Orthocide®	3 g/L + 3 g/L[a]
Superelongation disease (*Sphaceloma manihoticola*)	Difolatan®	6 g/L[c]
Insects and mites	Malathion (or Sistemin®)	3 cc/L (3 cc/L)[c]
Bacterial blight Root rots Insects and mites	Thermotherapy: immersion of stakes in water at 49 °C for 49 min[d]	
Pathogens of the vascular system (*Fusarium* spp., *Diplodia manihotis*, and *Phytophthora* spp.)	Immersion in suspension of *Trichoderma* (1 kg/bucket) for 10 min[d]	

a. CIAT (1987a).
b. Álvarez et al. (1998).
c. Lozano (1991).
d. Álvarez (pers. comm.).

If production costs of seed plants are defrayed by selling the roots, seed production costs would be then represented in postharvest activities (Table 4-21), with the costs being smaller if the materials are cut and packed immediately after harvest, and higher if they must be stored. In the latter case, the longer the storage, the higher the cost per stake, as increased stake deterioration leads to a higher proportion of waste.

Although, in the field, the best plants can produce up to 12 stakes at 12 months (2.3 branches per plant and 5 to 6 stakes per branch), in practice, 1 hectare planted at 1 × 1 m does not yield 120,000 stakes for the following reasons:

1. Most crops usually have some less developed plants that have one or more branches that do not meet the conditions for use as seed.

2. Waiting until plants are 12 months old before harvesting is neither practical nor profitable. Harvesting when plants are about 10 months old will give time to complete the harvest and prepare the land for a new planting. Commercially, 17,000 branches, that is, about 80,000 stakes, would be obtained from 1 ha (Table 4-22).

Collecting stems. If workers do not have to travel far, then, in 14 workdays, they can gather from 1 ha about 16,000 stems as suitable seed.

Cutting stems. Once having gathered the stems, these are cut into stakes 20 cm long. The number of workdays varies with the method used, such as:

- A worker, sustaining a stem in one hand and cutting it with a machete in the other would obtain 3000 soft-stem stakes in 1 workday.

- A worker, using a machete, but supporting the stem on a log, would obtain up to 8000 stakes per day.

- An operator, using a circular saw activated by a 3-hp motor, can cut between 15,000 and 18,000 stakes per day, depending on the variety. Those varieties that do not branch or branch late and have long stems yield more stakes.

Packaging. Consistently packing the same number of stakes in each sack is advisable, as this measure helps control the number of cut stakes (total and per workday), the number of stakes transported, and the number of stakes planted (total and per workday).

The way stakes are packed depends on the distance from the planting site. Thus, seed traveling a short distance can be packed without taking too many precautions, but seed being transported to distant sites should be packed in an orderly way, as illustrated in Figure 4-8. This method allows placing several bundles

Table 4-21. Estimate of direct production costs (in Colombian pesos) of cassava seed per hectare.

Item	Unit	Quantity	Unit cost	Total value
Additional costs during cropping				
Insecticides	Liter	1.5	24,000	36,000
Application	Workday	1.5	10,000	15,000
Subtotal				**$51,000**
Postharvest costs				
1. *Collection of 16,000 branches*				
Labor	Workday	14	10,000	140,000
Subtotal				**$140,000**
2. *Treatment and storage*				
Labor	Workday	7	10,000	70,000
Benlate®	Kilogram	0.5	86,000	43,000
Orthocide®	Kilogram	0.5	14,000	7,000
Sistemin®	Liter	0.5	24,000	12,000
Subtotal				**$132,000**
3. *Conditioning*				
Cut 80,000 stakes	Workday	16	10,000	160,000
Treatment	Workday	4	10,000	40,000
Benlate®	Kilogram	1	86,000	86,000
Orthocide®	Kilogram	1	14,000	14,000
Sistemin®	Liter	1	24,000	24,000
Zinc sulfate	Kilogram	6.5	2,000	13,000
Polypropylene sacks	Sack	160	500	80,000
Subtotal				**$417,000**
Total 1: direct costs, including storage				$740,000
Cost per stake				9.25
Total 2: direct costs, no storage				$608,000
Cost per stake				7.60

Table 4-22. Production of cassava stakes in a commercial plot.

Variety	Branches per plant	Number of stakes per:	
		Branch	Hectare
HMC-1	1.54	4.5	69,300
M Col 1468	1.47	4.5	66,100
M Col 1505	1.78	5.0	89,000
M Col 2215	1.60	4.5	72,000
CM 523-7	1.60	4.5	72,000
M Ven 77	1.61	5.5	88,500

of seed, one on top of the other, without causing physical damage to the stakes during loading, transport, and unloading. For 1 workday, about 20,000 stakes can be casually packed, and 10,000 in an orderly fashion.

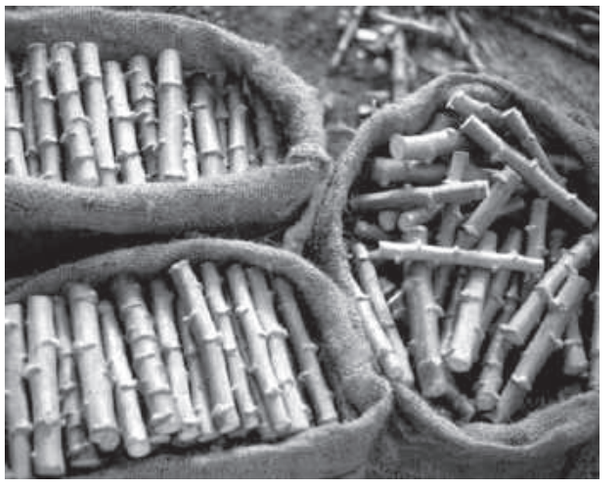


Figure 4-8. Cassava stakes should be packed in an orderly way, as seen in the sacks to the left.

Treating the stakes. The material with which the sacks are made influences the final cost of the stakes because of the cost of the sack itself on the one hand, and, on the other, the quantity of an aqueous solution of insecticides and fungicides (Table 4-22) used to treat the stakes. Although highly suitable for packing stakes, sisal sacks are the least recommendable as they cost five times as much, and absorb almost 10 times more solution than polypropylene sacks. Thus, 10,000 cassava stakes, placed in sisal sacks that are then soaked in solution, require 35 L of solution for adequate treatment. Only 10 L of these actually treat the stakes, with the other 25 L having soaked into the sacks themselves at a rate of 1 L per sack. In contrast, 10,000 stakes in polypropylene sacks need less than 15 L for adequate treatment.

Seed-Supply Systems

Improved seeds are the biological input through which new biogenetic technologies are incorporated into production systems. Consequently, scarcity can seriously constrain the dissemination and use of new varieties. In contrast, availability where and when seed is needed can decisively influence the adoption of technologies and agricultural development.

The development of organized seed-supply systems where crops have unstable and atomized markets is an under-researched field and almost non-existent for crops such as cassava. At best, some research on biological technologies is conducted on seed production and conservation. However, little attention has been given to the development of those essential functions that (1) enable the implementation of an organized system and (2) accelerate the flow of genetic technologies from research to widespread use.

Compounding this situation are the facts that cassava is mostly grown by farmers of few resources, the crop has a year-long growing period, and its multiplication rate is very low at 5–10 stakes per planted stake. The supply system is predominantly traditional, that is, farmers save their seed, having no tradition of buying and selling seed. The seed's bulkiness restricts its movement between regions and communities.

The appearance of improved varieties and the crop's incorporation into new industrial markets constitute positive factors that will help generate interest for improved seed. However, given the characteristics of the crop and its production systems, the organization and production technology of seed supply systems clearly must be adjusted to ensure operation under the crop's real conditions. In particular, cassava should not have imposed on it the formal requirements that exist for other crops with long histories of seed development.

Cassava seed production clearly does not attract large amounts of capital as does hybrid maize or rice. This means that thought must be given to creating subsidized governmental programs to produce and distribute seed, or to developing sustainable systems for the circumstances of the cassava farmer. Special attention must be paid to the farmer's socioeconomic status, the biological nature of the crop and its seed, and the limited availability of human, physical, and institutional resources in the targeted regions.

Importance and characteristics

Establishing a supply system of good quality stakes is important because it will:

- Increase the crop's productivity
- Reduce pest and disease dissemination
- Increase the genotypes' life cycle
- Permit more efficient use of agricultural inputs

Furthermore, if farmers have good quality seed, research projects in different fields (e.g., improvement, entomology, and pathology) will have an improved chance of producing the desired technological and economic impact.

Overall, a seed program will determine the possibility of guaranteeing supply in a region by establishing technical procedures and an organization that favors effective technology transfer with positive effects on cassava production. The following characteristics are desirable in a seed program:

- Ability to produce significant quantities of seed that will permit rapid expansion of the cultivated area or of new varieties.

- Possession of an efficient quality control mechanism.

- Production of seed at a quality that is at least equivalent to the best available source.

- Ability to sell seed at acceptable prices for users.

- Production of seed through a self-sustaining organizational scheme.

- Possession of efficient mechanisms to access new varieties, technical assistance, and training, among others.

Colombian case study

To produce high quality cassava stakes that would meet the category of certified, already established seed companies should preferably be in charge. These are well organized to distribute, have quality control systems, and can offer guarantees to produce high quality seed. In the absence of such companies, this work could be commissioned to progressive farmers who have experience in seed production.

Hence, a document was prepared, which established the minimum requirements that cassava stakes of different categories (basic, certified, and selected) should have. Production of this planting material was started. However, the scheme did not operate satisfactorily because:

a. The price of cassava roots is not stable over time. Root prices depend on the area planted. Larger or smaller areas lead to higher or lower supply, thus changing the price. When the price is high and farmers see an increased profitability of the crop, the demand for stakes increases and farmers are more willing to pay for them. But when the price for roots is low, demand for seed is not so high, thus discouraging farmers who may even opt to abandon the activity.

b. The farmer who purchases cassava stakes for the first time tries to continue to produce his or her own seed where possible. Conventional seed producers prefer crops for which seed hybrids can be produced that farmers cannot multiply. Thus, they maintain their clients "captive".

c. The production of cassava planting materials is, for conventional seed producers, a totally foreign activity, as they cannot use their current infrastructure of cleaning, conditioning, drying, storage, and other activities.

d. Seed companies centralize production to supply large areas. This is reasonable for grains but not for cassava stakes, which, because of their great weight and volume, hamper handling and transportation. Furthermore, they cannot be stored over prolonged periods.

A proposed system

Market conditions and the biological nature of this type of seed clearly suggest the need for an alternative production and distribution system. The proposed scheme is conceived as an organized system, in which different participants carry out different but complementary functions and, together, pursue a common objective: to ensure availability of good quality seed at the right time and at a reasonable price. These functions, which should relate to each other as links of a chain, are the generation of new varieties, production of basic seed, production and distribution of commercial seed, and use of that seed by farmers.

Generating varieties. National and international entities of research on plant breeding are responsible for generating varieties. Research includes activities such as trials on adaptation to different agroecosystems, pest and disease resistance, yield, and root quality.

Producing basic seed. This task should be carried out by national entities for research or seed production. Given the adaptation of varieties to specific regions and the bulky and perishable nature of the seed, such production should be regionalized. This stage can be successfully carried out, using a revolving fund with sales of roots and stakes maintaining the fund. The use of rapid propagation would be recommendable only for this stage because of the high costs of producing this type of planting material.

Producing commercial seed. Because a major aspect of seed production is continuity of offer, this activity should be carried out by experienced cassava farmers who grow cassava for the long term. Farmers who habitually produce crops other than cassava do not guarantee continuity of seed supply, as, given the first difficulty such as reduced root price, they will change to another crop.

Long-term cassava farmers have, as their main economic purpose, root production. They would also be able to produce seed, with technical assistance. Thus, in times of limited or no demand for seed, they would ensure their income through sales of roots until the seasons when demand for seed is high, which would then constitute an important additional income.

To avoid the drawbacks of extensive crops in terms of storing and transporting planting materials and the harvesting and marketing of large quantities of roots, production should not concentrate on a few producers to supply large areas. Instead, farmers should be strategically selected for their location in the region to supply small neighboring areas.

In areas with plant health problems and low-fertility soils, seed of traditional and improved varieties can be multiplied, producing high-quality stakes in terms of health and nutritional contents. They will then perform better than the region's usual seed. In those regions free of plant health problems and with acceptable soil fertility, the greatest impact is achieved through new varieties, as the quality of stakes from seed plots would be similar to that the farmers themselves produce.

Rapid propagation. Because cassava's low multiplication rate does not permit quick production of an abundant quantity of stakes from new varieties or from healthy stakes of traditional varieties, a methodology was implemented to help solve this problem. Although several variants have recently been developed, rapid propagation of cassava stakes can be carried out through two basic systems:

a. Shoot induction method. It consists of inducing shoots and their later rooting from stakes carrying two nodes. Adult plants are used, obtaining about 100 stakes from late-branching varieties or about 80 from early branching varieties. The two-noded stakes are planted in propagation chambers to produce shoots in quantities that depend on the variety and type of stake used. Thus, varieties with little vigor soon cease to produce shoots, while others continue producing them even after 1 year.

On the average, a stake with two buds produces eight shoots a year, cutting every 20 days, in alternate form, a shoot from each bud. This means that, from one late-branching adult plant about 800 shoots can be obtained in 1 year. The procedure is as follows:

- High-yielding, healthy, and mature plants of about 10 months old are selected from the field.
- Stakes with two buds are cut, using a saw disinfected with sodium hypochlorite, formol, or alcohol.
- The stakes are chemically treated by immersion for 5 min in a solution of one or more fungicides and including insecticides.
- The stakes are planted in a horizontal position in a substrate composed of sand and soil, placed on a gravel base that provides good drainage. The substrate must be placed into beds that measure 2.3 × 1.2 × 0.2 m, surrounded by a narrow groove into which water is deposited that, on evaporating, maintains high relative humidity.
- A roof of transparent plastic covers the container and groove, being placed in such a way that it forms a propagation chamber. The high temperature and high relative humidity stimulate sprouting in the buds (Figure 4-9).
- When they are 5–10 cm tall, the shoots are cut at 1 cm above the neck, using a sharp blade that has been disinfected with one of the products mentioned above. Each stake of two buds can provide about eight shoots, depending on the variety and vigor of the stake.
- From each shoot, leaves are cut off, leaving only those of the crown to prevent wilting. The little stem is cut exactly below a bud to stimulate rooting. Immediately afterwards, the shoots are placed in a container of cold boiled water to stop latex from escaping (Figure 4-10).
- To encourage rooting, the shoots are passed to bottles containing water, which are then placed in a rooting chamber, comprising a table carrying an aluminum or wooden structure that supports a plastic cover.

Figure 4-9. Humid chamber.

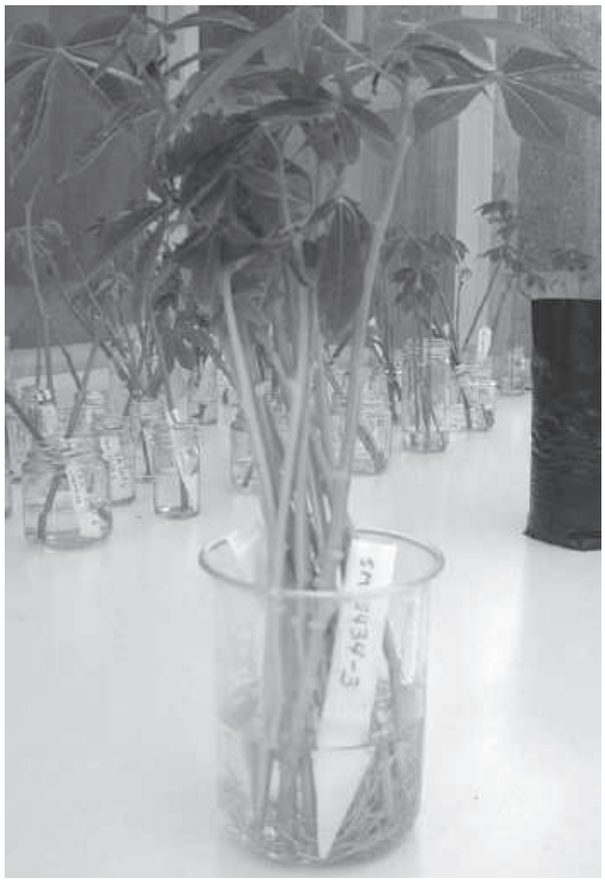


Figure 4-10. Shoots in water for rooting.

Figure 4-11. Plants in plastic bags.

- After 2 or 3 weeks, the shoots are ready for planting, either directly in the field or in plastic bags, where they acclimatize for their later transplanting (Figure 4-11). Acclimatization should preferably be done in a screenhouse with a special mesh that prevents entry of insects such as whiteflies that carry viral diseases (Figure 4-12).

One of two work modalities can be chosen. The first is *continuous production of planting materials*, where, every 3 weeks—the frequency of the cut—workers take to the field those shoots already acclimatized, in such a way that, by the 18th cut, 1 year has been completed. The shoots of the first cut will have become adult plants. The final total would be 8000 stakes, 20 cm long, from each mother plant.

The second modality is the *acquisition of shoots over 9 weeks*. If we take as an example planting in the first semester (April–May), then the next planting must

Figure 4-12. Screenhouse with a special mesh to prevent the transmission of viruses by insect vectors.

be done in January, in humid chambers, as, at this time, the mother plants planted in the previous season will be 8 to 9 months old. Planting in the chambers cannot be carried out any earlier because the mother plants will have little planting material.

On planting in January, the first cut is made in February. If cuts are made every 20 days, then a total of four cuts of shoots would be ready for planting before the rainy season ends. Under these conditions, about 300 shoots would be obtained and converted into plants and harvested all at the same time a year later, producing about 3000 commercial stakes.

b. Leaf-and-bud cuttings. Although more equipment is required than for the shoot acquisition system, its potential for propagation is much greater. That is, in 1½ years, about 60,000 stakes can be produced from a single mother plant. It consists of inducing the rooting of a bud that is removed, together with its corresponding leaf. The procedure is as follows:

- Well-developed leaves are cut from selected 3 to 4-month-old plants, using a sharp disinfected blade. The cut must include a small piece of stem. The folioles are also trimmed to less than half their length.

- The cuttings are immediately placed in a container with cold boiled water to prevent latex from escaping.

- They are then taken to the rooting chamber, which consists of a metallic table provided with an aluminum structure that is itself covered with plastic. The chamber has two sides where the plastic can be opened like a curtain to place or remove materials and permit aeration. In the upper part of the structure, very fine sprinklers are placed to continually mist the cuttings for 12 h per day.

- The cuttings are planted in plastic or asbestos trays, containing a substrate of sterilized coarse sand. The trays are placed on the table. The leaves are left at an angle, supported by wire rows placed at 20 cm from the table's surface.

- Between 8 and 15 days, when the roots are about 1 cm long and the petiole has detached, the shoots are ready for planting into plastic bags for acclimatization over 3 weeks in a screenhouse. They are then taken to the field and in 5 months will become new mother plants from which new leaf-and-bud cuttings may be obtained for propagation.

References

To save space, the acronym "CIAT" is used instead of "Centro Internaccional de Agricultura tropical".

Álvarez E; Barragán MI; Madriñan R. 1998. Pudrición radical y marchitez de la yuca. Information bulletin. CIAT; Universidad Nacional de Colombia, Cali, Colombia.

Bellotti AC; Schoonhoven A van. 1978. Plagas de la yuca y su control. CIAT, Cali, Colombia. 73 p.

Bellotti AC; Reyes Q, JA; Arias V, B; Vargas H, O. [1983]. Insectos y ácaros de la yuca y su control. In: Domínguez CE, ed. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (UNDP). Cali, Colombia. p 367–391.

CIAT. 1975. Informe anual 1975. Cali, Colombia.54 p.

CIAT. 1983. Informe anual 1983. Cali, Colombia.

CIAT. 1987a. Annual report 1986 [of the] Cassava Program. Cali, Colombia.

CIAT. 1987b. Selección y preparación de estacas de yuca para siembra—Guía de estudio para ser usada como complemento de la unidad audiotutorial sobre el mismo tema. Scientific contents: JC Lozano; JC Toro; A Castro; AC Bellotti. Cali, Colombia. 26 p.

Cock JH. 1989. La yuca, nuevo potencial para un cultivo tradicional. CIAT, Cali, Colombia. 240 p. (*Also available in English as Cock JH. 1985. Cassava: new potential for a neglected crop. Westview Press, Boulder, CO, USA.*)

Connor DJ; Cock JH; Parra G. 1981. Response of cassava to water shortage, 1: Growth and yield. Field Crops Res 4(1):181–200.

Enyi BAC. 1970. The effect of age on the establishment and yield of cassava sets (*Manihot esculenta* Crantz). Beitr Trop Subtrop Landwirtsch Tropenveterinarmedizin 8(1):71–75.

Gurnah AM. 1974. Effects of method of planting and the length and types of cuttings on yield and some yield components of cassava grown in the forest zone of Ghana. Ghana J Agric Sci 7(2):103–108.

Howeler RH. 1981. Nutrición mineral y fertilización de la yuca. CIAT, Cali, Colombia. 55 p.

Hunt LA; Wholey DW; Cock JH. 1977. Growth physiology of cassava. Field Crops Abstr 30(2):77–91.

Leihner DE. 1986. Physiological problems in the production of the cassava planting material. In: Cock JH, ed. Global workshop on root and tuber crops propagation—Proc regional workshop held at CIAT, Cali, Colombia, 1983. CIAT, Cali, Colombia. p 57–72.

López J. 1990. Producción comercial de semilla de yuca. Seed Unit [of] CIAT, Cali, Colombia. 33 p.

Lozano JC. [1983]. El peligro de introducir enfermedades y plagas de la yuca (*Manihot esculenta* Crantz) por medio de material vegetativo de propagación. In: Domínguez CE, ed. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (UNDP), Cali, Colombia. p 475–484.

Lozano JC. 1987. Alternativas para el control de enfermedades en yuca—Reunión de trabajo sobre intercambio de germoplasma: cuarentena y mejoramiento de yuca y batata. CIAT; Centro Internacional de la Papa (CIP), Cali, Colombia.

Lozano JC. 1991. Control integrado de enfermedades en yuca. Fitopatol Venez 4(2):30–36.

Lozano JC; Jayasinghe U. [1983]. Problemas fitopatológicos en la yuca diseminados por semilla sexual y asexual. In: Domínguez CE, ed. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (UNDP), Cali, Colombia. p 485–490.

Lozano JC; Laberry R. 1993. Hongos endófitos también en yuca. Bol Inf 17(2):5–6.

Lozano JC; Pineda B; Jayasinghe V. 1984. Effect of cutting quality on cassava performance. In: Symposium of the 4th International Society for Tropical Root Crops. Centro Internacional de la Papa (CIP), Lima, Peru.

Lozano JC; Bellotti AC; Vargas O. 1986. Sanitary problems in the production of cassava planting material. In: Cock JH, ed. Global workshop on root and tuber crops propagation—Proc regional workshop held at CIAT, Cali, Colombia, 1983. CIAT, Cali, Colombia. p 73–85.

Luna JM. 1984. Influencia de armazenamento de manivas de mandioca na produção de raizes e ramas. MSc thesis. Escola Superior de Agricultura de Lavras, Lavras, MG, Brazil. 100 p.

Mohankumar B; Kabeerathumma S; Nair PG. 1984. Soil fertility management of tuber crops. Indian Farming (spec issue) 33(12):35–37.

Villamayor Jr, FG. 1983. Root and stake production of cassava at different populations and subsequent yield evaluation of stakes. Philipp J Crop Sci 8(1):23–25.

CHAPTER 5

Soils and Fertilizers for the Cassava Crop

Luis Fernando Cadavid L.[1]

Introduction

Soil is usually studied as an "entity" in which the plants grow and develop. Yet, it should be considered as a *dynamic system* from the viewpoint of *fertility* and *productivity*. When considering crop nutrition, specifically cassava (*Manihot esculenta* Crantz), the relationships between soil, plant, and water should be taken into account and not only each factor separately. That is, the three factors should be studied as *a whole*.

Another important aspect of plant nutrition is the subject of fertilizer application as a management practice for recovering, sustaining, and maintaining soil fertility and increasing crop productivity. Overall, considerable ignorance exists on the adequate interpretation of the chemical and physical analyses of soil that form the basic diagnosis tools for recommending chemical or organic fertilizers.

A principal objective of this chapter is to bring readers up to date on concepts relating to nutrition of the cassava crop, basic aspects of soil, and how to make correct recommendations for fertilizers as a soil management practice.

Soil and Its Productivity

Traditional definition

Soil is a dynamic system that is usually composed of four phases: solid, liquid, gaseous, and biological. Figure 5-1 shows the ideal volumetric conditions of a soil for normal plant growth.

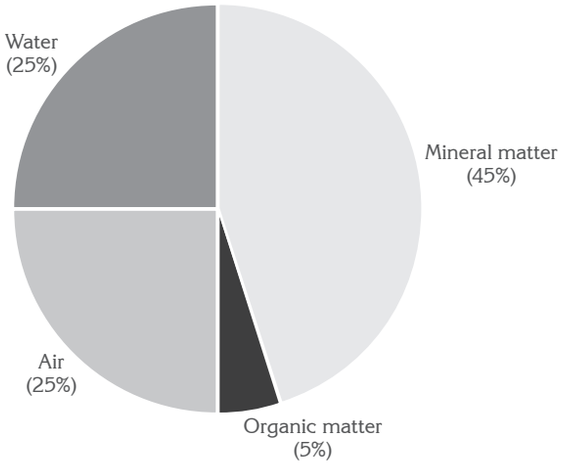


Figure 5-1. A soil's ideal volumetric condition for plant growth.

Logic supposes that this condition is not met and that soils present a real condition, which determines their potential for production. To better understand this point, we use two examples: a sandy soil located in Pivijay, Magdalena, Colombia, and another, clay, soil located in Santander de Quilichao, Cauca, also in Colombia (Figures 5-2 and 5-3).

These soils were continuously planted to cassava for 8 and 2 years, respectively. As observed, the volumetric percentage in each case is different, requiring different management (Cadavid L 2000).

A sandy soil has a higher percentage of macropores, more aeration, less water retention, less organic matter content and, thus, less N availability. In contrast, the clay soil has a higher number of micropores, less aeration, higher water retention, more organic matter content and, as a result, a higher cation exchange capacity (CEC)[2].

1. Soil Agronomist, formerly of Cassava Production Systems, CLAYUCA, Cali, Colombia.
E-mail: luisfernandocadavidlopez@yahoo.es

2. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

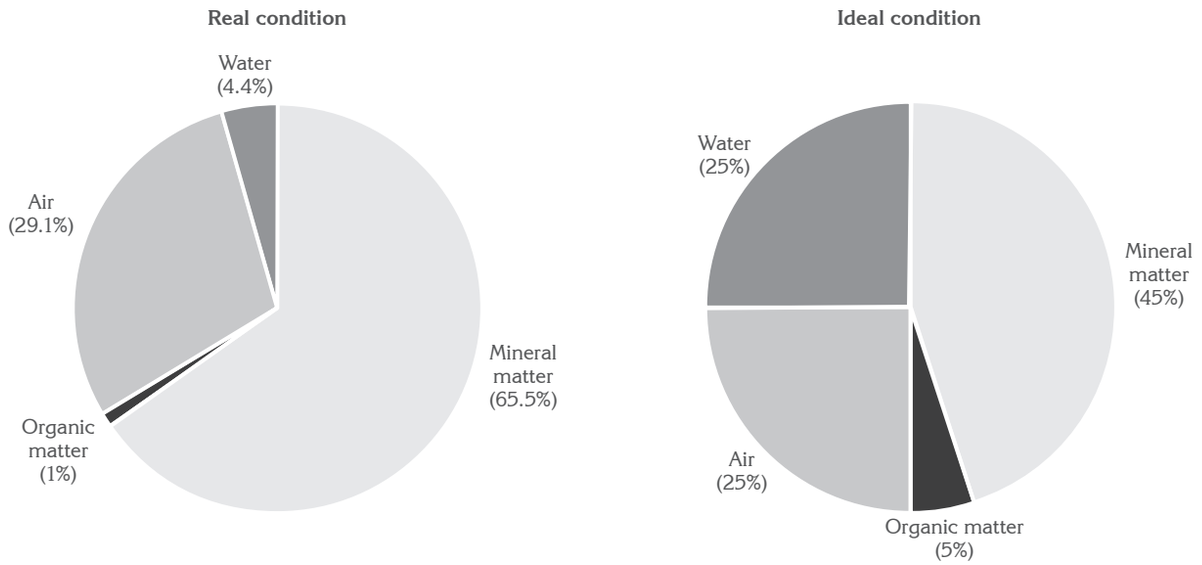


Figure 5-2. Comparing the ideal soil condition with the reality of a sandy soil in Pivijay, Magdalena, Colombia, planted to cassava over 8 consecutive years.

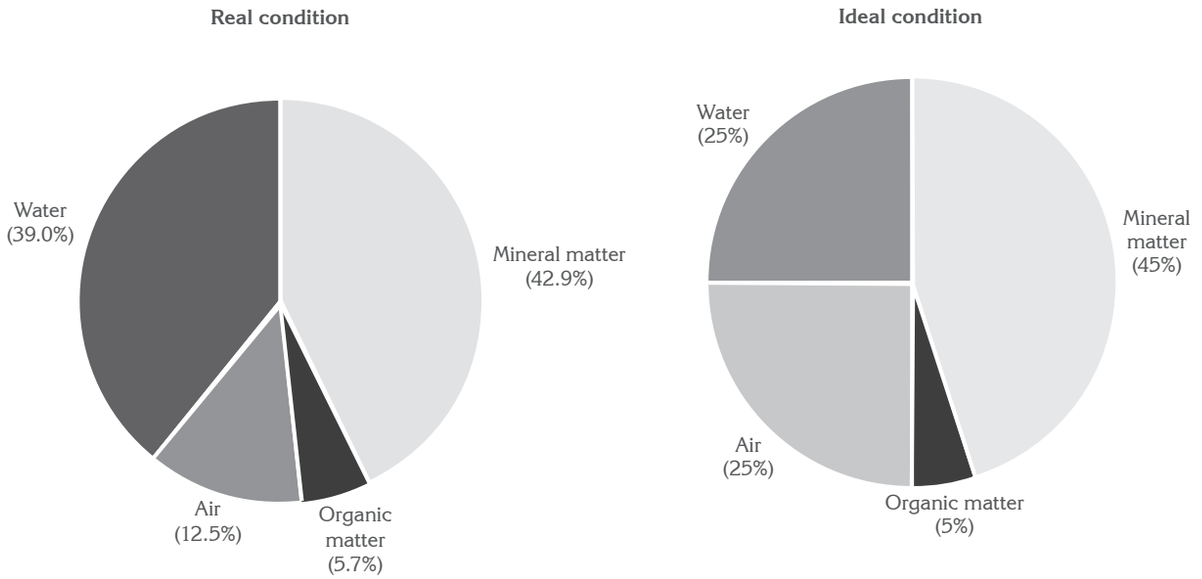


Figure 5-3. Comparing the ideal soil condition with the reality of a clay soil in Santander de Quilichao, Cauca, Colombia, planted to cassava over 2 consecutive years.

Agricultural definition

For agricultural purposes, soil should be studied from two viewpoints: fertility per se and productivity. To understand soil productivity, the soil–plant–water relationship must be studied. In these terms, soil is a *dynamic system* formed by five well-defined phases that interact with each other (Guerrero 1980, cited by Cadavid L 1995):

- Solid phase
- Liquid phase (soil solution)
- Exchange phase
- Root phase
- Aerial parts phase (foliage)

Figure 5-4 shows the nutrient dynamics in the soil–plant system. The topics treated below are considered basic to the mineral nutrition of the cassava crop.

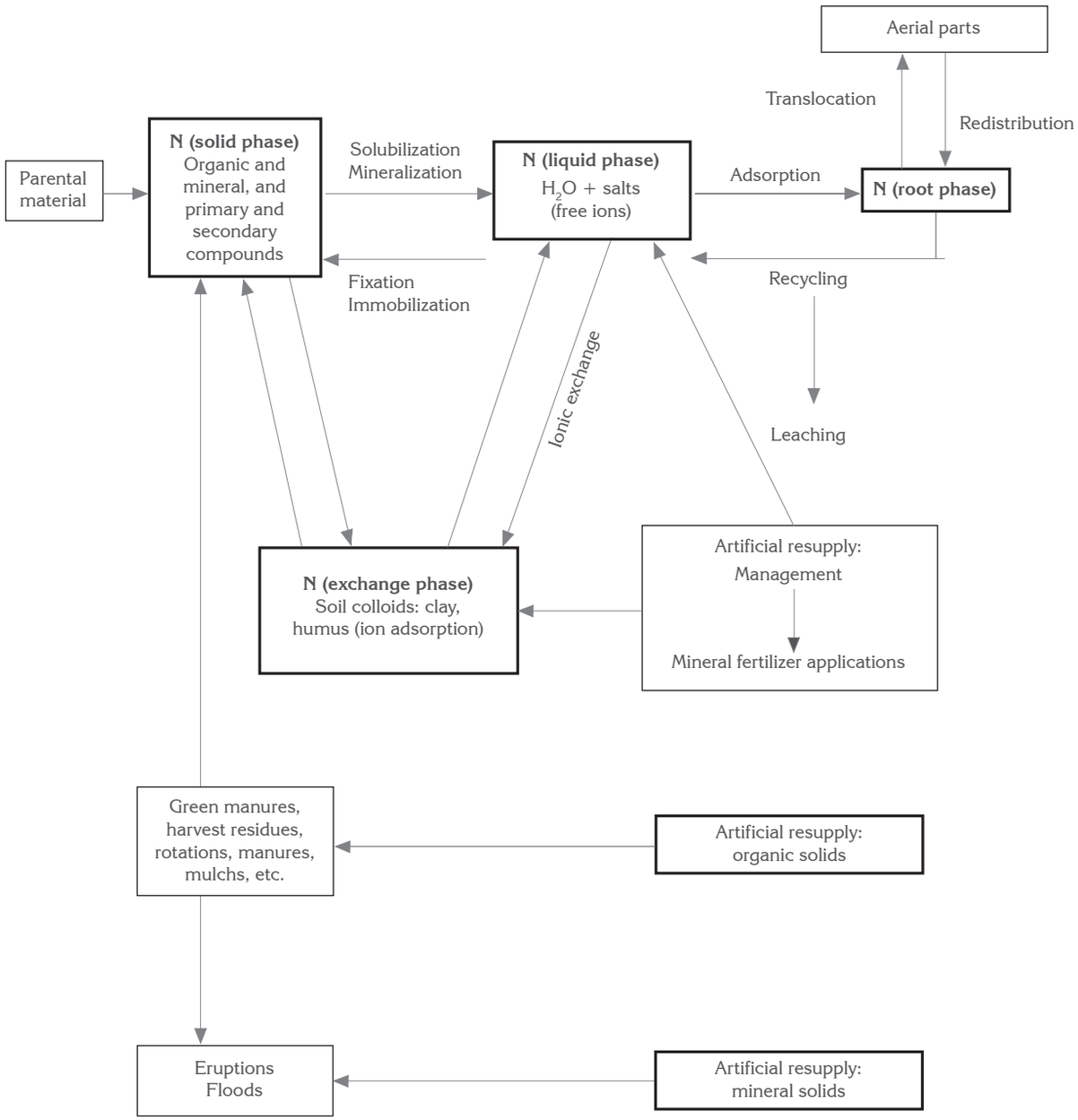


Figure 5-4. Components of the soil–plant system and the dynamics of nutrients (adapted from Guerrero 1980).

Soil solid phase. Its basic component comprises the parental materials made up of different rocks (igneous, sedimentary, and metamorphic). These, through weathering, contribute organic and inorganic solid matter to form soils. This matter is, in itself, insoluble. Plants cannot receive nutrients from it until it undergoes physical, chemical, and biological transformation.

Solid matter undergoes solubilization (inorganic solids) and mineralization (organic solids). As a result, it contributes to the soil nutrients (free ions) that can easily be taken up by plants. When this happens, the soil enters phase two (liquid phase) (Cadavid L 2000).

Soil liquid (soil solution) phase. This is made up of elements (free ions + water) contributed by the soil solid phase, through solubilization and mineralization. This stage, which nourishes the plant, in its turn, becomes exhausted very rapidly. Many of these nutrients are easily lost through leaching (e.g., Ca, Mg, K, and NO_3).

Other losses (irreversible) also occur through fixation and immobilization. Fixation occurs when soil nutrients, especially N, P, and K, become part of insoluble compounds and therefore difficult for plants to assimilate. Radicals such as NH_4^+, $H_2PO_4^-$, and K^+ remain lost from this phase through this process. When this happens with the participation of soil microorganisms (e.g., fungi, bacteria, and actinomycetes), organic matter becomes immobilized and the contribution of nutrients such as N, P, and S is reduced.

As this phase becomes exhausted through the losses previously described, uptake of nutrients by plants, and erosion, nutritional resupply occurs through ionic exchange in the soil exchange phase (Guerrero 1980; Cadavid L 2000).

Soil exchange phase. This phase is made up of clays, organic matter, and Fe and Al oxides and hydroxides (soil colloids), the constituents of which are minerals and organic solids in the soil. These colloids are responsible for chemical activity in soils. Hence, this phase is in continuous interaction with the liquid phase through ionic exchange in the soil. It restores nutrients exhausted in the liquid phase by the previously cited processes.

Ionic exchange is a phenomenon based on the presence of negative charges in clays and other soil colloids (Cassanova O 1996). Through these charges, ions are released from minerals previously subjected to weathering, or from decaying organic compounds, rainwater, irrigation water, and fertilizers. The ions can be *adsorbed* by soil particulates and, under these conditions, they are partially retained. However, such retention is sometimes not sufficient to prevent ions from being either exchanged with other ions in the soil solution or adsorbed by the plant's root system. According to Thompson (1965), Garavito (1979), and Cassanova O (1996), those ions weakly held on the surfaces of particulates in direct contact with soil solution can be rapidly replaced in exchange reactions. These ions are called *exchangeable*.

Other ions can be adsorbed with such tenacity or be located in barely accessible positions that their release or release is either hindered or it is very slow. These ions are called *non-exchangeable*. Potassium is an example of this situation, when it is held between laminas in the crystalline structure of *illite* and *micas*. Figure 5-5 illustrates the attraction of cations (+) for soil colloids (-).

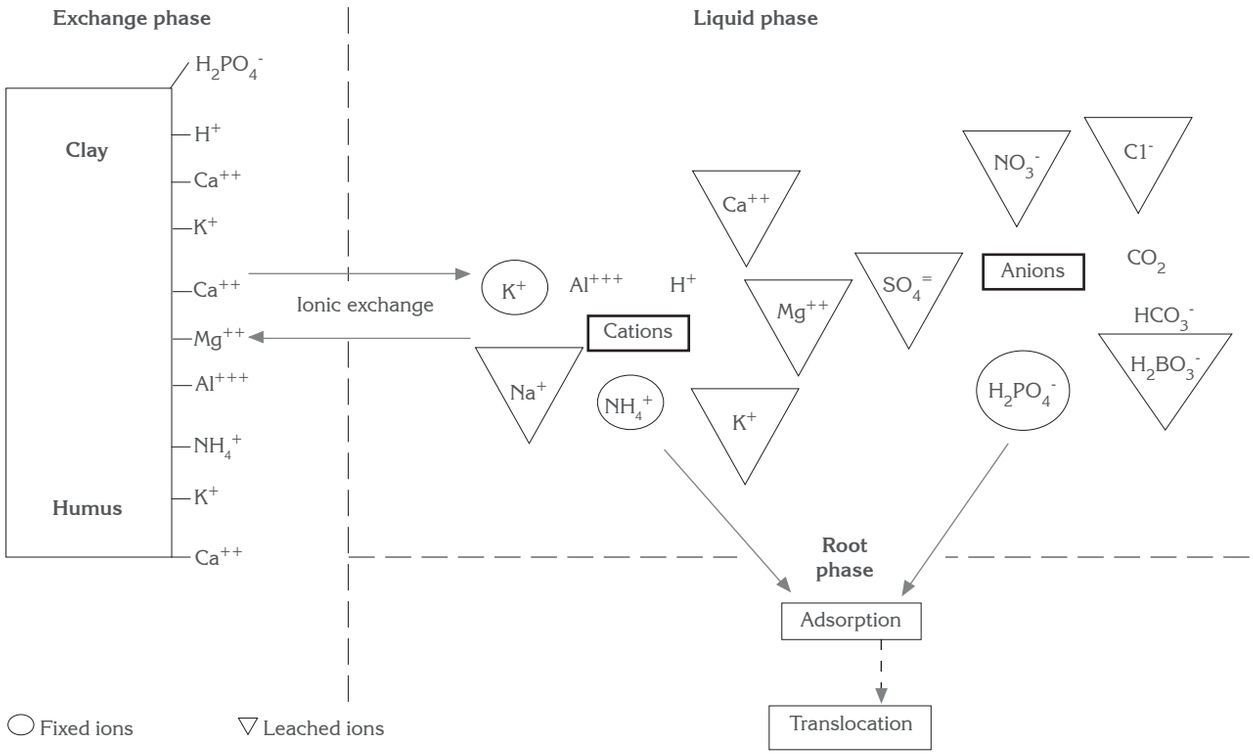


Figure 5-5. Exchange, liquid, and root phases of the soil, showing the dynamics of different ions.

The strength with which cations can be retained in exchange sites is as follows (Cassanova O 1996):

$$Al^{+3} > Ca^{+2} = Mg^{+2} > K = NH_4^{+} > Na^{+}$$

The CEC of a soil is defined as the quantity of cations retained in an exchangeable form within a given pH and is expressed in meq/100 g of soil (cmol/kg). Table 5-1 outlines data on the CEC of different soil components (meq/100 g of matter), as according to Cassanova O (1996).

From these data a soil's exchange matter can be deduced through its CEC. For example, if a soil has a CEC of 10 meq/100 g of soil, then *kaolinite* probably forms the predominant part of that soil's clay fraction, that is, clay 1:1, with little activity.

Root phase.

Adsorption. Soil nutrients are continually removed by the growing plant through adsorption. This is the process by which the element N leaves the substratum (nourishing solution), reaches a part of any root cell, and is then transported by xylem to other plant organs (Malavolta et al. 1989). Nitrogen is an element that may be:

- *Essential*, that is, the plant cannot complete its normal life cycle in the nutrient's absence (Garcidueñas 1993).
- *Beneficial:* It increases growth or production under given conditions.
- *Toxic*, by diminishing growth or production, or even causing death of tissues, organs, or the entire plant.

Table 5-1. Cation exchange capacity (CEC) of different soil components.

Exchange material	CEC (meq/100 g)	
	Average	Range
Organic matter	200	100–300
Vermiculite	150	100–150
Montmorillonite	80	60–100
Chlorite	30	20–40
Illite	30	20–40
Kaolinite	8	2–16
Sesquioxides	0–3	0–3

SOURCE: Cassanova O (1996).

In practical terms, a plant can very capably adsorb those elements necessary for its metabolism, even from relatively low concentrations in the soil. What is important is that this element is always present in the liquid phase that surrounds the roots (Calderón 1991). Adsorption depends on several factors (Malavolta et al. 1989; Calderón 1991; INPOFOS 1993), including:

- Availability of the element
- Soil moisture
- Aeration
- Organic matter content
- pH

Soil pH and availability. Soil pH has a major, direct influence on the solubility and availability of elements in the soil. When any symptom is observed in the field, the pH of the soil in which the plant is growing should be measured. Often, this factor is closely related to the causes of the symptom. Cadavid L (1980) reported P deficiency and low crop yields for cassava grown in Colombian Oxisols, Ultisols, and Inceptisols (soils with pH < 4.5), where the content of usable P (method Bray II) is < 3.0 ppm (for cassava, the critical level is 10 ppm). This is a clear example of low availability of an element being related to soil pH (Table 5-2).

Usually, adsorption is more intense in the 6.0 to 6.5 band of pH. At higher acidity (very low pH values), the availability of N, P, K, Ca, Mg, S, B, and Mo diminishes, whereas that of Cu, Fe, Mn, and Al increases. At high pH values (alkalinity), the availability of P, B, Cu, Fe, Mn, Zn, and Al diminishes, whereas that of Mo, S, and K increases (Figure 5-6).

Chemical fertilizer applications (especially of nitrogenous fertilizers such as ammonium sulfate), leaching of bases, carbonic acid excretion by plants, and high nutrient extraction (especially N, K, Ca, and Mg) contribute to soil acidification. An example of this situation was presented in a sandy soil of Pivijay, Magdalena, Colombia, which had been planted to cassava for 8 consecutive years (Table 5-3).

Other external factors that affect adsorption are aeration, soil temperature, speed of element adsorption, and presence of other ions.

Presence of other ions. As stated earlier, soil solution consists of a heterogeneous mixture of ions that includes essential, beneficial, or toxic elements. The speed of absorption of an element (anions: $NO_3^{-} > Cl^{-} > SO_4^{-2} > H_2PO_4^{-}$; cations: $NH_{4+} > K^{+} > Na^{+} > Mg^{+2} > Ca^{+2}$) can be increased, reduced, or

Table 5-2. Effect of applications of phosphorus, according to sources of differing pH, on cassava yield (t/ha) at 12 months old, Carimagua, Colombian Eastern Plains, in soils with pH below 4.5 and P less than 3 ppm.

Source	Yield[a] (kg/ha) at the level of P_2O_5 of:					
	0	50	100	200	400	X_n
	(kg/ha)					
Check	6.5	—	—	—	—	6.5
Triple superphosphate, applied in bands	—	13.9	19.8	18.4	22.3	19.9
Simple superphosphate, applied in bands	—	10.8	13.7	19.0	22.2	16.4
Mg phosphate, broadcast in bands	—	8.2	13.1	11.2	13.7	11.6
Basic slag (Thomas), applied in bands	—	10.9	10.9	11.9	13.8	11.9
Basic slag (Thomas), broadcast	—	16.1	19.8	20.9	25.2	20.5
Phosphoric rock (PR) (Huila) at 20% acidulated, broadcast	—	14.4	18.4	19.6	22.5	18.7
PR (Huila) + S, broadcast	—	15.7	19.7	21.6	21.8	19.7
PR (Huila), broadcast	—	13.0	17.4	18.9	19.6	17.2
Average of treatments	6.5	12.9	16.6	18.4	20.1	

a. Average of two checks.

SOURCE: Cadavid L (1980).

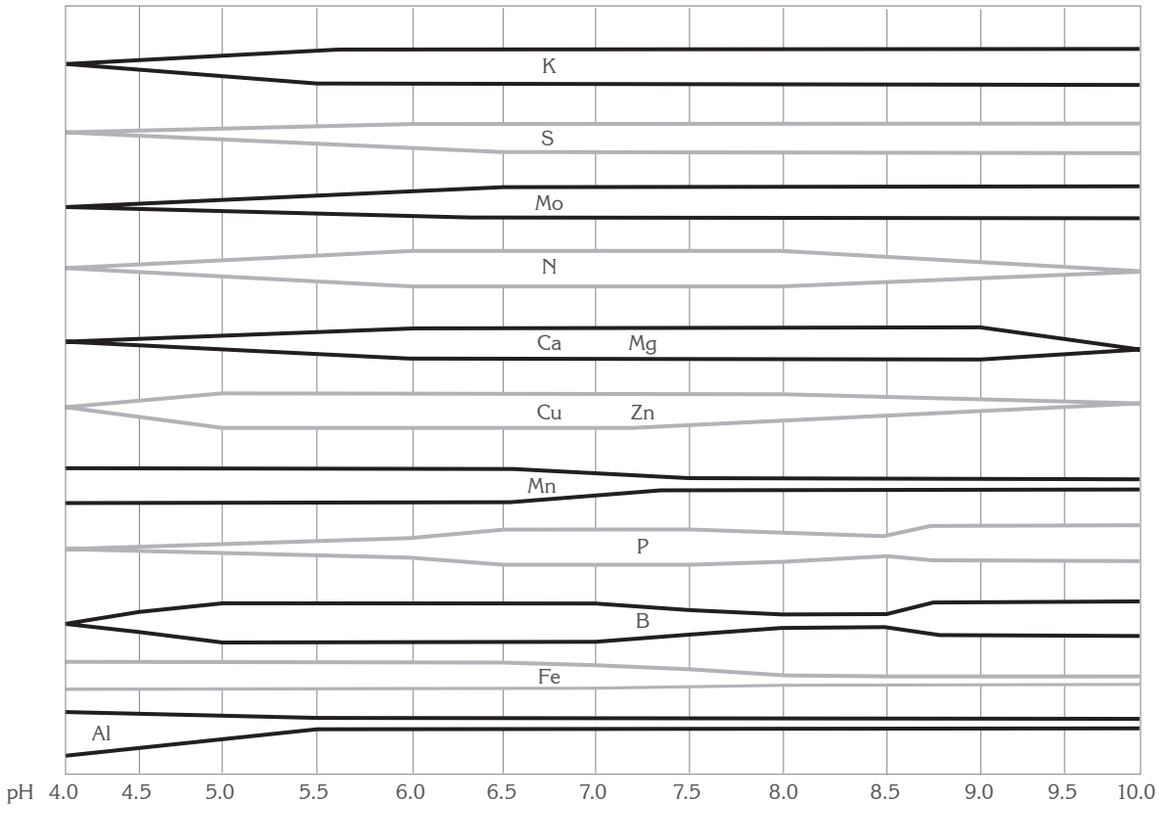


Figure 5-6. Availability of different nutrients in the soil with respect to pH.

Table 5-3. Monitoring of a sandy soil in Pivijay, Magdalena, Colombia, planted continuously over 8 years to cassava and with no chemical or organic fertilizer applications.

Year	pH	P (ppm)	K	Ca	Mg	Fertility
			(meq/100 g soil)			
1	6.50	8.38	0.05	0.87	0.28	Low
2	5.60	7.10	0.03	0.65	0.20	
3	5.30	4.70	0.04	0.55	0.13	
4	5.30	5.70	0.03	0.48	0.12	
5	5.30	6.35	0.04	0.43	0.11	
6	5.35	8.25	0.04	0.34	0.07	
7	4.85	7.65	0.05	0.35	0.09	
8	4.15	5.18	0.03	0.32	0.09	Very low

SOURCE: Cadavid L (2000).

otherwise influenced by the presence of another. These influences are commonly called relationships of antagonism, inhibition, and synergism:

- *Antagonism:* The presence of an element reduces the adsorption of another, thus preventing toxicity. For example, Ca^{+2} impedes excess adsorption of Cu^{+2} or Al^{+3}.

- *Inhibition:* Reduced adsorption of an element induced by the presence of another ion, usually causing deficiency. For example, K^{+} versus Ca^{+2} or Mg^{+2}; Al^{+3} versus $H_2PO_4^{-}$; Al^{+3} versus Ca^{+2} or Mg^{+2}; $H_2PO_4^{-}$ versus Zn^{+2}; Ca^{+2} versus K^{+} (in high concentration); and Ca^{+2} versus Zn^{+2}. Cadavid L et al. (1977) reported an example of this situation in the soils of the Eastern Plains of Colombia (Oxisols; Figure 5-7).

- *Synergism:* The presence of a given element increases the adsorption of another. For example, Ca^{+2} in low concentrations increases absorption of K^{+} or of $H_2PO_4^{-}$; Mg^{+2} versus $H_2PO_4^{-}$; and $H_2PO_4^{-}$ versus MoO_4^{-2}. This circumstance may have practical consequences in fertilizer application, as it represents a greater economy and better use of mineral fertilizers.

For cassava grown in acid-soil Oxisols, an application of 500 to 1000 kg/ha of dolomitic lime may increase P availability and its adsorption, because of the presence of Mg^{+2} and Ca^{+2} ions. Table 5-4 shows examples of the effect between ions.

Presence of mycorrhizae. Mutualistic symbiotic associations exist among the roots of many plants and

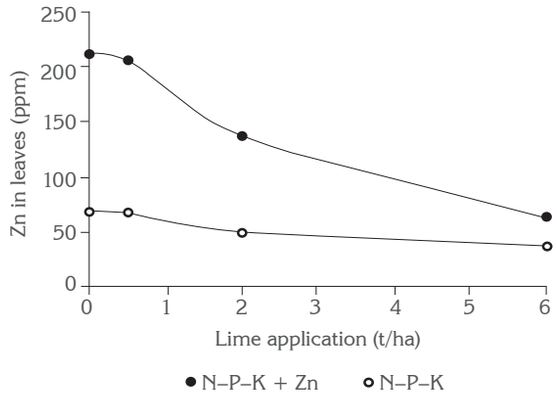


Figure 5-7. Effect of lime applications on Zn content in cassava leaves at 2 months, with or without applications of Zn to soil, Carimagua, Eastern Plains, Colombia (from Cadavid L et al. 1977).

Table 5-4. Effect of ions on each other in soil solution phase.

Ion	Second ion present[a]	Effect of the second on the first[b]
Cu^{2+}	Ca^{2+}	Antagonism
Mg^{2+}, Ca^{2+}	K^{+}	Competitive inhibition
$H_2PO_4^{-}$	Al^{3+}	Non-competitive inhibition
K^{+}, Ca^{2+}, Mg^{2+}	Al^{3+}	Competitive inhibition
H_2BO_3	NO_3^{-}, NH_4^{+}	Non-competitive inhibition
K^{+}	Ca^{2+} (hc)	Competitive inhibition
SO_4^{2-}	SeO_4^{2-}	Competitive inhibition
MoO_4^{2-}	Cl^{-}	Competitive inhibition
Zn^{2+}	SO_4^{2-}	Competitive inhibition
Zn^{2+}	Mg^{2+}	Competitive inhibition
Zn^{2+}	Ca^{2+}	Competitive inhibition
Fe^{2+}	H_2BO_3	Non-competitive inhibition
Zn^{2+}	Mn^{2+}	Competitive inhibition
K^{+}	$H_2PO_4^{-}$	Non-competitive inhibition
MoO_4^{2-}	Ca^{2+} (lc)	Synergism
MoO_4^{2-}	$H_2PO_4^{2-}$	Synergism
Cu^{2+}	MoO_4^{2-}	Non-competitive inhibition

a. hc = high concentration; lc = low concentration.
b. See text for explanation of terms.

SOURCE: Malavolta et al. (1989).

certain soil fungi. The plant receives nutrients through the mycelia of the fungus and this, in turn, receives carbohydrates from the plant (Cano 1999; Sánchez de P 1999). Plants that have been inoculated with mycorrhizae, in this case, cassava, possess an increased adsorption surface, adsorbing, in particular, P ions from the soil when concentrations of this element are low. Tables 5-5 and 5-6 show the action of vesicular-arbuscular mycorrhizae (VAM) in soils of Cuba and Colombia (Sieverding 1984; INIVIT 1999).

Table 5-5. Combined effect of mycorrhizae and N–P–K fertilizer on the production of cassava clone 'Señorita' under field conditions, Cuba.

Treatment	Fresh roots (t/ha)[a]
Check	42.3 c
Mycorrhizae	49.3 b
Myco. + 25% N–P–K	50.4 b
Myco. + 50% N–P–K	51.1 b
Myco. + 75% N–P–K	51.4 b
Myco. + 100% N–P–K	61.6 a
100% N–P–K	52.0 b
CV%	3.87
SE (+ or –)	1.17

a. Values with the same letters in the column are not significantly different at.

SOURCE: INIVIT (1999).

The mycorrhizae that affect the absorbent roots of cassava and many other crops belong to the group known as vesicular-arbuscular endomycorrhizae. Their hyphae *grow between and within* root cortex cells, producing ramifications within them. These are called arbuscules and vesicles. Hyphae also grow in soil, where they can extend for several centimeters along roots (Howeler 1983). Other more common, but also efficient fungi found in the cassava crop include *Glomus manihotis*, *Entrophospora colombiana*, and *Acaulospora mellea* in Colombian soils.

Aerial parts phase.

Accumulation and distribution of dry matter in cassava. The concentration of nutrients in cassava varies considerably between plant parts and also during the growth cycle (Howeler 1983; Cadavid L 1988a). As the plant grows, N, P, and K contents decline in leaves (leaf blade and petiole), but tend to increase in stems and roots.

In a study conducted by Howeler and Cadavid L (1983), the authors indicated that, with cv. M Col 22, the roots accumulated, at the end of the 12-month cycle, sufficient N, P, K, Cu, Fe, and B; whereas Ca, Mg, S, Mn, and Zn accumulated mainly in the stems. The authors also found that the maximum increase in nutrient accumulation during the growth cycle occurred between 2 and 4 months after planting. This period corresponded to the maximum accumulation of dry matter for M Col 22 and other cultivars. After 6 months, the adsorption rate for most nutrients declined.

Nijholt, cited by both Howeler (1981) and Howeler and Cadavid L (1983), indicated that total accumulation of dry matter continues throughout the growth cycle. However, it declines in leaf blades and petioles after 6 months, whereas it increases until the end of the cropping cycle in stems and roots.

Tables 5-7 and 5-8 show the accumulation of dry matter and nutrients of different cassava cultivars in the acid soils of Santander de Quilichao, Cauca, Colombia (El-Sharkawy et al. 1998).

Nutrient extraction. The cassava crop extracts large amounts of nutrients from the soil, sufficient to be considered as an extra loss. Table 5-9 describes the average nutrient extraction (kg/ha) per ton of harvested fresh roots. The high export of elements, particularly N, K, and Ca, is notable (Howeler and Cadavid L 1983; Cadavid L 1988a, 1995, 1997).

Nutritional disorders of the crop. The plant, in itself, determines its "state of health". When stress occurs through scarcity or excess of water, deficiency or toxicity of a nutrient, or physical or mechanical injury to organs, the plant manifests *characteristic symptoms* that indicate that something is wrong. This condition of *anomaly* manifesting in one or more symptoms becomes another tool for diagnosis (see below under *Deficiencies and toxic effects …*).

In cassava, the frequent absence of clear symptoms of macronutrient deficiency means that nutritional problems can be easily overlooked (Howeler

Table 5-6. Effectiveness of different species of vesicular-arbuscular mycorrhizae (VAM) for the cassava crop, Colombia.

Species	Cassava growth	Effectiveness for:		Capacity to compete with other microorganisms
		P adsorption	Root length	
Glomus manihotis	High	High	Average	High
Entrophospora colombiana	High	High	High	Little
Acaulospora mellea	Average	Average	High	Average

SOURCE: Sieverding (1984).

Table 5-7. Biomass of aerial parts and tuberous root yield (t/ha, dry weight) of cassava plants with high, medium, and low height. Means taken at 2, 4, 6, and 10 months after planting, Santander de Quilichao, Cauca, Colombia.

Height of cultivar	Yield (t/ha) of aerial biomass at months:							
	2	4	6	10	2	4	6	10
	1994/95				1995/96			
Tall								
CG 402-11	0.3	2.3	3.6	7.1	0.2	2.3	5.5	8.8
M Pan 51	0.3	1.8	4.9	4.7	0.3	2.5	3.4	5.0
Average								
CM 507-37	0.2	2.4	2.6	3.7	0.3	2.6	3.2	5.6
SG 107-35	0.3	1.3	1.7	3.2	0.3	2.3	2.3	4.9
Short								
CG 1141-1	0.2	1.2	1.8	2.6	0.2	1.4	1.8	2.1
M COL 22	0.2	1.4	1.2	3.0	0.2	1.5	1.3	2.0

Height of cultivar	Tuberous root yield (t/ha) at months:							
	2	4	6	10	2	4	6	10
	1994/95				1995/96			
Tall								
CG 402-11	0.01	0.9	1.5	9.2	0.01	0.6	5.4	14.5
M Pan 51	0.01	1.6	2.4	8.7	0.01	1.2	5.0	8.6
Average								
CM 507-37	0.01	1.7	2.6	11.6	0.02	1.4	5.8	13.2
SG 107-35	0.02	2.3	2.9	11.0	0.02	1.9	6.5	11.7
Short								
CG 1141-1	0.01	2.6	4.0	15.0	0.01	1.6	6.2	10.3
M COL 22	0.01	2.2	2.7	9.7	0.01	1.9	5.4	7.3

SOURCE: El-Sharkawy et al. (1998).

1981). In such cases, the state of availability of soil nutrients must be known and confirmed by plant tissue analyses and the plant's responses to fertilizer applications.

Sometimes, symptoms of nutritional disorders can be confused with those of fungal diseases such as necrosis caused by anthracnose, insect attack (e.g., Zn deficiency with thrip attack), herbicidal damage (chlorosis and necrosis), and poor drainage and excess water (chlorosis or yellowing of leaf blades).

Mobility of nutrients in the phloem. When attempting to detect nutritional deficiency by observation of visual symptoms, the mobility of nutrients in the phloem should be taken into account (Table 5-10). According to Howeler (1981), Kramer (1989), Malavolta et al. (1989), and Calderón (1991), some ions are distributed more easily than others and can show very different mobility within the phloem. According to this criterion, deficiency symptoms are expected to first appear in cassava plants as follows:

- Mobile elements in lower and older leaf blades. These leaf blades yield their nutrients by phloematic translocation to the youngest leaf blades.
- Elements of intermediate mobility in young plant parts and expanded leaf blades (upper leaf blades).
- Immobile elements in young meristematic leaf blades and root meristems. The elements present in the old leaf blades are not translocated to the youngest leaf blades or new tissues.

Functions of Nutrients in the Cassava Plant

Some nutrients have a structural function. Others help establish enzymes (prosthetic group) or activate them and intervene in different processes within the plant. More information is found in Figure 5-8.

Table 5-8. Dry matter content (DM, g per plant) and nutrient content (mg per plant) in several parts of cassava plants (cultivar M Col 22) receiving fertilizer applications over a 12-month cycle, Santander de Quilichao, Cauca, Colombia.

		Contents in month:								
		1	2	3	4	5	6	8	10	12
DM	Leaf blades	1.8	22.7	76.0	100.6	56.2	100.2	50.5	58.7	67.0
	Petioles	0.2	4.9	21.5	38.2	19.0	27.4	8.6	12.1	11.5
	Stems	14.1	29.1	58.9	125.2	182.1	269.1	302.7	428.6	459.9
	Roots	0.1	7.1	80.5	229.6	360.0	571.9	782.6	942.4	1387.0
	Total	16.2	63.8	236.9	493.7	617.3	968.6	1144.4	1441.8	1925.4
N	Leaf blades	89	1231	4230	5300	2703	4877	2206	2702	3350
	Petioles	6	134	368	485	202	378	144	182	207
	Stems	117	422	1146	1919	3022	4191	4707	5984	6930
	Roots	—	125	1078	2250	4428	5605	7043	9424	9709
	Total	212	1912	6824	9954	10,355	15,051	14,100	18,292	20,196
P	Leaf blades	5	71	267	227	137	288	136	147	174
	Petioles	—	10	35	34	16	31	10	20	18
	Stems	37	71	157	205	358	422	482	378	766
	Roots	—	11	153	344	576	629	861	1036	1387
	Total	42	163	612	810	1087	1370	1489	1581	2345
K	Leaf blades	24	337	1408	1716	507	1564	712	817	945
	Petioles	9	161	598	744	347	561	159	201	207
	Stems	58	213	872	1681	2581	2588	2817	3233	3676
	Roots	5	123	1248	2870	4176	4463	5635	6879	10,402
	Total	96	834	4126	7011	7611	9176	9323	11,130	15,230
Ca	Leaf blades	15	157	583	924	525	857	424	452	435
	Petioles	4	68	212	393	248	420	125	165	186
	Stems	216	244	485	864	1061	1704	1986	2412	3083
	Roots	1	20	113	321	432	915	939	1508	1248
	Total	236	489	1393	2502	2266	3895	3474	4537	4952
Mg	Leaf blades	9	67	248	411	166	276	146	146	174
	Petioles	2	23	77	142	68	130	32	41	56
	Stems	93	125	216	401	424	586	707	746	1147
	Roots	—	9	72	230	288	400	626	660	693
	Total	104	224	613	1184	946	1392	1511	1593	2070
S	Leaf blades	2	61	203	335	185	256	101	88	241
	Petioles	—	4	5	—	14	30	7	7	14
	Stems	15	19	63	101	227	383	360	337	578
	Roots	—	5	8	—	216	171	391	283	555
	Total	17	89	279	436	642	840	859	715	1388

SOURCE: Howeler and Cadavid L (1983).

Table 5-9. Average extraction of nutrients per ton of fresh roots harvested from several cassava cultivars (total plant).

Cultivar	Extraction (kg/ha) of:						Source
	N	P	K	Ca	Mg	S	
Several	4.91	1.08	5.83	1.83	0.79	—	Howeler (1981)
M Col 22	4.66	0.54	3.52	1.14	0.48	0.32	Howeler and Cadavid L (1983)
CM 523-7	6.90	0.88	3.71	1.47	0.74	0.51	Cadavid L (1988a)
M Col 1468	3.97	0.62	3.56	1.53	1.28	—	Caicedo (1993)
M Col 1684	3.13	0.44	2.70	1.35	0.86	—	Caicedo (1993)
CM 507-37	3.89	0.60	2.76	1.09	0.78	—	Caicedo (1993)
CM 523-7	3.46	0.55	3.02	1.10	0.78	—	Caicedo (1993)
Mean of authors	4.42	0.67	3.58	1.36	0.82	0.42	

SOURCE: Cadavid L (1995).

Table 5-10. Mobility of nutrients through the phloem.

Mobile	Intermediate	Immobile
Nitrogen	Sulfur	Calcium
Phosphorus	Copper	Boron
Potassium	Iron	Strontium
Magnesium	Manganese	
Sodium	Zinc	
Chlorine		
Molybdenum		
Rubidium		

SOURCES: Howeler (1981); Kramer (1989); Malavolta et al. (1989); Calderón (1991).

Deficiencies and toxic effects in the cassava crop

A plant that presents any symptoms of any kind is a "diseased" plant. *Disease* is a detrimental physiological activity provoked by a *primary causal agent*. It manifests as an abnormal activity and is expressed through characteristic pathological conditions known as *symptoms* (Sánchez 1968), which can be necrotic (e.g., spots, blight, dieback, chlorosis, and cankers), hypoplastic (e.g., chlorosis, witches' broom, etiolation, and dwarfism), and hyperplastic (e.g., abscission, anther apoptosis, and leaf roll).

According to Sánchez (1968), the soil's chemical composition can directly cause *physiogenic* diseases or indirectly favor the development of *pathogenic* diseases (caused by other live organisms such as fungi, bacteria, and nematodes). An example is that of cassava crops growing in soils deficient in K and where anthracnose, *Phytophthora* induced diseases, and other fungal diseases causing, for example, necrosis, dieback, and root rots, can develop, drastically reducing tuberous root production.

Deficiencies. Howeler (1981) outlined the principal symptoms of deficiencies in the cassava crop, as follows:

Nitrogen (N). Stunted plant growth; and, in some cultivars, uniform yellowing of leaf blades that begins on the lower surfaces and rapidly extends to the entire plant.

Phosphorus (P). Reduced plant growth, smaller leaf blades and lobes, and thin stems. Under severe conditions, lower leaf blades become yellow, flaccid, and necrotic, and fall easily to the ground. Reddish coloring is sometimes presented.

Potassium (K). Stunted plant growth, small leaf blades. Under very severe conditions, purple spots appear, apexes and margins of lower or middle leaf blades suffer yellowing and become necrotic; necrosis of petioles or stem tissues; fine cracks appearing in stems and, runners.

Calcium (Ca). Reduced root growth, upper leaf blades are small and deformed.

Magnesium (Mg). Marked intervenal chlorosis in lower and middle leaf blades; plant height reduced to some degree.

Sulfur (S). Uniform yellowing of upper leaf blades; similar symptoms have sometimes been observed in the rest of the plant.

Boron (B). Reduced plant height; short internodes and petioles; young leaf blades small and deformed; purple-gray spots in completely extended leaf blades; sticky exudation on stems and petioles; reduced lateral root development.

Iron (Fe). Uniform chlorosis of upper leaf blades and petioles, which become white under severe conditions; reduced plant growth; young leaf blades small but not deformed.

Manganese (Mn). Intervenal chlorosis of upper or middle leaves; uniform chlorosis under severe conditions; reduced plant growth; young leaf blades small but not deformed.

Zinc (Zn). Yellow or white intervenal spots in young leaf blades that, under severe conditions, become narrow and develop chlorosis in the vegetative apex; necrotic spots on lower leaf blades; reduced plant growth; often confused with thrip attack.

Toxic effects. Howeler (1981) also outlined the principal symptoms of toxicity in the cassava crop.

Aluminum (Al). Reduced plant height and root growth; yellowing of old leaf blades under severe conditions.

Boron. Necrotic spots appear in old leaf blades, especially on the margins.

Manganese. Yellowing of old leaf blades, with purple-brown or blackish spots throughout the nervura; leaf blades become flaccid and fall to the ground.

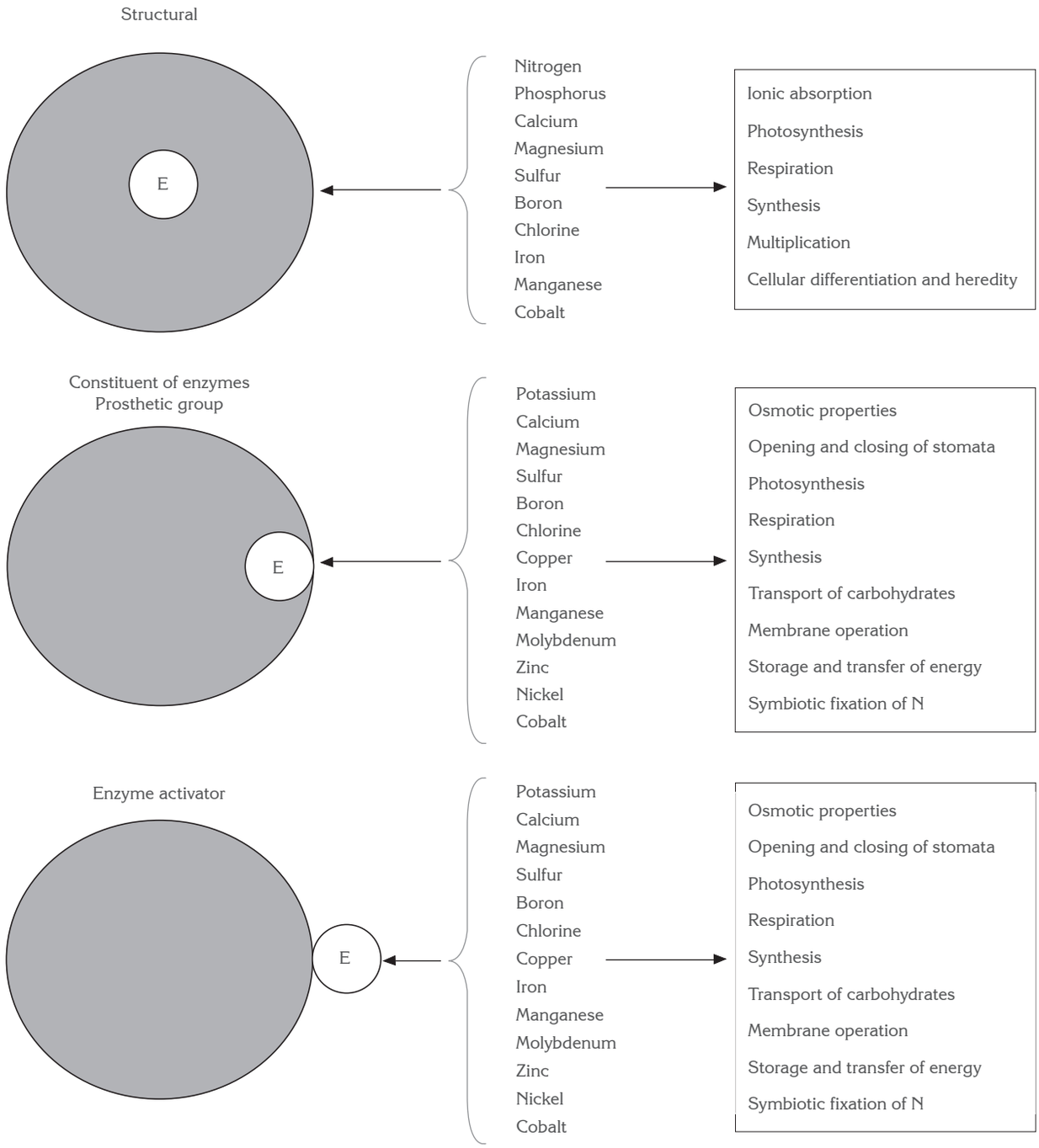


Figure 5-8. Functions of nutritional elements in the plant (adapted from Malavolta et al. 1989).

When the liquid and exchange phases of the soil are exhausted for lack of nutrients because of constant loss, and deficiency symptoms begin to appear, an artificial resupply of these through chemical fertilizer application becomes necessary. This is also true for N in the solid organic phase of the soil, which can be replenished only through organic fertilizer application.

Deficiency is presumed to occur when the following conditions are fulfilled:

When solubilization + mineralization $\leq$ fixation + immobilization + extraction + leaching (losses)

Soil Fertility and the Crop's Nutritional Status

When fertilizer application is considered necessary, a *diagnosis* of the soil must be made to determine possible deficiencies and correct them in a timely fashion before a crop is established. If this crop is cassava, possible limitations of the soil where the crop will be established must be known, including the availability of soil nutrients and the crop's nutritional requirements.

A diagnosis of nutritional problems in the soil aims to discover the availability of nutrients in a given soil and how these levels would affect an established crop. The fundamental objective of chemical diagnosis is to evaluate the soil's *capacity* to provide nutrients to the plant, that is, to measure its *fertility*. Diagnosis of soil fertility and nutritional problems for crops is usually carried out by:

- Chemical and physical analyses of the soil*
- Plant tissue analyses*
- Critical levels of nutrients in the soil or plant tissues of a specific crop (i.e., cassava in our case)*
- Knowledge of nutritional disorders (deficiencies, toxic effects)
- Crop's response to fertilizer applications*
- Crop's nutritional requirements (i.e., nutrient extraction)*
- Knowledge of original materials of a specific soil
- Knowledge of the soil's taxonomic classification
- Knowledge of previous crop and its exploitation of that soil and its intensity.

Chemical Soil Analyses

Soil sampling and later analyses before planting become very important tools in diagnosing and correcting nutritional problems, thereby preventing deficiencies from affecting plant growth and development. In cassava, the absence of clear symptoms of macronutrient deficiencies makes nutritional problems difficult to see easily. Thus, leaf and chemical analyses become key tools for determining a plant's nutritional status (Howeler 1981).

Soil analyses help monitor the state of soil fertility over the years, providing information on whether fertility is reduced, maintained, or increased (INPOFOS 1993). Table 5-3 shows an example of a sandy soil from the North Coast in Colombia, where soil fertility increased or declined according to management, time, and crop.

The success of analysis lies in obtaining a good soil sample. Usually, the following are determined: organic matter, P, K, Ca, Mg, S, Al, Na, Zn, B, soil acidity (pH), and soil texture (Figure 5-9). Laboratory data are given in local and international units, usually: percentage (%), parts per million (ppm), and milliequivalents per 100 g of dry soil (meq/100 g of dry soil) or g/kg, mg/kg, and cmol/kg, respectively, according to the latest laboratory regulations, not only in Colombia, but also in most of the world.

Critical levels of soil parameters

Howeler (1981), Cadavid L (1988b), and Howeler and Cadavid L (1990) have established a series of parameters (critical levels) that serve as tools for correctly interpreting a soil analysis (Table 5-11).

To more clearly understand the definition of *critical level*, the following example is given:

If, for the cassava crop, the critical level for P is 10.0 ppm (Bray II) and the soil analysis gives a value of 1.0 ppm, then, P can be considered as a limiting element in this soil. The crop would most probably manifest deficiency of this nutrient. Also, any P applications are highly likely to induce a positive and highly significant response, as manifested in increased yields (i.e., increased fresh-root production in t/ha). If the determined value is higher than the critical level, then the crop would probably not respond to applications of this nutrient.

With laboratory data and knowledge of critical levels of soil parameters already established for cassava, a good *interpretation* can be achieved but not necessarily a correct *recommendation*. For example, some Oxisol soils of the Colombian Eastern Plains, as in the case of Carimagua (Altillanura plains) in the Department of Meta, usually have chemical and physical characteristics as presented in Table 5-12.

When these values are compared with the already established critical levels, the analysis indicates those nutrients in deficiency. In this specific case, the soil obviously has average N content. It is also very low in P, K, Ca, and Mg. Its zinc content is average to low; and pH is extremely acid. Content of exchangeable Al is high and Al saturation is 77.4%. Sulfur content may be low (although this datum does not appear in this example).

* The analyses marked with asterisks are of the greatest interest, as they form the basis on which to calculate a formula for applying fertilizers to a given crop and its soil.

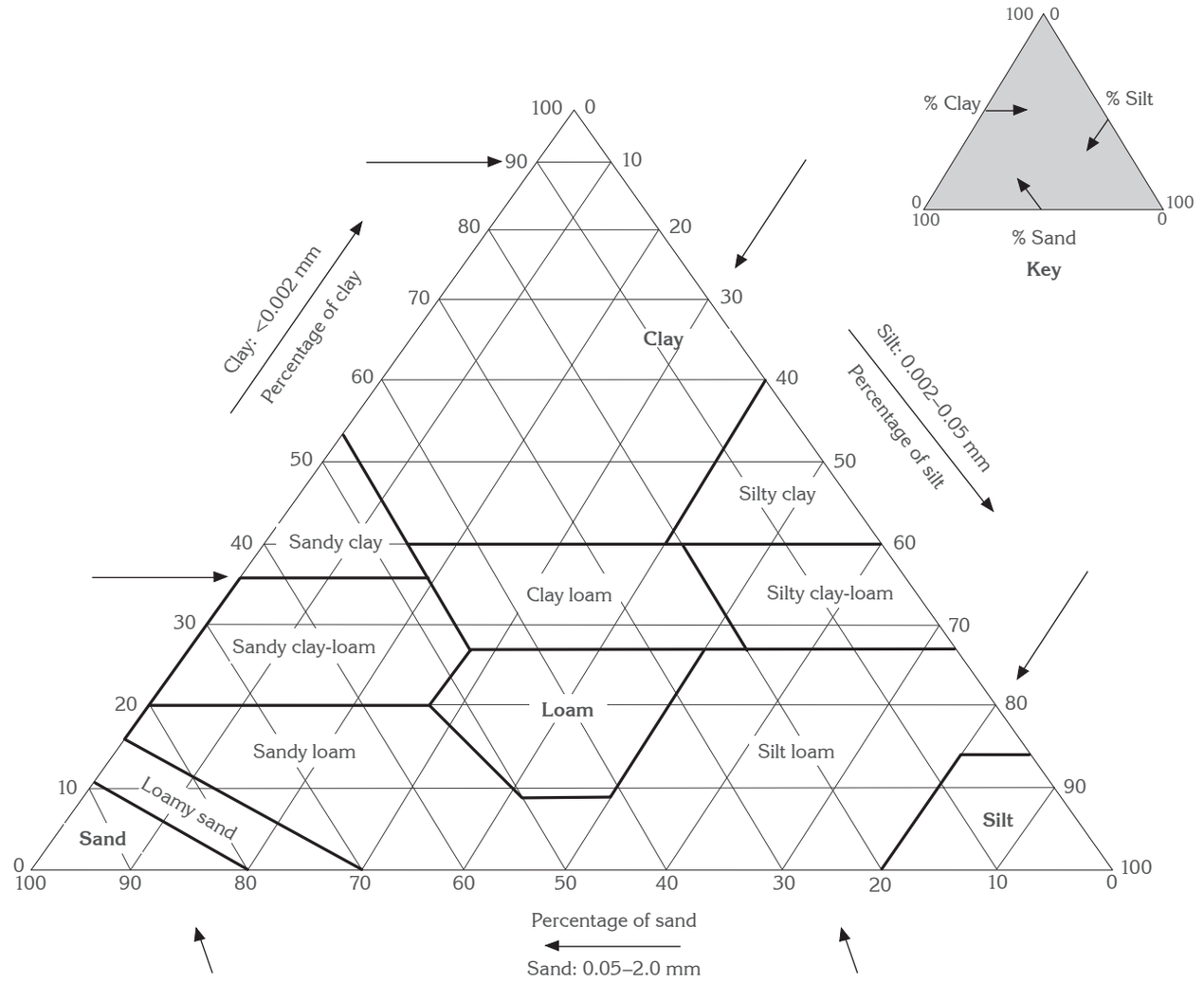


Figure 5-9. USDA soil texture triangle as applied to Colombian soils (unmarked arrows).

Table 5-11. Critical levels of soil parameters for the cassava crop.

pH	Al sat. (%)	P (ppm)	K	Ca	Mg	Zn	S
			(meq/100 G dry soil)			(ppm)	
4.0	80	7.0*	0.15	0.25	0.12[a]	1.0	8.0
8.0		10.0**	0.17				

a. Bray I method.
b. Assuming that the ideal Ca/Mg ratio for the cassava crop is 2:1 (LF Cadavid L, pers. comm.).
c. Bray II method.

Fertilizer recommendations or amendments. Fertilizer application is a management mechanism and, as such, should be conceptualized in terms of recovering, maintaining, and sustaining soil fertility and increasing crop productivity. It is important to know when a crop needs fertilizer application, which can be determined through the use of the following formula (Guerrero, 1980):

$$NF = \frac{WRC - S_N}{E} * 100$$

where,

NF = need for fertilizer application (kg/ha)
WRC = weighted requirement of crop (kg/ha)
S_N = availability of the nutrient in the soil (kg/ha)
E = efficiency of the fertilizer (%)
100 = percentage constant

Crop's nutritional requirements. This value refers to the nutrients extracted by the plant that have been quantified at the end of the cropping cycle (i.e., at

Table 5-12. Chemical and physical characteristics of the soil at Carimagua, Colombian Eastern Plains.

Texture	pH	OM[a] (%)	P (ppm)	Al	Ca	Mg	K	Zn
				(meq/100 g dry soil)			(ppm)	
Clay loam[b]	4.44	4.56	3.0	3.15	0.54	0.30	0.08	1.5
Interpretation[c]	Acid	M	M–L	M–H	L	L	M–L	M–L

a. OM = organic matter.
b. When data on texture are given as percentages of sand, silt, and clay; to determine textural class, see Figure 5-9.
c. H = high; L = low; M = medium.

harvest). Cassava is a plant that extracts large amounts of nutrients from the soil, especially N, K, and Ca. If the entire plant is considered, then for 1 ton of fresh roots harvested, cassava extracts 4.42 of N, 0.67 of P, 3.58 of K, 1.36 of Ca, 0.82 of Mg, and 0.42 of S (kg/ha each) (Cadavid L 1995).

If this soil (Oxisol from the Altillanura plains, Carimagua, Meta, Colombia) is taken as an example and, assuming that the average production (with intermediate-level technology) of the local variety ICA-Catumare (CM 523-7) is 15 t/ha but farmers want to achieve a weighted production of 30 t/ha, then the cassava crop will need the levels of nutrients as described in Table 5-13.

Nutritional requirements indicate the amount of nutrients that a plant needs to fully develop. This quantity is provided by the soil alone or by the soil plus fertilizers. The amount of nutrients extracted or removed from the soil in the final harvest has given rise to a criterion for fertilizer application: the *restitution* or *return* to the soil of nutrients that were extracted from it to maintain fertility at the original level. Thus, it is not an ascertained recommendation, as nutrient availability is not included in the soil.

Nutrient availability in the soil. This factor is determined in the laboratory through chemical analysis. Nutrients occur in term of values for available N; usable P and S; and exchangeable K, Ca, and Mg. The availability of a given nutrient is quantified according to results of the analysis (%, ppm, and meq/100 g of dry soil), expressed in kg/ha.

Table 5-13. Nutrients extracted from cassava according to yield.

Nutrient	Extraction (kg/ha) for fresh-root yield	
	Estimated (15 t/ha)	Weighted (30 t/ha)
N	66.3	132.6
P	10.1	20.1
K	53.7	107.4
Ca	20.4	40.8
Mg	12.3	24.6

Hence, the apparent density of the soil must be considered (which, in this type of soil, is 1.3 g/cm^3), on which depends the weight of a hectare of soil. The weight, in its turn, depends on plowing depth as a function of the average depth of the crop's root system (which, for cassava, is 20 cm).

W_s = weight of hectare of soil = V_s (cm^3) ∗ (g/cm^3)
V_s = $L * L * D$ = volume of 1 ha of soil (cm^3)

where,
L = length of plot side (cm)
D = working depth of plot (cm)

Thus, in our case:

V_s = 10,000 cm ∗ 10,000 cm ∗ 20 cm = 2×10^9 cm^3
W_s = 2×10^9 cm^3 ∗ 1.3 g/cm^3 ∗ kg/1000 g = 2.6×10^6 kg

However, meq/100 g of dry soil should be expressed in kg/ha. Starting with the term *equivalent-gram* (i.e., element's atomic weight divided by its valence), and if we take as an example, potassium (K), then:

An equivalent-gram (*Eq*) of K = molecular weight in g/valence
Eq K = 39/1 = 39 g
1 meq K = 39 g/1000 = 0.039 g

Hence,

0.039 g K is found in 100 g dry soil
X kg K will therefore be present in 2.6×10^6 kg/ha
X = 1014 kg K/ha

In other words:

1 meq K/100 g = 0.039 g K = 1014 kg K/ha

If the datum reported by the soil laboratory is 0.08 meq/100 g of dry soil, then the availability of the nutrient in the soil is:

1.0 meq K/100 g soil
1014 kg K/ha, for one of 1.3 g/cm^3
0.08 meq/100 g soil; X kg K/ha
X = 81.12 kg K/ha

The same procedure is used with Ca and Mg. When data reported in soil analyses are given in ppm, they are converted to kg/ha, as follows:

1 ppm is equivalent to having:

1 kg in 1×10^6 kg
1 kg P in 1×10^6 kg soil
X kg P in 2.6×10^6 kg/ha soil
X = 2.6 kg P/ha

That is, 1 ppm P = 2.6 kg P/ha

If in our example, 3.0 ppm of P were reported, then, the availability of P in the soil is:

1.0 ppm P is in 2.6 kg/ha
3.0 ppm P will be in X kg/ha
X = 7.8 kg P/ha

Continuing with our formula for determining the need for fertilizer application, the term *efficiency* still needs to be defined. It is merely the efficiency of fertilizer application on the basis of different losses of a soil nutrient after application. These losses may occur through:

- Leaching (NO_3^-, K^+, Ca^{+2}, and Mg^{+2})
- Volatilization (NH_2^-, NH_3, and N_2O)
- Fixation (NH_4^+, $H_2PO_4^-$, and K^+)
- Immobilization (N, P, and S)
- Erosion (N, P, K, Ca, and Mg)
- Adsorption by the plant

With the data of weighted requirement of the crop (WRC), availability of the nutrient in the soil (S_N), and efficiency of fertilizer application (E), an approximate fertilizer application formula can be readily established. We point out that the efficiency of fertilizers carrying P is 10% to 30%, depending on the amount of fixed P (this factor is closely linked to the soil class and its colloidal materials). These soils, for example, fix large amounts of this element (around 500 ppm). In fertilizers that include N and K, efficiency is between 50% and 70%. In fertilizers carrying Mg and Ca as lime, efficiency is between 50% and 60%. For NF, we will use the case of K:

WRC = 107.4 kg/ha
S_N = 81.1 kg/ha
E = 70.0%

$$NF = \frac{107.4\ kg - 81.1\ kg * 100}{70}$$

NF_K = 37.6 kg/ha

If we complete this formula for P, Ca, Mg, and N, the results would be:

NF_P = 61.2 kg/ha
NF_{Ca} = –400 kg/ha
NF_{Mg} = –115 kg/ha

Thus, to determine the need for fertilizer application for total nitrogen (TN), then:

$$TN = \frac{OM\%}{20}, \text{ thus } TN = \frac{4.56}{20} = 0.228 \text{ (high level)}$$

AN = 0.228 × 0.025 = 0.0057

"AN" is usable nitrogen and 2.5% is a percentage of average mineralization (this factor may be between 1% and 5%).

$$AN = \frac{0.0057 \times 2{,}600{,}000\ kg/ha}{100} = 148.2\ kg/ha$$

NF_N = –22.0 kg/ha

According to these data, the fertilizer applications required would be 60 kg P/ha and 40 kg K/ha. The formula is adjusted according to the data on response to fertilizer application in terms of area. Hence, for this type of soil, 50 kg N/ha + 60 kg P/ha + 50 kg K/ha + 500 kg/ha of dolomitic lime would be recommended. The recommendation would also be to apply 280 kg/ha of diammonium phosphate (DAP), which would contribute 50 kg N/ha and 58 kg P/ha, and add 100 kg/ha of potassium chloride (KCl) or 119 kg/ha of potassium sulfate if sulfur is less than 8 ppm and 10 kg/ha of borax (equivalent, on breaking up, to 1 kg B/ha). The lime would contribute about 100 kg Ca/ha and 50 kg Mg/ha. The applications of DAP and KCl + borax are carried out between day 30 and day 45 after planting, in simple band and covering to prevent losses. Lime is applied by broadcast 15 days

before planting and incorporating with the last task of soil preparation.

Cassava response to chemical and organic fertilizer applications

A viable alternative for recovering, maintaining, and increasing the fertility and productivity of soils dedicated to cassava cropping, and for increasing crop yield and quality, is fertilizer application, either chemical or organic.

Different studies conducted on the response to applications of chemical or organic fertilizers have been most useful, as observed in results: the beneficial and highly significant effect on the production and recovery of soil fertility. Tables 5-2 and 5-14 to 5-22, and Figures 5-10 to 5-12 confirm these results.

In a clay loam soil (kaolinitic) of the Colombian Eastern Plains (Carimagua, Meta), with relatively low content of P (3 ppm, Bray II method), P applications of up to 400 kg/ha, regardless of source and form of application, showed a highly significant response in yields (Table 5-2). However, with an application of 50 kg/ha of P, yield almost tripled.

Table 5-14 outlines the beneficial effect of high applications of P on the content of this element in the soil. Differences are notable between sources: highly water soluble, superphosphate type, and slow-release sources such as phosphoric rock and calfos.

The results of this type of trial underscore the importance of phosphoric fertilizer application in soils deficient in P. They show that response to applications of this element occurs and that slow-release sources may constitute an excellent alternative, as, when applied by broadcasting, they are more efficient, thus reducing the high fixation of P existing in this type of soils (Haplustox) (Cadavid L 1980).

Table 5-14. Phosphorus content (ppm) in a soil at Carimagua, Meta, Colombia, at 13 months after sources of P were applied.

Treatment[a]	P content (ppm) of levels of P_2O_5 at:					
	0	50	100	200	400	X_4
	(kg/ha)					
Check	1.7	—	—	—	—	1.7
Triple superphosphate, applied in bands	—	1.6	2.6	3.0	3.6	2.7
Simple superphosphate, applied in bands	—	1.7	4.6	3.7	3.0	3.3
Mg phosphate, broadcast in bands	—	2.3	2.3	3.1	23.7	7.9
Basic slag (Thomas), applied in bands	—	3.7	2.0	5.9	14.6	6.6
Basic slag (Thomas), broadcast	—	2.5	6.3	12.3	31.1	13.1
Phosphoric rock (PR) (Huila) 20%, acidulated, broadcast	—	4.2	4.9	7.7	40.6	14.4
PR (Huila) + S, broadcast	—	3.7	4.2	9.6	28.3	11.5
PR (Huila), broadcast	—	3.1	12.1	21.8	25.7	15.7
Mean of treatments	1.7	2.9	4.9	8.4	21.3	

SOURCE: Cadavid L (1980).

Table 5-15. Chemical characteristics of a soil at Santander de Quilichao, Cauca, Colombia, after one application of phosphorus.

Year	P[a]	OM[b]	pH	Al	Ca	Mg	K	P[c]	Al sat.
	(kg/ha)	(%)		(cmol/kg)				(mg/kg)	(%)
1979	0	6.28[d]	4.2	3.88	0.98	0.32	0.20	2.80	72.1
1995	0	4.95	4.0	3.21	0.88	0.33	0.26	2.85	68.8
1995	75	5.80	4.1	3.33	1.38	0.34	0.28	35.10	62.3

a. Annual application.
b. OM = organic matter.
c. Bray II method.
d. 1985.

Table 5-16. Dry-root yield and index of adaptation to low P for 32 cassava clones in soils of Santander de Quilichao, Cauca, Colombia, 1994/95.

Clone	Dry-root yield (t/ha)		Index of adaptation to low P[a]	
	Zero P	75 kg P/ha		
CG 333-4	7.4	10.4	1.89	
SG 779-9	7.1	10.4	1.81	
SM 380-3	6.0	11.2	1.65	
CM 5830-4	6.6	10.1	1.63	HA[b]
CM 4365-3	6.3	10.1	1.56	
CM 4774-2	6.1	10.1	1.51	
CM 849-1	6.7	9.5	1.47	
CM 3555-6	6.8	8.8	1.47	
SG 545-7	5.7	10.0	1.40	
CG 1141-1	5.3	10.6	1.38	
CG 1355-2	5.4	10.4	1.38	
CM 3311-3	5.9	9.4	1.36	
CG 95-1	6.1	8.4	1.26	
M Bra 589	5.5	9.2	1.24	IA[b]
CG 5-79	5.4	9.0	1.19	
SM 366-2	6.2	7.6	1.15	
M Col 1468	5.4	8.5	1.13	
CM 507-37	5.4	8.2	1.09	
M Cub 32	5.2	8.4	1.07	
CG 996-6	4.3	10.0	1.05	
M Col 1505	4.6	8.9	1.00	
SG 495-19	4.9	7.4	0.89	
CM 523-7	4.4	7.8	0.84	
M Bra 390	5.5	6.2	0.84	
CM 4772-3	4.4	7.6	0.82	
CG 522-10	3.6	8.8	0.78	
HMC-1	3.5	6.0	0.51	LA[b]
M Col 1684	3.0	6.6	0.49	
CM 5586-1	3.1	5.8	0.44	
M Bra 191	4.3	4.1	0.43	
CG 915-1	3.3	2.1	0.17	
CM 2766-5	1.9	2.4	0.11	
M Pan 51	2.8	1.2	0.08	
Average of all clones	5.1	8.0		
LSD 5%	1.5	1.8		

a. Index of adaptation to low P: yield at zero P; yield at 75 kg P/ha; and average of yield at zero P; average of yield at 75 kg P/ha.
b. HA = high adaptation; IA = intermediate adaptation; LA = low adaptation.

In Ultisol clay soils in Santander de Quilichao, Cauca, Colombia, which have a very low P content (2.80 ppm, Bray II), cassava was planted continuously over 15 years to observe responses to applications of P (triple superphosphate as the source) and determine an index of adaptation to low P (Tables 5-15 and 5-16).

The data given in the previous tables show a marked response to the constant application of 75 kg P/ha, as the soil, after 15 years, recorded a substantial increase of this element (35.1 ppm, compared with 2.85 ppm without application), thus increasing its fertility.

For yield, Table 5-16 shows a positive and highly significant response to applications of P. Differences between genotypes were observed when the index of adaptation to low P was considered. Many clones have high yields with and without applications of P; and some (e.g., CG 333-4, SG 779-9, SM 380-3, and CM 4774-2) had indices of adaptation to low P of more than 1.5, indicating a high level of tolerance of low P, as well as high response to phosphoric fertilizer applications.

Considering the continuous planting of cassava for more than 15 years and the average to low levels of productivity without applications of P, acid soils with low available P, but high organic matter contents, can probably support sustainable yields with moderate applications of this nutrient (i.e., <50 kg P/ha). This is related to the presence of vesicular-arbuscular mycorrhizae and degree of infection.

In soils of Santander of Quilichao, cassava roots of all clones show a high percentage of infection, indicating effective fungus-cassava association.

In soils where cassava is planted over long periods, K must be taken into account. Because of high extraction, these soils lose their reserves easily, presenting deficiencies of this nutrient. According to research conducted in different types of soil in the country, K is an essential and limiting element in cassava production (Cadavid L 1997; El-Sharkawy and Cadavid L 2000).

In an Ultisol of Santander de Quilichao, planted with cassava over 12 consecutive years, a highly significant response to K is shown in tuberous root production with applications of 50 kg/ha or more (Table 5-17). The soil showed a significant recovery in K content, increasing from 0.06 to 0.33 cmol/kg, which is considered high for this type of soil.

Table 5-17. Effect of applications of N–P–K fertilizer on yield and fertility of a soil planted to cassava over 12 consecutive years, Santander de Quilichao, Cauca, Colombia..

Application (kg/ha)			Fresh roots of M Col 1684 (t/ha)		OM (%)		Bray II P (mg/kg)		K (cmol/kg)		Critical level[a]	
N	P	K	1983/84	1994/95	1984	1995	1984	1995	1984[b]	1995	P (mg/kg)	K (cmol/kg)
0	0	0	16.4	8.3	6.2	5.2	4.0	6.4	0.06	0.12	10.0	0.15
50	50	50	25.3	21.5	6.0	5.3	3.9	15.9	0.08	0.14		
0	100	100	30.2	20.5	5.7	5.2	4.6	40.6	0.11	0.48		
50	100	100	32.3	22.8	5.7	5.3	3.8	48.6	0.08	0.34		
100	100	100	32.8	22.0	5.9	5.3	3.8	46.2	0.09	0.33		
100	0	100	23.8	16.2	5.9	5.4	4.2	10.1	0.09	0.27		
100	50	100	32.8	23.4	6.2	5.4	3.7	24.8	0.09	0.19		
100	100	0	25.7	10.3	5.8	5.3	3.7	46.0	0.06	0.09		
100	100	50	29.7	21.0	5.8	5.1	4.0	37.1	0.07	0.14		

a. As according to Howeler (1981).
b. In 1983, 0.07 cmol/kg, and 5 years earlier (continuous plantings of cassava), 0.30 cmol/kg.
SOURCE: Cadavid L (1995).

In an Inceptisol (clay soil) of Santander de Quilichao, which had a high content of organic carbon (4.8%), low P (2.0 mg/kg), and average content of K (0.18 cmol/kg), 14 cassava clones were evaluated over 5 continuous years (Table 5-18). Although the K level in the soil was average, dry-root yield indicated a positive and significant response to K applications of up to 50 kg/ha, on average, for all clones in the first cycle. In the fifth cycle, almost all clones showed a positive response up to 100 kg K/ha. Yield, however, declined through the constant removal of this nutrient from the soil and other losses in the system.

Table 5-18 also shows the effect of applications of K on the quality of tuberous roots in terms of total hydrocyanic acid content (ppm). The positive effect is notable, as HCN content drops as the rate of K application increases (El-Sharkawy and Cadavid L 2000).

Tables 5-17 and 5-19 and Figures 5-10 and 5-11 show the beneficial effects of N, P, and K applications on yield in soils of Santander de Quilichao, Mondomo, and Pescador in Cauca, Colombia.

Beneficial effects on soil fertility and productivity, and on cassava crop yield also occur when organic sources are used such as manures, incorporated green manures, or mulch. These not only help improve soil fertility and increase yield by releasing nutrients, but they also help improve soil structure and aggregation, increase water retention, and increase microbial activity in soils (Cadavid L 1995). Tables 5-20, 5-21, and 5-22, and Figure 5-12 illustrate the positive response to this class of fertilizers.

When a complete or simple fertilizer is selected, knowledge of the levels of elements that the product has is essential, that is, the way the contents of a fertilizer are expressed in the product, such as N, P_2O_{10}, K_2O, CaO, MgO, $CaCO_3$, and $MgCO_3$, and the percentage. For example, the chemical fertilizer 13–13–21 is expressed as 13% of N, 13% of P_2O_5, and 21% of K_2O. This means that 100 kg of commercial product contains 13 kg of N, 13 kg of P_2O_5, and 21 kg of K_2O.

To recommend fertilizers, such expressed values cannot be used. Instead, values must be expressed in terms of kg of N, P, K, Ca, and Mg. Hence, the expression given by the manufacturer must be converted to the real expression. For this purpose, conversion tables, taken from a literature review on fertilizer application, are given in Table 5-23.

The quantity of commercial product that will be applied in accordance with the recommended nutrient levels (element base) must be known. Thus, the following formula is taken into account (Cadavid L and Calle C 1997):

$$CP = \frac{RN}{ha} * \frac{100\ CP}{DNCP} * A$$

where,

CP = commercial product (kg or t/ha)
RN = recommended nutrient (kg/ha)
100 CP = 100 kg of commercial product (kg)
ha = 1 ha (10,000 m^2)
DNCP = grade of nutrient element in the commercial product (kg)
A = area of application (ha or m^2)

Table 5-18. Effect of potassium fertilizer applications on dry-root yield (t/ha) and on total HCN content (ppm) of 14 cassava cultivars in a soil in Cauca, Colombia, 1989–1994.

Cultivar	Dry roots (t/ha)							
	In year 1 of potassium fertilizer application (kg/ha) at:				In year 5 of potassium fertilizer application (kg/ha) at:			
	0	50	100	200	0	50	100	200
M Col 1505	12.6	17.0	14.4	14.9	4.5	8.5	9.0	9.1
CM 91-3	11.6	15.5	15.0	17.6	3.3	7.7	5.2	7.4
CM 489-1	12.5	17.2	15.3	16.1	5.7	8.0	10.4	11.3
CM 507-37	14.6	18.3	17.1	16.0	5.8	10.8	12.7	14.1
CM 523-7	12.4	15.7	16.9	13.0	6.4	9.7	12.2	11.9
CM 1585-13	14.5	15.4	14.6	14.4	5.9	7.2	11.4	11.1
HMC-1	16.2	19.2	18.5	19.5	8.3	9.0	10.8	9.1
HMC-2	15.0	14.5	15.4	13.2	4.2	5.4	7.2	5.8
CMC 40	10.1	13.4	12.5	11.6	3.2	4.9	4.2	3.8
M Col 1684	14.0	13.9	14.3	16.2	4.4	10.0	10.5	9.5
M Cub 74	13.1	14.1	14.2	14.9	4.8	7.9	8.8	10.5
M Pan 70	14.9	16.6	16.4	16.1	5.6	9.9	10.9	9.2
M Ven 25	14.3	15.3	15.7	14.2	8.5	10.7	12.2	12.4
SG 105-35	14.9	15.8	16.2	15.4	3.9	9.1	11.8	10.7
Average	13.6	15.9	15.5	15.2	5.3	8.5	9.8	9.7
LSD 5% for cultivars	2.6	2.8	3.9	2.8	2.2	2.2	2.3	2.7
LSD 5% for K levels	1.2	1.2			0.6			

Cultivar	Total HCN content (ppm)							
	In year 2 of potassium fertilizer application (kg/ha) at:				In year 5 of potassium fertilizer application (kg/ha) at:			
	0	50	100	200	0	50	100	200
M Col 1505	297	183	171	216	329	259	243	210
CM 91-3	217	173	157	140	264	263	225	179
CM 489-1	308	190	160	158	334	201	133	161
CM 507-37	671	401	406	401	1169	1049	674	780
CM 523-7	281	163	142	134	331	313	370	265
CM 1585-13	201	148	168	148	219	205	153	178
HMC-1	206	187	163	141	202	173	193	188
HMC-2	307	149	134	112	449	423	370	353
CMC 40	185	140	177	182	124	163	147	103
M Col 1684	765	570	523	647	986	1074	996	754
M Cub 74	297	177	124	127	282	221	246	273
M Pan 70	271	236	182	208	216	256	206	181
M Ven 25	1034	955	812	926	1969	1625	1462	1403
SG 105-35	417	203	241	214	281	209	190	647
Average	390	277	254	268	511	460	401	405
LSD 5% for cultivars	255	141	143	105	207	208	227	651
LSD 5% for K levels	75				48			

SOURCE: El-Sharkawy and Cadavid L (2000).

Table 5-19. Response of cassava to applications of several levels of N, P, and K in five sites of the region covering Mondomo and Pescador, Cauca, Colombia, 1983.

Fertilizer[a]	Fresh-root yield (t/ha)					Average
	Mondomito	Agua Blanca	Telecom	Tres Quebradas	Pescador	
$N_0P_0K_0$	8.5	12.7	13.0	10.2	3.3	9.5
$N_0P_2K_2$	11.0	25.5	25.9	16.5	12.6	18.3
$N_1P_2K_2$	13.6	20.5	21.8	18.4	13.1	17.5
$N_2P_2K_2$	11.0	24.8	27.1	23.2	16.2	20.5
$N_3P_2K_2$	13.8	29.7	27.3	29.2	19.7	23.9
$N_2P_0K_2$	8.0	13.2	16.0	9.3	6.0	10.5
$N_2P_1K_2$	14.3	25.2	23.5	21.5	15.0	19.9
$N_2P_3K_2$	12.0	24.6	26.4	24.7	19.6	21.5
$N_2P_2K_0$	10.6	25.5	23.1	14.8	7.4	16.3
$N_2P_2K_1$	14.3	24.9	25.9	17.8	16.5	19.8
$N_2P_2K_3$	14.4	26.3	24.6	24.8	16.7	21.4
$N_3P_3K_3$	18.5	28.0	27.3	29.9	12.3	23.2

a. Sources of fertilizer:
$N_0 = 0$ $N_1 = 50$ $N_2 = 100$ $N_3 = 200$ kg N/ha as urea.
$P_0 = 0$ $P_1 = 50$ $P_2 = 100$ $P_3 = 200$ kg P/ha as triple superphosphate.
$K_0 = 0$ $K_1 = 50$ $K_2 = 100$ $K_3 = 200$ kg K/ha as potassium chloride.

SOURCE: Cadavid L and Howeler (1984).

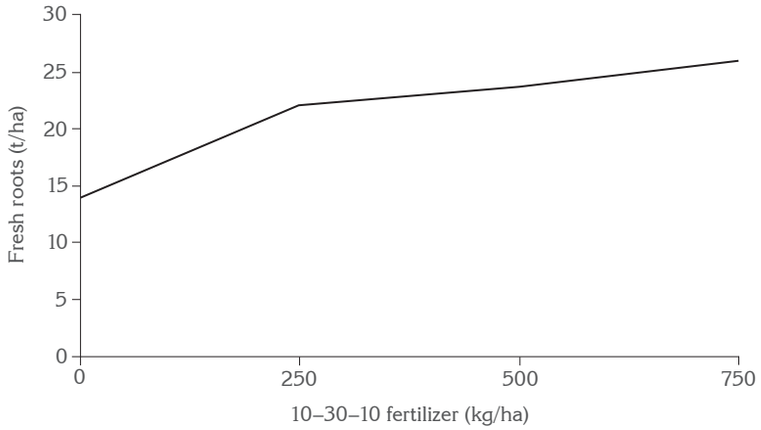


Figure 5-10. Effect of chemical fertilizer application on average yield of cassava cv. CMC 92 in the Mondomo Region, Cauca, Colombia (from Cadavid L 1997).

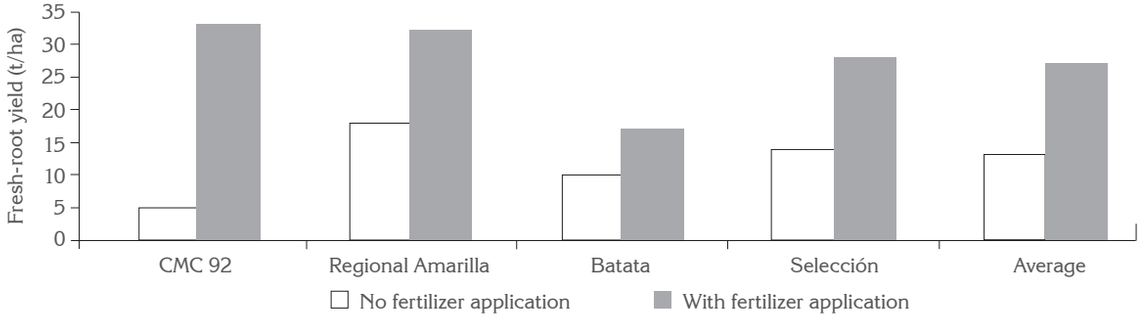


Figure 5-11. Effect of chemical fertilizer application on yield of four cassava cultivars in soils prepared by plowing with ox (one pass), Mondomo, Cauca, Colombia (from Cadavid L 1997).

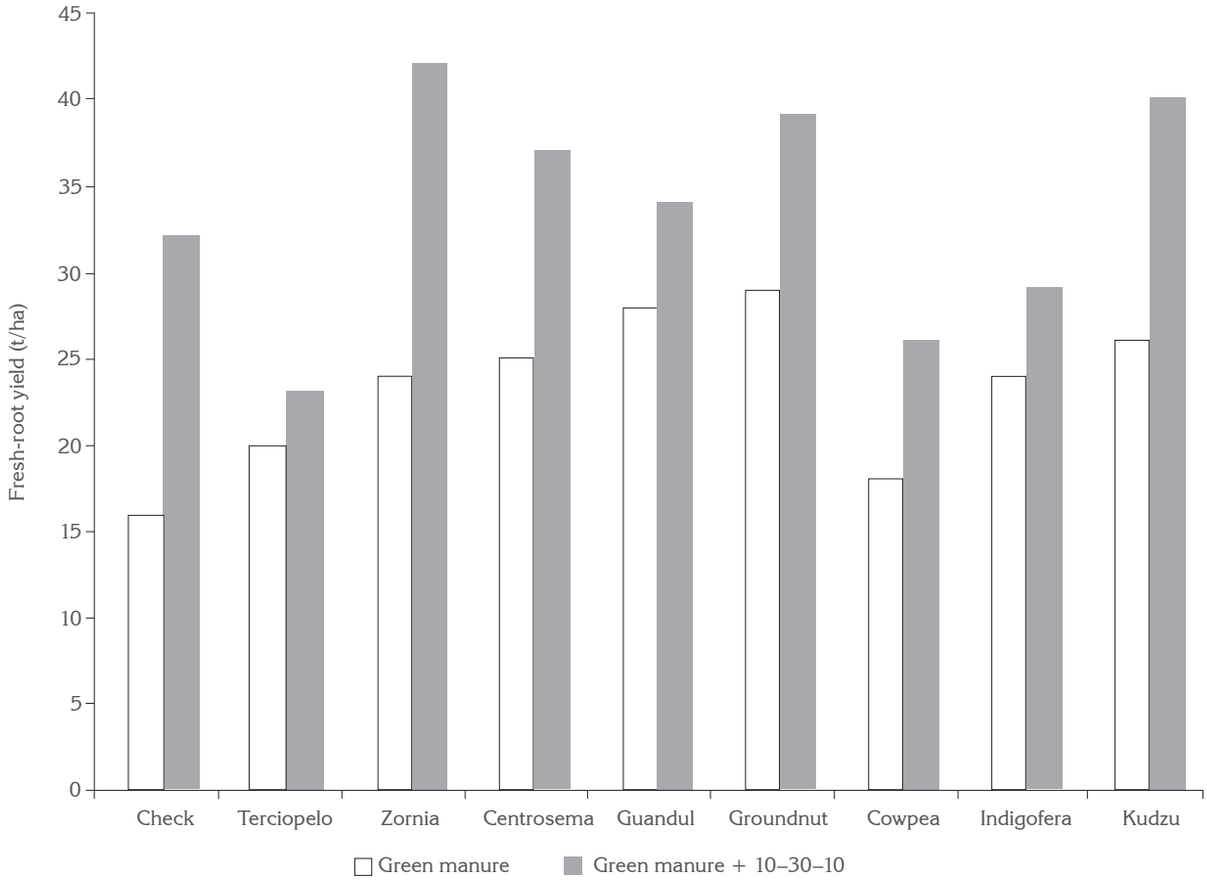


Figure 5-12. Effect of (1) incorporating green manures and (2) these plus 10–30–10 fertilizer on yield of cassava cultivar M Col 1684 in an exhausted Ultisol of Santander de Quilichao, Cauca, Colombia, 1984 (from Cadavid L 1995; Cadavid L 1987).

Table 5-20. Effect of source and application of P on cassava yield at two sites (San Julian and Mondomito), Cauca, Colombia.

P (kg/ha)	Fresh-root yield (t/ha)					
	San Julian[a] 1981		Mondomito[b] 1983		P source[c]	Application (t/ha)
	M Col 1684	M Col 1458	CMC 92	M Col 1468		
0	46.9	29.4	25.8	12.7		
25	57.2	31.1	25.5	18.1	Manure	4.2
50	50.5	33.5	28.1	19.3		8.4
25	57.8	41.9	25.3	13.0	Chicken manure	1.9
50	52.7	33.5	26.7	23.7		3.8
25	49.9	39.2	28.2	17.8	10–30–10	0.191
50	49.1	36.5	26.2	16.5		0.382

a. Santander de Quilichao, virgin plot.
b. Mondomo.
c. Sources of phosphorus (analysis):

P source	Content (%) of:				
	N	P	K	Ca	Mg
Manure	2.0	0.6	1.7	2.9	0.6
Chicken manure	2.7	1.3	2.0	7.7	0.7
10-30-10	10.0	13.1	8.3		

SOURCE: Cadavid L (1995).

Table 5-21. Effect of green manure on yield of cv. CM 507-37 in an exhausted soil of Santander de Quilichao, Cauca, Colombia, planted over 3 consecutive years (1990–1993), with no chemical fertilizer applications.

Green manure incorporated	Fresh-root yield (t/ha) in			
	1st cycle	2nd cycle[a]	3rd cycle[a]	All 3 cycles
No green manure	27.4	22.5	12.7	20.9
Zornia latifolia	34.1	26.6	19.7	26.8
Common weed[b]	32.3	21.0	16.3	23.2
Pueraria phaseoloides	47.1	27.3	16.1	30.2
Arachis pintoi	37.9	22.8	18.3	26.3
Macroptilium gracile	30.5	23.6	16.1	23.4
Centrosema acutifolium	45.5	25.3	20.9	30.6
Desmodium ovalifolium	43.4	24.1	21.5	29.7

a. Residual effect of green manure.
b. Common grass (*Paspalum* sp.).

SOURCE: Cadavid L (1995).

Table 5-22. Effect of tilling, mulching, and chemical fertilizer applications on the chemical characteristics of a sandy soil, Pivijay, Magdalena, Colombia, over 6 years.

Tilling method	15–15–15 fertilizer at 330 kg/ha						No chemical fertilizer application						Period
	OM	Bray II	P	Ca	Mg	K	OM	Bray II	P	Ca	Mg	K	
	(%)	(1:1 pH)	(ppm)	(meq/100 g soil)			(%)	(1:1 pH)	(ppm)	(meq/100 g soil)			
Soil before tilling[a]	—	—	—	—	—	—	0.18	6.10	3.38	0.87	0.28	0.05	
Conventional	1.20	5.40	18.88	0.34	0.08	0.05	1.10	5.35	8.25	0.34	0.07	0.04	1988/89
Conventional with mulch[a]	1.33	6.25	23.43	0.79	0.38	0.13	1.45	6.50	13.65	0.86	0.49	0.17	to
Zero tilling	1.05	5.53	17.30	0.36	0.08	0.05	1.08	5.30	9.43	0.36	0.07	0.04	1993/94
Zero tilling with mulch[a]	1.48	6.28	27.03	0.77	0.45	0.16	1.45	6.43	14.50	0.80	0.46	0.16	

a. Previous crops: cassava, maize, and sesame.

SOURCE: Cadavid L et al. (1995).

Table 5-23. Factors for converting expressions in oxide bases to expressions in element bases and vice versa.[a]

P_2O_5	×	0.44	or	(0.4364)[a]	=	P
P	×	2.29	or	(2.2914)	=	P_2O_5
K_2O	×	0.83	or	(0.8302)	=	K
K	×	1.20	or	(1.2046)	=	K_2O
CaO	×	0.71	or	(0.7147)	=	Ca
Ca	×	1.40	or	(1.3992)	=	CaO
MgO	×	0.60	or	(0.6030)	=	Mg
Mg	×	1.66	or	(1.6582)	=	MgO
SO_4	×	0.33	or	(0.3333)	=	S
S	×	3.00	or	(3.0000)	=	SO_4

a. Values in parentheses should be used for calculations demanding high accuracy.

SOURCE: Monómeros Colombo-Venezolanos (1989).

To better understand this formula, let us observe the following example:

RN = 70.0 kg K/ha
A = 89 ha
PC = potassium chloride (KCl from 60% K_2O)

In the first place, we must convert K_2O to K:

60% K_2O × 0.8302 = 49.81 K or,
more exactly:
60% K_2O/1.2 = 50 K

This means that 100 kg of commercial product (KCl) has 50 kg of K (DNCP), giving rise to the formula:

$$CP = \frac{70 \text{ kg K}}{1 \text{ ha}} \times \frac{100 \text{ kg KCl}}{50 \text{ kg K}} \times 89 \text{ ha}$$

CP = 140 kg KCl × 89 = 12,460 kg = 12.46 t KCl

References

To save space, the acronym "CIAT" is used instead of "Centro Internacional de Agricultura Tropical".

Cadavid L, LF. 1980. El uso de rocas fosfóricas en el cultivo de la yuca (*Manihot esculenta* Crantz). CIAT, Cali, Colombia. 38 p.

Cadavid L, LF. 1987. Abonos verdes en suelos agotados dedicados a la siembra de yuca (*Manihot esculenta* Crantz). Suelos Ecuat 17(2):178–183.

Cadavid L, LF. 1988a. Efecto de fertilización y humedad relativa sobre la absorción y distribución de nutrientes en yuca (*Manihot esculenta* Crantz). Master's thesis. Facultad de Ciencias Agropecuarias, Universidad Nacional de Colombia–Palmira, Colombia. 290 p.

Cadavid L, LF. 1988b. Respuesta de la yuca (*Manihot esculenta* Crantz) a la aplicación de NPK en suelos con características diferentes. Facultad de Ciencias Agropecuarias, Universidad Nacional de Colombia–Palmira, Colombia. 199 p.

Cadavid L, LF. 1995. Utilización de abonos verdes en suelos dedicados a la siembra de yuca (*Manihot esculenta* Crantz). 17 p. (Multicopied.)

Cadavid L, LF. 1997. Manejo productivo de suelos de ladera cultivados con yuca (*Manihot esculenta* Crantz). In: Seminar on "Fertilidad del suelo y su potencial productivo, fundamentos para la interpretación de análisis de suelos, plantas y aguas para riego: Seminario fertilidad del suelo y su potencial productivo", held in Palmira, Valle del Cauca, 1995. Sociedad Colombiana de la Ciencia del Suelo (SCCS), Bogotá, DC, Colombia. p 134–143.

Cadavid L, LF. 2000. Nutrición del cultivo de la yuca (*Manihot esculenta* Crantz). In: Training course on "Sistemas de producción de yuca, Santo Domingo de los Colorados, Ecuador, febrero 2000". Consorcio Latinoamericano y del Caribe de Apoyo a la Investigación y al Desarrollo de la Yuca (CLAYUCA), Palmira, Colombia.

Cadavid L, LF; Calle CF. 1997. La fertilización de la yuca (*Manihot esculenta* Cranz). 13 p. (Multicopied.)

Cadavid L, LF; Howeler RH. 1984. La fertilización de la yuca (*Manihot esculenta* Crantz) en la región de Mondomo y Pescador, Cauca. Suelos Ecuat 17(2):178–183.

Cadavid L, LF; Calvo FA; Howeler RH. 1977. La interacción de cal con fósforo y elementos menores en la producción de yuca (*Manihot esculenta*) en Oxisoles de los Llanos Orientales de Colombia. CIAT, Cali, Colombia. 25 p.

Cadavid L, LF; Acosta A; El-Sharkawy M. 1995. Efecto de preparación, mulch y abonamiento en el cultivo de la yuca (*Manihot esculenta* Crantz) en suelos arenosos de Colombia. Suelos Ecuat 25:7–8.

Calderón SF. 1991. Concepción moderna de la nutrición vegetal. In: Fundamentos para la interpretación de análisis de suelos, plantas y aguas para riego. Sociedad Colombiana de la Ciencia del Suelo (SCCS), Bogotá, DC, Colombia.

Cano CA. 1999. Las micorrizas arbusculares, su importancia y usos en la agricultura. La Mina S.A., Guatemala. 12 p. (Multicopied.)

Cassanova O, EF. 1996. Introducción a la ciencia del suelo. 2nd ed. Universidad Central de Venezuela, Caracas, Venezuela. 379 p.

El-Sharkawy MA; Cadavid L, LF. 2000. Genetic variation within cassava germplasm in response to potassium. Exp Agric (UK) 36(3):323–334.

El-Sharkawy MA; Cadavid L, LF; Mejía de Tafur S; Caicedo JA. 1998. Genotypic differences in productivity and nutrient uptake and use efficiency of cassava as influenced by prolonged water stress. Acta Agron 48(1–2):9–22.

Garavito NF. 1979. Propiedades químicas de los suelos. 2nd ed. Instituto Geográfico "Agustín Codazzi" (IGAC), Subdirección Agrológica, Bogotá, DC, Colombia. 321 p.

Garcidueñas RM. 1993. Fisiología vegetal aplicada. 4th ed. MacGraw-Hill/Interamericana, Mexico City, DF, Mexico. 275 p.

Guerrero RR. 1980. Hacia la formulación de un modelo suelo-planta. In: Silva MF, ed. Fertilidad de suelos: Diagnóstico y control. 12th ed. Sociedad Colombiana de la Ciencia del Suelo (SCCS), Bogotá, DC, Colombia. p 1–10.

Howeler RH. 1981. Nutrición mineral y fertilización de la yuca (*Manihot esculenta* Crantz). CIAT, Cali, Colombia. 55 p.

Howeler RH. 1983. La función de las micorrizas vesículo-arbusculares en la nutrición fosfórica de yuca. Suelos Ecuat 13(2):51–61.

Howeler RH; Cadavid L, LF. 1983. Accumulation and distribution of dry matter and nutrients during a 12-month cycle of cassava. Field Crops Res 7:123–139.

Howeler RH; Cadavid L LF. 1990. Short- and long-term fertility trials in Colombia to determine the nutrient requirements of cassava. Fertil Res 26(1–3):61–80.

INIVIT (Instituto Nacional de Investigaciones de Viandas Tropicales). 1999. Hoja divulgativa. Cuba. 2 p.

INPOFOS (Instituto de la Potasa y el Fósforo). 1993. Diagnóstico del estado nutricional de los cultivos. Quito, Ecuador. 55 p.

Kramer PJ. 1989. Relaciones hídricas de suelos y plantas, una síntesis moderna. Editorial Harla, Mexico. 538 p.

Malavolta E; Vitti GC; Oliveira SA de. 1989. Avaliação do estado nutricional das plantas: Princípios e aplicações. Associação Brasileira para Pesquisa de Potassa e do Fosfato (POTAFOS), Piracicaba, Brazil. 201 p.

Monómeros Colombo-Venezolanos. 1989. Los fertilizantes químicos, propiedades y comportamiento agronómico. Serie Punto Verde, No. 6. Bogotá, Monómeros Colombo Venezolanos, S.A. 54 p.

Sánchez PA. 1968. Conferencias de fitopatología y control de enfermedades. Facultad de Ciencias Agropecuarias, Universidad Nacional de Colombia–Palmira, Colombia. 146 p.

Sánchez de P, M. 1999. Endomicorrizas en agroecosistemas colombianos. Departamento de Ciencias Básicas, Universidad Nacional de Colombia–Palmira, Colombia. 227 p.

Sieverding E. 1984. Aspectos básicos de la investigación de la micorriza vesículo arbuscular. In: Sieverding E; Sánchez de P, M; Bravo O, N, eds. Investigaciones sobre micorrizas en Colombia: Proc. Primer Curso Nacional sobre Micorrizas en Colombia, Palmira, febrero 1984. Facultad de Ciencias Agropecuarias, Universidad Nacional de Colombia–Palmira, Colombia. p 1–14.

Thompson LM. 1965. El suelo y su fertilidad: Propiedades físicas, biológicas y químicas del suelo en relación con su formación, clasificación y tratamientos desde el punto de vista de la fertilidad. 3rd ed. Editorial Reverté S.A., Barcelona, Spain. 410 p.

CHAPTER 6

Conservation of Soil under Cassava Cultivation

Luis Fernando Cadavid L.[1]

General Considerations

Cassava is a hardy crop, able to endure long dry periods and adapt to a wide range of soils and climates. It is planted in soils with textures that range from sandy through loamy to clayey. It is grown at altitudes between sea level and 1700 m, but prefers temperatures that average 24 °C and a relative humidity of about 72%.

Table 6-1 outlines the principal chemical and physical characteristics of the soils where cassava is planted in Colombia. As can be observed, a high percentage of these soils, which occupy a large area of our national territory (Figure 6-1), presents low contents of N, P, K, Ca, Mg, S, B, and Zn, thus constituting limitations for the crop's development and growth. Chapter 5 of this volume describes the critical levels of soil parameters established for cassava.

Normally, this crop is planted in flat areas or in regions where slopes are less than 15%. However, because of population pressure on land to produce food, hillsides are being brought under cassava cultivation, thus changing their potential use. According to Cadavid L (1987, 1988, 1990, 1997) and Howeler and Cadavid L (1984), results have been disheartening in that deforestation has increased and, therefore, so have soil loss to erosion (whether hydric or anthropic erosion), and soil nutrient loss to both runoff and high extraction by the crop (chemical erosion).

In recent decades, soil erosion has increased alarmingly, because of misuse of this resource. Such degradation of soils (both physical and chemical, especially in hillsides) produced by humans has caused widespread poverty among rural inhabitants and, consequently, given rise to mass migration towards large cities, which, in turn, has created more belts of extreme poverty (Cadavid L 1990).

Colombia has 114,179,000 hectares, of which 49.5% present some form of erosion, whether severe, moderate, or light. In 9,705,150 of these hectares (8.52%), the soil situation is serious, perhaps difficult to recover, according to data outlined in Table 6-2 (IGAC 1987, cited by Cobo 1998).

Howeler (1986) indicates that, according to a United Nations study, Colombia is losing every year 426 million tons of soil, which corresponds to 3.7 t/ha of national territory. One example is in the upper Cauca where, according to Suárez (1984, cited by Cadavid L 1987, 1988, 1990), of the 2,200,000 ha under CVC jurisdiction, 800,000 present problems of erosion and, of these, 100,000 suffer severe to very severe erosion (Table 6-3).

We point out that, in this country, a high percentage of cassava is planted in hillside areas, on slopes of more than 15%, in soils of low fertility, and under poor management. Such cases include the region of Mondomo, Pescador, and San Antonio in

1. Soil Agronomist, formerly of Cassava Production Systems, CLAYUCA, Cali, Colombia.
E-mail: luisfernandocadavidlopez@yahoo.es

Table 6-1. Chemical and physical characteristics of the soils where cassava is planted in Colombia.

Site	Department	pH	OM	Al	Na	Ca	Mg	K	Al	Na	P	S	Zn	B	Mn	EC	Bouyoucos	BD
	1:1	(%)		(meq/100 g)					sat. (%)	sat. (%)	(ppm)					(mmhos/cm)[a]	texture[b]	(g/cm^3)
Nus	Antioquia	5.1	4.0	0.70	—	1.60	0.70	0.10	22.6	—	7.0	—	2.00	0.10	—	—	SCL	1.40
Luruaco	Atlántico	7.5	2.7	—	0.39	22.10	10.10	0.45	—	1.18	42.5	—	—	—	—	—	C	1.50
Malambo	Atlántico	6.2	0.6	—	0.17	1.67	1.00	0.06	—	5.86	4.2	—	—	—	—	—	S	—
Caloto	Cauca	5.7	10.4	—	—	21.40	12.00	0.20	—	—	3.0	—	—	—	—	—	C	—
S. de Quilichao	Cauca	4.3	8.1	2.73	—	1.95	0.82	0.22	47.7	—	10.5	—	2.40	0.46	—	—	C	1.00
Paz de Ariporo	Casanare	4.7	0.9	1.40	0.10	0.18	0.06	0.10	76.1	5.43	3.5	—	0.26	—	0.86	0.07	SL	1.50
Paz de Ariporo	Casanare	4.5	2.2	2.00	0.11	0.10	0.06	0.16	82.3	4.53	2.0	—	0.27	—	3.09	0.10	SL	1.50
Yopal	Casanare	4.5	1.9	3.70	0.10	1.40	0.90	0.20	58.7	1.58	97.0	1.5	4.90	0.10	—	—	L	—
Ayapel	Córdoba	4.8	2.8	2.20	—	0.30	0.20	0.05	80.0	—	3.0	—	1.00	0.20	—	—	SC	1.30
Ricaurte	Cundinamarca	7.5	2.2	—	0.16	26.55	3.00	0.48	—	0.53	215.0	—	—	—	—	—	SiCL	1.50
Armenia	Quindío	5.8	1.6	0.15	0.22	4.63	0.86	0.49	2.4	3.46	21.0	7.0	5.80	0.04	0.18	—	SL	1.40
Barragán	Quindío	5.6	2.9	0.18	0.10	4.50	1.40	0.45	2.7	1.50	36.0	9.0	16.00	0.01	—	—	SiL	1.20
Montenegro	Quindío	5.5	2.1	0.08	0.28	3.17	0.86	0.83	1.5	5.36	30.0	8.0	7.00	0.10	0.25	—	SL	1.43
Villavicencio	Meta	4.7	4.6	2.86	—	0.49	0.17	0.13	78.4	—	11.8	—	0.30	—	—	—	C	1.30
La Tebaida	Quindío	6.0	1.1	—	0.09	5.10	2.36	0.59	—	1.11	9.0	0	7.70	0.01	0.41	—	SL	1.40
Montenegro	Quindío	5.5	0.7	0.12	0.09	4.45	1.11	0.74	1.8	1.38	26.0	3.0	0.30	0.01	0.50	—	SL	1.40
Candelaria	Valle	6.9	1.4	—	0.46	11.30	4.62	0.39	—	2.74	83.0	—	—	—	—	—	SCL	1.35
El Zulia	Norte de Santander	6.3	2.9	—	—	0.77	1.70	0.60	—	—	108.0	—	2.60	—	—	—	SC	—
El Zulia	Norte de Santander	6.9	2.7	—	—	4.20	1.40	0.32	—	—	15.0	—	4.50	—	—	—	SCL	1.50
San Cayetano	Norte de Santander	5.2	1.9	0.20	—	1.30	0.60	0.14	8.9	—	2.0	—	14.80	—	—	—	SC	—
LQ1 CIAT	Valle	6.8	2.8	—	0.17	14.90	7.32	0.36	—	0.74	41.5	15.0	3.70	0.56	—	—	SiC	1.49
LN3 CIAT	Valle	6.9	6.1	—	0.17	9.21	7.60	0.85	—	0.95	79.0	35.5	—	0.62	—	—	CL	1.60
Jamundí	Valle	4.7	6.0	1.59	—	3.24	0.71	0.39	26.8	—	6.3	127.4	3.20	0.49	—	—	C	1.10
B/bermeja	Santander	4.8	2.4	1.47	—	1.25	0.37	0.06	16.7	—	2.8	—	0.40	0.20	2.60	—	SCL	1.34
El Zulia	Norte de Santander	6.1	1.0	—	0.08	2.50	0.42	0.13	—	2.56	5.0	5.0	2.10	0.32	27.30	—	CL	1.35
LP3 CIAT	Valle	7.2	2.2	—	0.26	12.62	8.36	0.77	—	1.18	53.5	0.33	4.83	0.78	0.69	—	SiC	1.60
Jamundí	Valle	5.0	6.0	0.26	—	5.86	1.47	0.72	3.1	—	5.3	95.5	3.28	0.54	—	—	C	1.10
Buga	Valle	6.3	1.4	—	0.22	8.33	5.56	0.11	—	1.55	40.2	42.0	4.08	0.35	—	—	CL	1.58
Caicedonia	Valle	5.5	2.6	0.21	—	5.42	0.74	0.38	3.1	—	49.8	46.2	9.47	0.39	—	—	SCL	1.35
Ortega	Tolima	7.4	1.4	—	0.23	19.90	4.10	0.56	—	0.93	44.9	—	0.70	—	52.6	—	SL	1.50
Purificación	Tolima	6.8	0.5	—	0.17	11.30	3.90	0.42	—	1.08	40.9	—	2.30	—	37.3	—	SL	1.50
Agua Azul	Casanare	5.5	0.8	0.09	1.09	3.76	1.21	0.46	1.4	16.5	47.0	15.0	6.60	0.03	41.0	0.42	SL	—
Sardinata	Norte de Santander	5.1	1.8	0.40	—	0.90	0.40	0.08	22.5	—	18.0	—	0.10	—	36.2	—	CL	1.35
Espinal	Tolima	6.0	0.3	—	0.33	4.50	1.10	0.17	—	5.40	23.3	—	—	—	—	—	SL	1.40
Mondomo	Cauca	4.5	7.2	5.70	—	0.79	0.30	0.23	73.0	—	1.76	—	—	—	—	—	C	0.87
Pescador	Cauca	4.6	8.5	3.10	—	0.47	0.15	0.11	81.0	—	1.20	—	—	—	—	—	C	—
Santo Tomás	Atlántico	5.8	1.5	—	—	1.43	0.41	0.11	—	—	3.10	—	—	—	—	—	S	1.48
Media Luna	Magdalena	6.1	0.2	—	—	0.87	0.28	0.05	—	—	8.3	—	—	—	—	—	S	1.50

a. EC = electrical conductivity.
b. C = clay, CL = clay loam, L = loam, S = sandy, SC = sandy clay, SCL = sandy clay loam, SiCL = silty clay loam, SiC = silty clay, SiL = silt loam, SL = sandy loam.

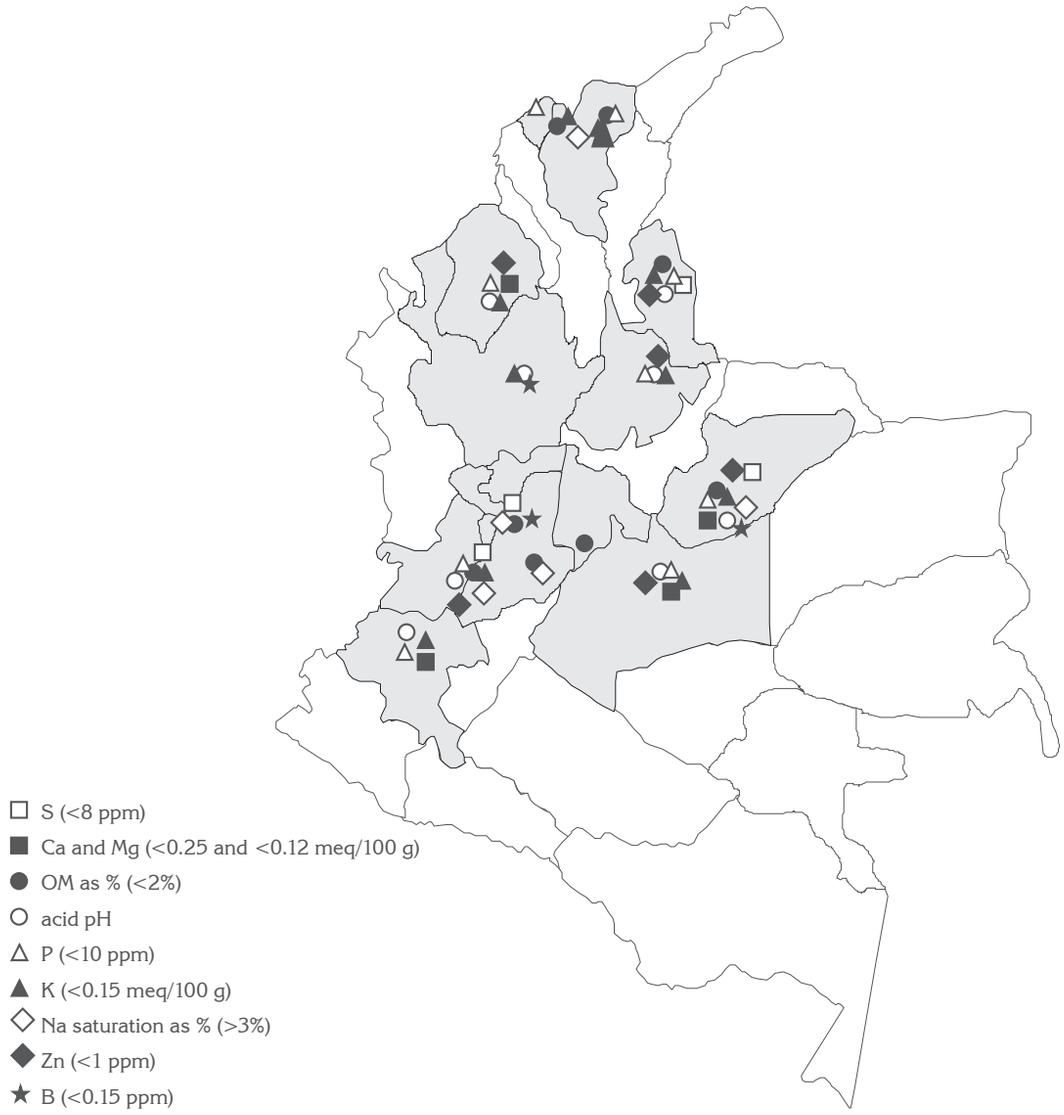


Figure 6-1. Nutritional problems of the cassava crop in Colombia, by region.

Table 6-2. Erosion records, Colombia.

Intensity	Current intensity of erosion in Colombia	
	Affected area (ha)	Proportion of country's surface area (%)
Very severe	829,575	0.73
Severe	8,875,575	7.79
Moderate	14,706,795	12.90
Light	26,337,546	23.11
Very light	5,675,950	4.96
No erosion	55,508,310	48.53
Other areas[a]	2,259,049	1.98
Total	114,174,800	

a. They correspond to marshes, swamps, rivers, and urban areas.

SOURCE: Cobo (1998).

Table 6-3. Degrees of erosion according to the universal soil loss equation (USLE).

Loss (t/ha per year)	Degree
10	1 very light
10 to 20	2 light
20 to 100	3 moderate
100 to 300	4 severe
300	5 very severe
	0 irreversible damage

SOURCE: Curiel (1986, cited by Cadavid L 1987).

northern Cauca; hillside areas of northern Valle del Cauca; and many areas of Quindío, Risaralda, Tolima, and Norte de Santander. Cassava is planted under the current production system of monoculture, with two or more continuous plantings and no agronomic management practices.

Except for the soils of Quindío, Risaralda, and Norte de Santander, many of these regions present soils with very low contents of P, K, Ca, Mg, and Zn (Table 6-1), particularly presenting deficiencies of P and K. Hence, yields are less than 10 t/ha (Figure 6-2; Cadavid L 1997). These demonstrate how the state of soil erosion determine yield and that applying only P cannot re-establish soil productivity lost through this cause (Howeler 1984).

Because of inadequate practices of both soil and cassava crop management in a soil classified as Inceptisol (Typic Dystrandept; an Andosol in the recent classification) in Mondomo, Cauca, Colombia, about 100 t/ha of dry soil were lost from a planting of cassava that alternated with cowpea (*Vigna sinensis*) after 10 months (Figure 6-3; Howeler 1984; Cadavid L 1990). Also in the same soil, when cassava was planted in monoculture and without agronomic management practices, about 40 t/ha of dry soil were lost in a cycle of 10 months (Figure 6-3).

Table 6-4 indicates soil loss, according to management, in a field at Agua Blanca, Mondomo,

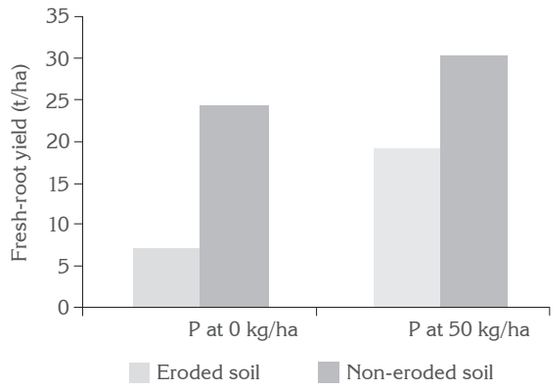


Figure 6-2. Effect of applying P on the production of cassava cv. CMC 92 in eroded and non-eroded soils, Mondomito, Cauca, Colombia.

SOURCE: Howeler and Cadavid L (1984, cited by Cadavid L 1997).

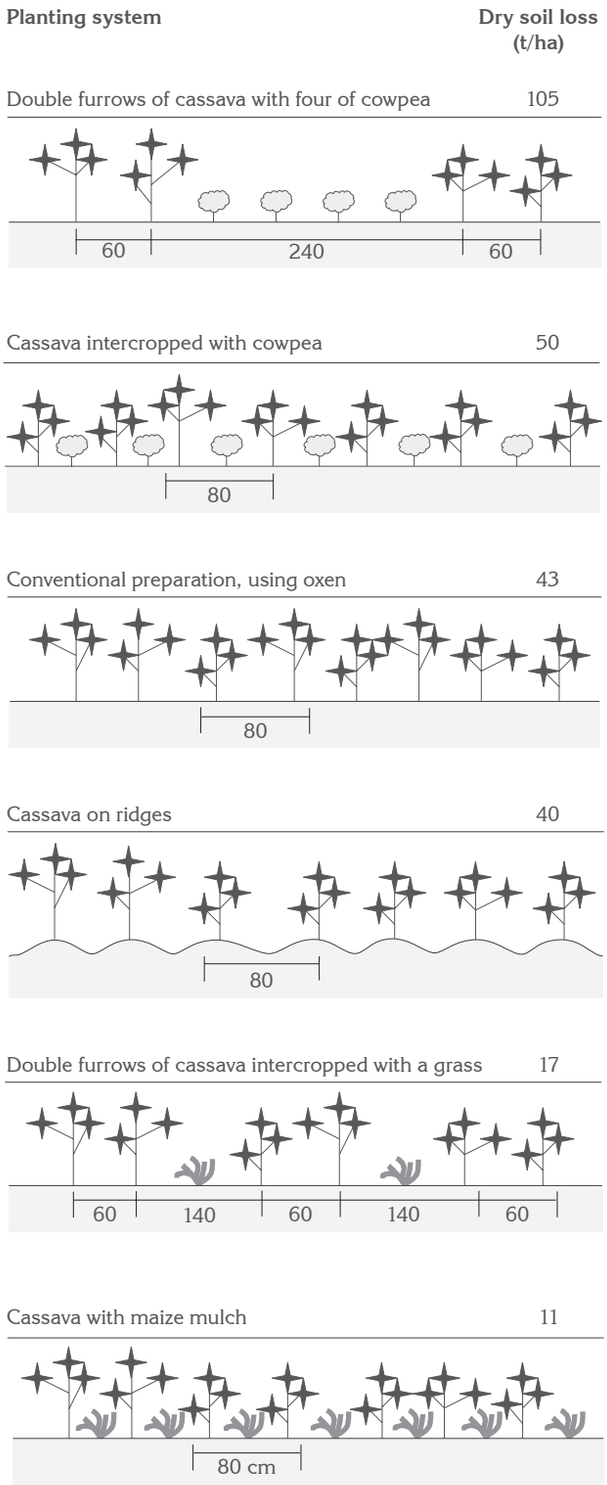


Figure 6-3. Effect of several cassava planting systems on soil loss through erosion over 10 months, Mondomito, Cauca, Colombia.

SOURCE: Howeler and Cadavid L (1982).

Table 6-4. Cassava yield and total quantity of eroded soil after receiving various soil conservation practices, Agua Blanca, Cauca, Colombia.

Treatment	Cassava yield (t/ha)[a]	Dry soil erosion (t/ha)[b]
1. Preparation with oxen; applications of lime, no fertilizer, planting at 80 × 80 cm	6.9	35.9
2. Preparation with oxen; applications of lime and fertilizer, planting at 80 × 80 cm	13.6	22.9
3. Preparation with oxen; applications of lime, fertilizer, and maize mulch; planting at 80 × 80 cm	15.9	15.1
4. Preparation with hoe, strips 1 m wide with double furrows; 1 m no preparation	15.6	14.1
5. Preparation with oxen; double furrows; cassava alternating with 1 m of imperial grass	15.8	19.8
6. Preparation with oxen; double furrows; cassava alternating with 1 m of *Brachiaria* grass	13.3	9.8
7. No preparation; planting with a *barretón* (long-handled digging stick) at 80 × 80 cm; applications of lime and fertilizer	17.6	9.8

a. Average of three varieties: CMC 92, Batata, and Regional Amarilla.
b. Loss over 14 months between planting and harvesting the cassava crop.

SOURCE: Howeler (1984).

Cauca, Colombia, planted with cassava (cvs CMC 92, Batata, and Regional Amarilla) in a 14-month cycle. As observed, soil losses are high as soil preparation tasks intensify and increase even more when fertilizers are not applied.

Because of these and other inadequate practices of soil use and management, the Mondomo Region and other similar areas of the national territory show symptoms of hydric erosion, chemical degradation (high extraction by crop and runoff), and severe biological degradation (Figure 6-4).

Research on these alarming results has demonstrated that the formation of 1 cm of soil from sandy material requires 200 to 400 years, or 3000 to 12,000 years are needed to develop a deep soil, suitable for cultivation (Ortiz 1986). However, paradoxically, within a period of no more than 10 years, land with steep slopes and no conservation practices to protect it from erosion, will lose a layer of up to 1 cm thick (Torres 1981).

Figure 6-4. Severe erosion in the Mondomo Region, Cauca, Colombia.
SOURCE: Cadavid L (1987).

Productive Management of Soils under Cassava Cultivation

Despite the constraints mentioned above, viable alternatives exist for recovering, conserving, and increasing the fertility and productivity of soils under cassava cultivation. Increases can be made in terms of yield of tuberous roots, their improved quality, and planting materials of excellent vigor.

Managing hillside soils

With the current management of hillside soils under cassava cultivation, farmers obtain very low yields and cause irreversible damage to the soil through high erosion rates. The recommendation is to intensify the crop, making it more profitable through increasing yield per hectare. This, in its turn, makes reducing the planting area and preparation systems feasible, thus leaving the steepest soils in fallow or under forest (Howeler 1984).

The idea is to change the predominant scheme of migratory (slash-and-burn) or subsistence agriculture in many areas of the American tropics and arrive at a sustainable, more profitable, and competitive agriculture. Table 6-5 lists viable management alternatives for achieving this objective, as according to several research projects.

Preparing the soil. It is usually believed that, for a cassava crop to successfully germinate, grow, and

Table 6-5. Practices for improving the management of hillside soils and increasing cassava yields.

1. Improve planting materials through selection and treatment of cassava stakes.
2. Reduce planting area by using improved farming techniques and reducing planting on steep slopes.
3. Reduce land preparation (zero and minimum tilling).
4. Prepare the soil and plant seed according to contour lines.
5. Use suitable fertilizer applications.
6. Plant strips of live barriers.
7. Cover soil with mulches of sugarcane, maize, or weeds themselves.
8. Plant green manures and incorporate them.

develop, indiscriminate use of agricultural machinery (plows, rakes, and rotovator) are needed to break up the ground, leaving it as loose as possible for planting. However, this results in negative consequences, not only for soil structure by increasing aggregation and compaction, but it also leads to later soil loss through erosion (Cadavid L 1987).

In soils with slopes of more than 10%, a team of oxen is normally used, together with a plow. However, by planting cassava and being ignorant of adequate management techniques, farmers place pressure on these lands, causing severe damage to soil structure and loss of organic matter and nutrients through hydric erosion (Tables 6-6, 6-7, and 6-8).

Table 6-6. Total loss of dry soil (t/ha) through erosion after removing eight species from that land during 1989–1993, Sri Racha, Thailand. The soil is a sandy loam and has a 7% slope.

	Cropping cycles (no.)	First period (28 months)	Second period (22 months)	Total (50 months)
Cassava for root production	4	168.5 a	142.8 a	311.3
Cassava for leaf production	2	138.5 ab	68.8 b	207.3
Maize	5	35.5 cd	28.5 d	64.0
Sorghum	5	46.1 cd	42.9 c	89.0
Groundnut	5	36.2 cd	37.6 cd	73.8
Mung bean	6	55.3 cd	70.9 b	126.2
Pineapple[a]	2	21.3 d	31.4 cd	52.7
Sugarcane[b]	2	94.0 bc	—	—
F test		**	**	
CV (%)		42.7	11.4	

a. The second cycle is the ratoon crop.
b. Only for a second period of 28 months.

SOURCE: Putthacharoen et al. (1998, cited by Howeler 2001).

Table 6-7. Nutrients found in sediments eroded from cassava plots that had received various treatments, Thailand and Colombia.

Site and treatment	Dry soil loss (t/ha per year)	Missing nutrients (kg/ha per year)			
		N[a]	P[b]	K[b]	Mg[b]
Cassava, 7% slope, Sri Racha, Thailand[c]	71.4	37.1	2.18	5.15	5.35
Cassava, 5% slope, Pluak, Daeng, Thailand[d]	53.2	22.3	1.25	3.27	—
Planted cassava, 7% to 13% slope, Quilichao, Colombia[e]	5.1	11.5	0.16	0.45	0.45
Cassava with legume cover, Quilichao, Colombia[e]	10.6	24.0	0.24	0.97	0.81
Cassava with grass barriers, Quilichao, Colombia[e]	2.7	5.8	0.06	0.22	0.24
Cassava planted on a 12%–20% slope, Mondomo, Colombia[e]	5.2	13.3	1.09	0.45	0.36
Cassava with a legume cover, Mondomo, Colombia[e]	2.7	6.5	0.04	0.24	0.20
Cassava with grass barriers, Mondomo, Colombia[e]	1.5	3.5	0.02	0.13	0.10

a. N total.
b. Available P and interchangeable K and Mg.

SOURCE: As cited by Howeler (2001): (c) Putthacharoen et al. (1998); (d) Tongglum et al. (2000); (e) Ruppenthal et al. (1997).

Table 6-8. Effect of two contrasting management treatments (T_1 and T_2)[a] of soil and crop on both runoff and soil loss through erosion such as nutrients lost in runoff and on the sediments eroded over 2 years of cropping cassava on a 7%–13% slope in Santander de Quilichao and on a 13%–20% slope in Mondomo, both sites in Colombia, cropping years 1987/88 and 1988/89.

Variable or element	Santander de Quilichao				Mondomo			
	1987/88		1988/89		1987/88		1988/89	
	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
Runoff (m^3/ha)	950	1750	1400	2420	340	1470	540	1000
Nutrients lost through runoff (kg/ha)								
Total P	0.16	0.33	0.22	0.47	0.08	0.39	0.13	0.26
Total K	1.49	2.79	1.58	3.08	0.61	3.26	1.47	3.96
Total Ca	2.67	3.50	2.96	5.45	1.29	5.11	2.88	7.56
Total Mg	0.43	0.58	0.30	0.75	0.14	1.22	0.20	1.01
Nutrients lost through	3.00	30.40	5.10	68.00	1.50	33.80	2.60	12.60
Dry soil loss (t/ha) eroded sediments (kg/ha)								
Interchangeable P	0.08	0.41	0.07	1.12	0.01	0.44	0.03	0.18
Interchangeable K	0.34	2.73	0.42	5.05	0.17	3.04	0.27	1.11
Interchangeable Ca	4.08	32.83	6.94	73.44	2.58	31.10	4.47	11.59
Interchangeable Mg	0.25	2.92	0.33	7.08	0.10	3.00	0.19	0.61

a. T_1 = cassava planted according to contour lines; T_2 = cassava planted in rows following the slope.

SOURCE: Adapted from Reining (1992, cited by Howeler 2001).

If the intensity of tilling is reduced, soil loss through erosion can be diminished without significantly affecting cassava production. Moreover, by following contour intervals, unprepared strips can be left and only the planting site is prepared or left without tilling (Tables 6-9 and 6-10; Figure 6-5; Howeler and Cadavid 1982; Howeler 1984; Cadavid L 1987, 1990, 1995).

Zero and minimal tilling are systems in which soil losses through erosion are minimized, diminishing from 50–100 t/ha of dry soil to less than 10 t/ha (Figure 6-3). Costs are less and implementation is directly related to the soil structure; degree and class of plant cover (organic matter content is an important factor); prior soil management (e.g., quantity of chemical fertilizers and dung applied in previous plantings); degree of erosion,

Table 6-9. Cassava yield and total quantity of eroded soil after applying various soil conservation practices, San Emigdio, Valle, Colombia.

Treatment	Cassava yield (t/ha)[a]	Dry soil erosion (t/ha)[b]
1. Preparation of the entire land with a pick; fertilizer application; planting cassava at 80 × 80 cm	24.1	3.2
2. Preparation of 5-m-wide strips with a pick; planting cassava at 80 × 80 cm; alternating with unprepared strips with 1-m width	20.1	2.0
3. Preparation with a pick; fertilizer application; planting of two furrows of cassava, alternating with 1 furrow of *Brachiaria humidicola*	9.7	2.6
4. Preparation with a pick; applications of fertilizer and maize mulch; planting at 80 × 80 cm	18.7	0.3
5. Preparation with a pick; 1-m-wide strips with double furrows of cassava, alternating with unprepared strips with 1-m width	30.5	2.2
6. No preparation; fertilizer application; planting with a *barretón* (digging stick) at 80 × 80 cm	21.6	1.9
7. Preparation; little fertilizer application; planting with two furrows of cassava, alternating with 1 furrow of imperial grass	18.9	1.7
8. No preparation; no fertilizer application; planting with a *barretón* at 80 × 80 cm	6.5	2.4

a. Average of two varieties.

b. Loss over 13 months between planting and harvesting the cassava crop.

SOURCE: García (1984, cited by Howeler 1986).

Table 6-10. Effect of soil management on cassava yield and on soil loss through erosion on a plot with a 30% slope, Mondomito Region, Cauca, Colombia, 1985/86.

Management systems	Dry soil loss (t/ha)[a]	Yield of cultivar (t/ha)[b]			
		1	2	3	$\bar{X}$
Oxen (one pass), no fertilizer	6.0	17.0	12.4	21.2	16.9
Oxen (one pass), with fertilizer	3.4	9.3	27.8	27.3	21.5
Strips, alternating with unprepared strips, with fertilizer	1.2	7.1	4.8	17.2	9.7
No preparation, with fertilizer	2.1	27.5	20.5	29.4	25.8
Oxen, with fertilizer, imperial grass barrier	3.5	20.4	14.4	24.1	19.6
Strip of cassava, with fertilizer, alternating with beans	2.3	18.6	19.0	11.3	16.3

a. 13 months after planting.
b. 1 = Regional Amarilla; 2 = Selección 40; 3 = CMC 92 (Algodona).
SOURCE: Cadavid L (1987).

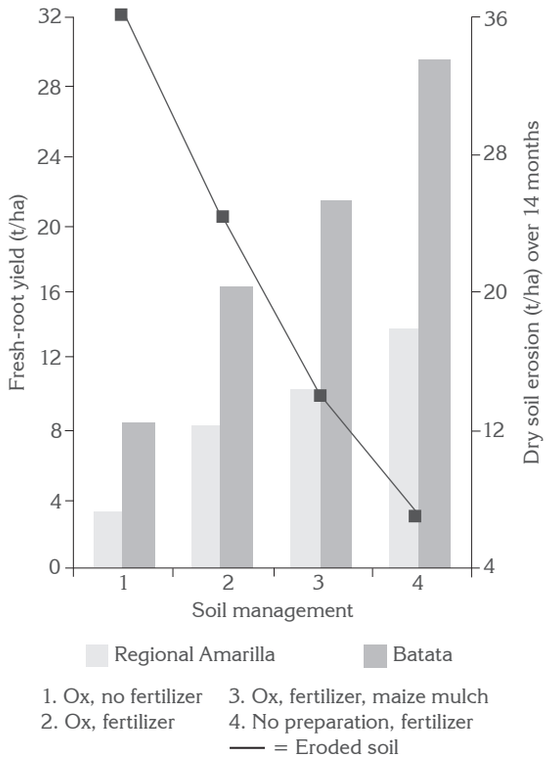


Figure 6-5. Effect of tilling method and fertilizer application on the yield of two cassava cultivars and soil loss in an Inceptisol with a 45% slope, Agua Blanca, Mondomo, Cauca, Colombia, 1982/83.
SOURCE: Adapted from Cadavid L (1990).

soil group or class, and the soil's natural and potential fertility; type and amount of weeds; and the variety to be planted (Howeler 1984; Cadavid L 1987, 1990).

Live barriers. The live barriers are strips or rows of permanent plants, of dense growth, and planted across the slope. The objective of these is to reduce the velocity of runoff, thus preventing soil drag and consequent loss of nutrients.

This method aims to reduce the prepared area by 50%. One example is the case of cassava strips planted two furrows to one of native grass without soil preparation. The whole area can be prepared and intercropped with strips of grasses or legumes, 1 or 2 m wide, and alternating with strips of cassava planted on double furrow according to contour lines and across the slope.

Figures 6-6, 6-7, 6-8, 6-9, and 6-10 outline research results on the effect of live barriers on cassava production of the crop and on soil loss through erosion in the Mondomo Region, Cauca, Colombia (soils

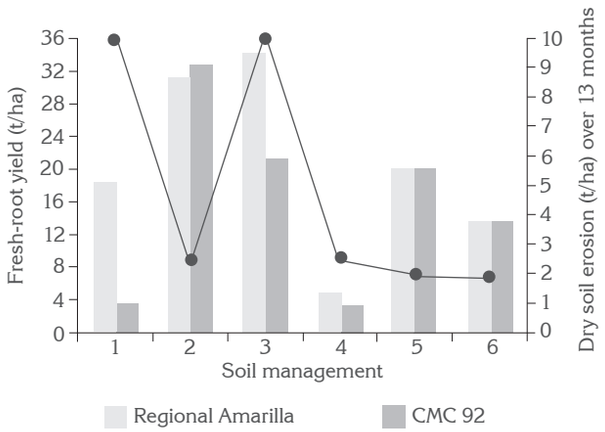
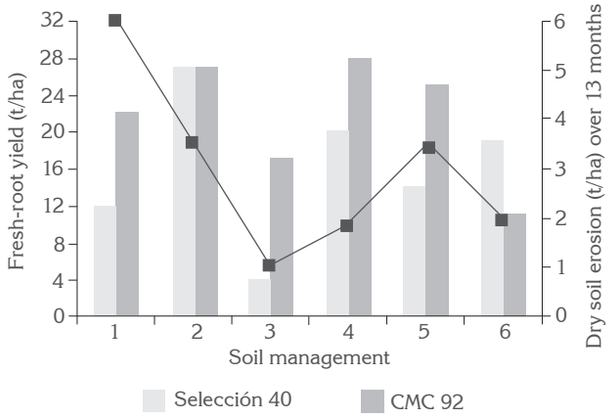


Figure 6-6. Effect of preparation method with weeding and fertilizer application on the yield of two cassava cultivars and on soil loss through erosion with a 40% slope. Tres Quebradas, Mondomo, Cauca, Colombia, 1985/86.
SOURCE: Cadavid L (1990).

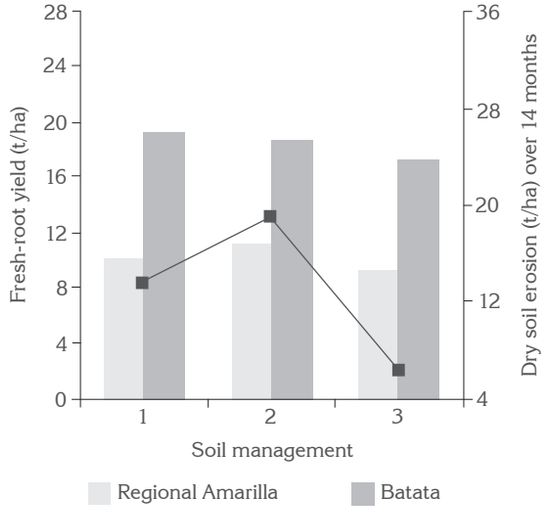


1. Ox (1 pass), no fertilizer
2. Ox (1 pass), fertilizer
3. Ox (1-m strips), fertilizer
4. No preparation, fertilizer
5. Ox (1 pass), fertilizer, imperial grass barrier
6. Ox (1 pass), fertilizer, cassava + beans

—— = Eroded soil

Figure 6-7. Effects of different agronomic practices on the yield of two cassava cultivars and dry soil loss with a 30% slope, Mondomito, Mondomo, Cauca, Colombia, 1985/86.

SOURCE: Cadavid L (1987, cited by Cadavid L 1990).

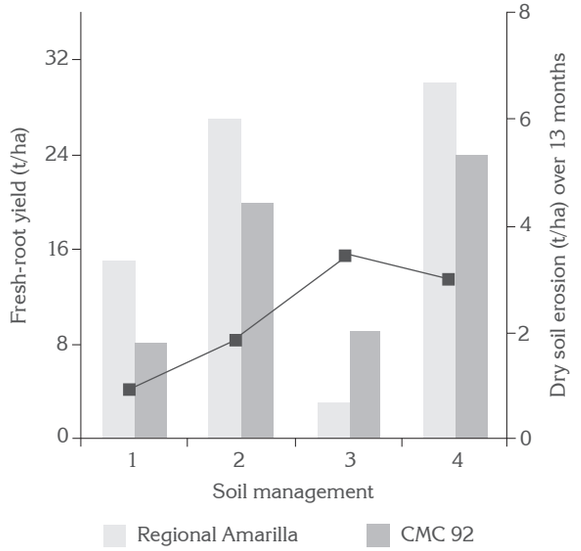


1. Strip, hoe + native grass
2. Ox, strip of imperial grass
3. Ox, strip of *Brachiaria humidicola*

—— = Eroded soil

Figure 6-8. Effect of live barriers on the yield of two cassava cultivars and soil loss from an Inceptisol with a 45% slope, Agua Blanca, Mondomo, Cauca, Colombia, 1982/83.

SOURCE: Adapted from Cadavid L (1990).



1. 1-m strips of native grass
2. Ox, barrier of imperial grass
3. Ox, barrier of king grass
4. Ox, strips of cassava and beans

—— = Eroded soil

Figure 6-9. Effect of live barriers and associated crops on the yield of two cassava cultivars and on soil loss through erosion with a 40% slope, Tres Quebradas, Mondomo, Cauca, Colombia, 1985/86.

SOURCE: Cadavid L (1990).

Figure 6-10. Cassava alternating with strips of *Brachiaria humidicola*, Mondomo Region, Cauca, Colombia.

SOURCE: Cadavid L (1987).

classified as Inceptisols). As can be observed, this management alternative is adequate and does not prejudice crop yield. What is most important is the management of the companion row or strip.

Imperial (*Axonopus scoparius*) and brachiaria (*B. decumbens* and *B. humidicola*) are grasses that, although they compete for light, are acceptable barriers—the yield of intercropped cassava is acceptable—compared with king grass (*Saccharum sinense*), which causes drastic decline in production.

Cassava strips alternating with strips of native grasses (*Pennisetum* sp., *P. purpureum*, and *Paspalum notatum*) provide an intermediate alternative, although the grasses' aggressiveness and competitiveness need controlling. Other recommendable live barriers plants are vetiver (*Vetiveria zizanioides*), lemon grass (*Cymbopogon citratus*), and citronella grass (*C. winterianus*) (Ruppenthal 1995) (Table 6-11).

Fertilization effect. Without a doubt, this agronomic management practice has the most impact on a soil's fertility and productivity and on cassava yields. Howeler (1986, 2001) and Cadavid L (1987, 1997) indicate that applying fertilizers to this crop not only increases yield, but it also produces more vigorous plants that also possess greater leaf area. Hence, soil is protected against the impact of rain drops and risk of erosion is reduced (Table 5-19; Figure 5-11). This theme was amply dealt with in Chapter 5, this volume.

Mulch effect. Howeler (1984, 1986) and Cadavid L (1987, 1990, 1997) report that the protection of soil against the impact of rain is also obtained by applying mulch, that is, plant residues such as maize stubble, grass, beans, rice straw, and banana leaves.

Over time, mulch benefits both soil and crop, providing nutrients, increasing soil moisture, decreasing soil temperature, increasing macrofaunal activity (e.g., earthworms), and improving the water infiltration rate (Tables 6-9 and 6-12; Figure 6-5).

Table 6-12. Effect of mulches of several grasses and legumes on the yields of maize, soybean, cowpea, and cassava in an Alfisol, Nigeria.

Mulch	Yield (t/ha)			
	Maize	Soybean	Cowpea	Cassava
Check, no mulch	2.1	0.51	0.43	8.0
Panicum maximum	1.7	0.50	0.62	3.5
Brachiaria ruziziensis	3.8	1.14	1.04	17.4
Melinis minutiflora	3.4	0.77	0.87	1.8
Centrosema pubescens	3.7	0.75	0.76	15.0
Pueraria phaseoloides	3.4	0.80	0.79	19.5
Stylosanthes guianensis	3.1	0.91	0.67	19.8

SOURCE: Lal et al. (1981, cited by Howeler 1986).

Table 6-11. Fresh-root yield of some cassava cropping systems in Santander de Quilichao and Mondomo for the first 4 to 5 years of the experiment[1].

Cropping system	Yield (t/ha) in:						
	Quilichao[2] in period:				Mondomo[2] in period:		
	1987/89[3]	1989/90[4]	1990/91	1991/92	1988/89[5]	1990/91	1991/92
Monoculture							
Following contour lines	30.7 a	28.4	35.6 a	23.3 a	15.3 a	15.4 abc	13.4 a
In furrows on slope	28.3 a	—	—	—	15.4 a	—	—
On flat land	31.9 a	28.5	35.7 a	22.7 ab	19.7 a	18.4	13.5 a
Minimum tillage	7.7 c	—	—	—	15.7 a	—	—
With mulches	—	30.9	—	—	—	—	—
With grass barriers							
Cassava + *V. zizanioides*	—	—	28.6 a[6]	23.5 a	—	12.4 bc	12.2 a
Cassava + *P. purpureum*	30.2 a[7]	24.4	23.6 a	16.2 ab	18.2 a	12.8 abc	11.0 a

1. Values with the same letters in a column are not significantly different.
2. In cropping periods 1990/91 and 1991/92, cassava was harvested at 11 months in Quilichao and at 8 and 9 months in Mondomo.
3. Average of two cropping periods, planting cassava variety CM 523-07; data from Reining (1992, cited by Ruppenthal 1995).
4. Data from LF Cadavid L, CIAT researcher, Santander de Quilichao, Colombia, The cassava variety was CM 507-37.
5. Cassava variety M Col 1522 (Algodona); data from Reining (1992, cited by Ruppenthal 1995).
6. 10-month-old cassava.
7. Only in the first 2 years; *Paspalum notatum* was planted as a grass barrier, following contour lines.

SOURCE: Ruppenthal (1995).

According to Cadavid L (1990; 1997), mulch is a system that can have mixed results. It may lead to excellent cassava yields and reduce risks of erosion (from 60% to 70%). However, it can have two serious drawbacks: (1) if mulch is not handled properly, yields are low; and (2) if it is not available on the farm (e.g., as residues of maize, beans, or the weeds themselves such as brachiaria or guinea grass), it is costly to transport.

Managing soils in flat lands

Soil preparation and mulches. Hulugalle et al. 1987 (cited by Cadavid L et al. 1993) indicate that literature on the optimal tilling system for the cassava crop is scarce, as few studies have been conducted on this topic.

According to Cadavid L et al. (1993), a high percentage of tropical soils present low fertility and are characterized by being very acid with low contents of N, P, K, Ca, and Mg. Furthermore, soils may have undesirable physical conditions such as poor drainage, low capacity for water retention, high soil temperatures, and fast infiltration rate. To these adverse factors are added nutrient loss through runoff and leaching by hydric and wind erosion, and high compaction caused by poor soil management, as already commented above.

Little research has been conducted on the optimal tilling system for cassava. However, some experiences with different soil classes in Africa and other tropical regions have been reported in the last 13 years and may serve as an example of the different soils in which cassava is planted in Colombia.

In a study carried out on a clayey and highly weathered soil (Typic Paleudult) in southeastern Nigeria, the cassava crop was affected by tilling and time (Gnahoua and Kabrah 1988). In the first planting year, conventional tilling (subsoiling–raking–plowing) increased yield by 10 t/ha, that is, 28.6 t/ha versus 18.6 t/ha for zero tilling.

We point out that, in the same study, the authors indicated that after 4 consecutive years, the positive effects of conventional tilling disappeared and, as a result, yield declined from 28.6 to 16.8 t/ha, while under zero tilling, yield remained constant at about 18 t/ha.

In an acid and low fertility Ultisol (Typic Paleudult) of Nigeria, Hulugalle et al. (1990, cited by Cadavid L et al. 1995) studied the effect of tilling and cover on soil properties and cassava yield over 5 consecutive years. They found that the interchangeable levels of K, Ca, and Mg were higher with cover; and that yield increased with applications of mulch, but not with tilling.

As cited by Cadavid L et al. (1993), Hulugalle et al. (1985) and Wade and Sánchez (1982) suggested that, in tropical Ultisols and without chemical fertilizer applications, crop yields may increase when tilling is combined with mulch applications, permitting increased absorption of nutrients, especially K. They may also minimize soil crusting, reduce soil temperature, and improve water infiltration, thereby protecting the soil more.

According to the Food and Agriculture Organization of the United Nations (FAO)[2], in a sandy soil classified as a Cambic Arenosol, and planted for 8 consecutive years with cassava in Media Luna, Magdalena, Colombia, the use of mulch, together with the preparation method, had a beneficial effect, being highly significant for soil fertility and productivity and cassava yield (Cadavid L et al. 1993, 1995, 1998, Tables 5–23; Figures 6-11 and 6-12; Tables 6-13 to 6-15).

Green manures effect. Green manures are crops, usually legumes, that are planted and, before flowering, incorporated into the soil to improve it chemically and

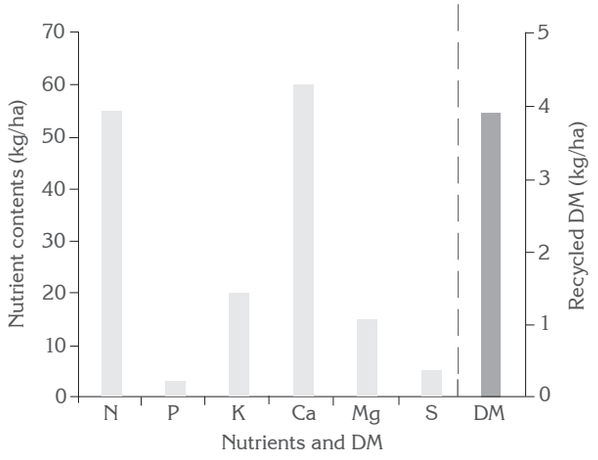


Figure 6-11. Nutrient recycling (fallen leaves and petioles) in cassava plants (cv. CM 523-7) at 10 months after planting and treatment with fertilizer applications, Santander de Quilichao, Cauca, Colombia.

SOURCE: Cadavid L (1988).

2. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Table 6-13. Effect of tilling, mulching, and chemical fertilizer application on the chemical characteristics of a sandy soil over 6 years, Pivijay, Magdalena, Colombia.

Management	With 330 kg/ha at 15–15–15						No chemical fertilizers						Time
	OM (%)	pH (1:1)	P (ppm) Bray II	Ca	Mg	K	OM (%)	pH (1:1)	P (ppm) Bray II	Ca	Mg	K	
				(meq/100 g soil)						(meq/100 g soil)			
Soil before management[a]	—	—	—	—	—	—	0.18	6.10	8.38	0.87	0.28	0.05	1988/89
Conventional management	1.20	5.40	18.88	0.34	0.08	0.05	1.10	5.35	8.25	0.34	0.07	0.04	1993/94
Conventional management + mulch	1.33	6.25	23.43	0.79	0.38	0.13	1.45	6.50	13.65	0.86	0.49	0.17	
Zero tilling management	1.05	5.53	17.30	0.36	0.08	0.05	1.08	5.30	9.43	0.36	0.07	0.04	
Zero tilling management + mulch	1.48	6.28	27.03	0.77	0.45	0.16	1.45	6.43	14.50	0.80	0.46	0.16	

a. Previous crops: cassava, maize, and sesame.

SOURCE: Cadavid L et al. (1995).

Table 6-14. Response, on average, of the aerial biomass, yield, and dry matter content of cassava (over 8 years of trials) and of total HCN content of roots (over 5 years of trials) to the following cultivation practices: mulching with plant residues, fertilizer applications, and tilling in sandy soils of northern Colombia. On-farm trials were initiated in 1988/89 in Media Luna, Magdalena, Colombia.

Main treatment	With fertilizer application[a]				No fertilizer application			
	Root yield (dw, t/ha)[b]	Aerial biomass (dw, t/ha)	Roots (DM, %)[b]	HCN in foliage and roots (dw, mg/kg)	Root yield (dw, t/ha)[b]	Aerial biomass (dw, t/ha)	Roots (DM, %)[b]	HCN in foliage and roots (dw, mg/kg)
Conventional tilling	5.51	3.18	30.2	158	2.19	1.43	30.1	227
Conventional tilling + mulch	5.92	3.98	30.9	146	4.66	2.93	30.6	149
No tilling	4.42	2.77	29.5	150	1.93	1.43	29.2	224
No tilling + mulch	6.11	3.85	31.0	140	4.66	2.95	30.4	158
Average	5.49	3.45	30.4	148	3.36	2.19	30.1	189
LSD 5%, Duncan's[d]	0.26	0.31	NS[c]	12				
LSD 5%, Duncan's[e]	0.77	0.68	0.88	18	0.35	0.49	0.77	0.32

a. Equal doses were applied per treatment of N, P, and K (50, 21, and 41 kg/ha, respectively) at 30 and 60 days after planting cassava.
b. dw = dry weight; DM = dry matter.
c. NS = not significant at a probability of 5%.
d. Comparison of treatments of fertilizer applications.
e. Comparison of means of treatments of fertilizer application.

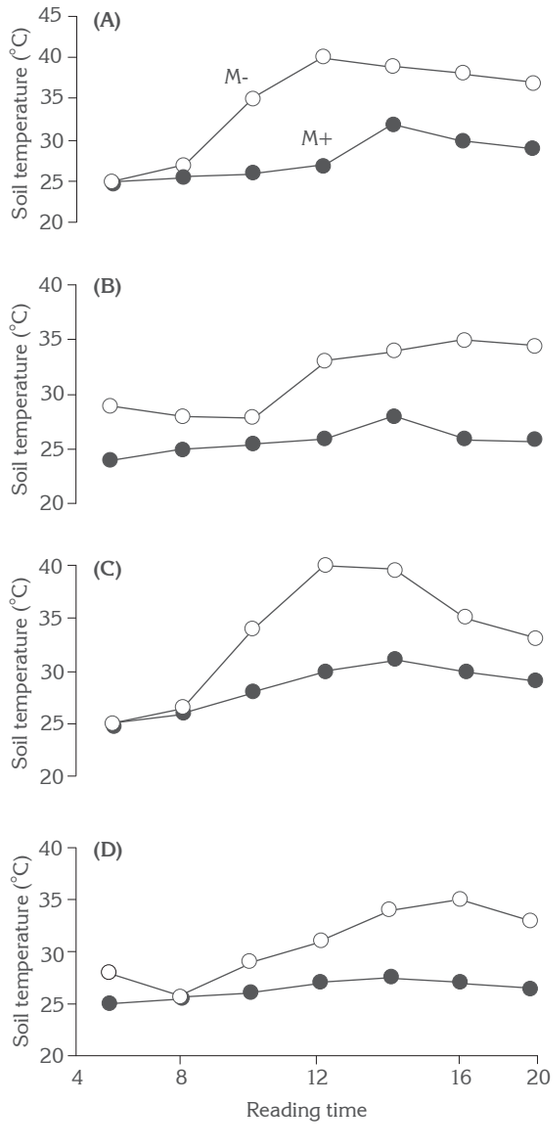
SOURCE: Cadavid L et al. (1998).

Table 6-15. Average response over 4 years (1993 to 1996) of nutrient contents of soil to cropping practices—mulching with plant residues, fertilizer application, and tilling—in sandy soils of northern Colombia. On-farm trials were initiated in 1988/89, in Media Luna, Magdalena, Colombia.

Principal treatment	With fertilizer application[a]						No fertilizer application					
	C (mol/kg of DS)[b]	P	K	Ca	Mg	Soil pH	C (mol/kg of DS)[b]	P	K	Ca	Mg	Soil pH
		(mmol/kg of DS)[b]						(mmol/kg of DS)[b]				
Conventional tilling	0. 54	0.56	0.49	1.85	0.46	4.99	0.50	0.22	0.37	1.78	0.43	4.91
Conventional tilling + mulch	0.62	0.68	1.14	3.64	1.70	5.76	0.69	0.37	1.36	3.85	2.04	5.93
No tilling	0.52	0.50	0.41	1.79	0.42	5.01	0.56	0.26	0.38	1.71	0.37	4.87
No tilling + mulch	0.67	0.65	1.25	3.62	1.85	5.73	0.66	0.40	1.41	3.57	1.97	5.89
Average	0.59	0.60	0.83	2.73	1.11	5.37	0.60	0.31	0.88	2.73	1.20	5.40
LSD 5% Tukey's[d]	NS[c]	0.04	NS	NS	NS	NS						
LSD 5% Tukey's[e]	0.14	NS	0.14	0.89	0.25	0.31	0.06	0.08	0.30	1.01	0.39	0.36

a. Equal doses were applied per treatment of N, P, and K (50, 21, and 41 kg/ha, respectively) at 30 and 60 days after planting cassava.
b. DS = dry soil.
c. NS = not significant at a probability of 5%.
d. Comparing treatments of fertilizer application.
e. Comparing means of treatments of fertilizer application.

SOURCE: Cadavid L et al. (1998).



(A) At 5 cm, conventional tilling
(B) At 20 cm, conventional tilling
(C) At 5 cm, no tilling
(D) At 20 cm, no tilling

● = with mulch (M+)
○ = no mulch (M-); measurement during the dry season (3 Feb 1991).

Figure 6-12. Soil temperature of a cassava crop (M Col 1505) in which the sandy soil was covered with mulch, North Coast Region, Colombia.

SOURCE: Cadavid L et al. (1998).

physically (Prager and Angel, 1989). Some legumes perform better as green manures than others when incorporated, as they increase the amount of organic matter and assimilable nitrogen in the soil (Burbano 1989).

According to Cadavid L (1995) and Howeler et al. (2000), several trials were established in Santander de Quilichao (Cauca) and Media Luna (Magdalena), Colombia, over several years. The highly significant results are indicated in Tables 6-16 to 6-21, which verify the beneficial effects of green manures on the cassava crop.

The use of green materials incorporated into soil is an excellent alternative for improving the physico-chemical conditions of soils under cassava. For this purpose, the following materials should be selected: zornia, kudzu, centrosema, desmodium, guandul, groundnut, and indigofera (Table 6-16). *Sesbania rostrata* and *Crotalaria juncea* should also be selected, although dry weight increases with each of them.

The possibility of establishing green manure banks should also be sought by planting small areas with materials that can resist several cuttings for this purpose.

A trial was established in a soil of Santander de Quilichao, Cauca, Colombia, to prove the effect of cutting in several legumes and a forage grass, and observe their persistence through time and thus evaluate their qualities as green manures for the cassava crop (Table 6-21). The conclusions made from the trial are summarized as follows:

1. Most of these materials adapt to soil acid conditions and were proven in several trials (already described) as green manures.

2. The groundnut and cowpea do not permit several cuts, but one only, although, because of its high nutrient content, the groundnut is recommended as green manure.

3. Most of these materials had medium to high concentrations of nutrients and their contribution of dry weight to the soil is good, as is their persistence, as they can resist several cuttings. Those that stood out include indigofera, kudzu, zornia, brachiaria, and the genera *Stylosanthes*, *Codariocalyx*, *Desmodium*, and *Styzolobium*.

The results of this study and the benefits reported for the cassava crop make this management practice recommendable. This technology should be validated to make better use of soil as a resource (Cadavid L 1995; Howeler et al. 2000).

Table 6-16. Nutrient contents of eight legumes incorporated into an exhausted soil, Santander de Quilichao, Cauca, Colombia (corrected and adapted from Cadavid L 1987).

Legume	Concentration (%)			Quantity (kg/ha) contributed to the soil of:[d]					
	N	P	K	dw (t/ha)	TN	FN	AN	P	K
Styzolobium spp.[a]	2.16	0.24	1.10	2.0	43.2	28.0	15.2	4.8	22.0
Zornia latifolia 728	1.65	0.22	0.78	0.6	9.9	8.4	1.5	1.3	4.7
Centrosema pubescens 438	3.50	0.21	1.25	0.9	31.5	12.6	18.9	1.9	11.3
Cajanus cajan[b]	1.48	0.20	0.55	2.0	29.5	28.0	1.6	4.0	11.0
Groundnut cv. ICA Tatui	1.74	0.15	0.87	1.8	31.3	25.2	6.1	2.7	15.7
Cowpea cv. TVX 1193-059 D	1.29	0.18	0.98	0.5	6.5	7.0	-0.5	0.9	4.9
Indigofera hirsute 700	1.93	0.20	0.70	1.9	36.7	26.6	10.1	3.8	13.3
Pueraria phaseoloides[c]	2.27	0.37	1.60	1.0	22.7	14.0	8.7	3.7	16.0

a. Black velvetbean.
b. Guandul.
c. Kudzu.
d. dw = dry weight; TN = total nitrogen; FN = nitrogen fixed in humus (Torres 1981); AN = available nitrogen [TN minus FN, according to Torres (1981)].

SOURCE: Cadavid L (1995).

Table 6-17. Effect of green manure on fresh-root yield (t/ha) of two cassava cultivars in an exhausted soil of Santander de Quilichao, Cauca, Colombia, during 2 consecutive years (1983/84 and 1984/85).

Treatment	Weight of roots (t/ha)			
	M Col 1684		CM 91-3	
	1st cycle	2nd cycle	1st cycle	2nd cycle
No green manure	16.9	13.6	16.5	10.3
Velvetbean	19.9	19.0	18.4	17.0
Zornia	24.1	22.3	23.7	14.2
Centrosema	25.2	15.2	20.5	12.2
Guandul	28.6	18.8	25.4	12.0
Groundnut	29.4	24.6	29.6	15.6
Cowpea	19.0	19.5	15.0	11.4
Indigofera	25.7	12.7	27.6	9.5
Kudzu	26.9	13.8	30.5	11.5

SOURCE: Cadavid L (1995).

Nutrient Recycling

The cassava plant extracts large amounts of N, K, and Ca from the soil, which indicates that, within the plant, large amounts of these nutrients are recycled throughout its growth cycle. According to CIAT, in a cropping cycle as long as cassava's, the possibility exists that not only are nutrients recycled within the plant, but large amounts return to the soil and is then taken up again by the crop. The return is possible, partly through the fall of leaves and petioles during the growth cycle. On average, cassava begins to lose its leaves from the third month after planting and progressively does so until the development cycle ends, by which time the plant has lost more than 80% of its leaf area. Figure 6-11 indicates how chemical fertilizer application can exert a highly beneficial effect on the production of fallen leaves and petioles.

Table 6-18. Dry weight (dw) and nutrient contents (kg/ha) of green manuresincorporated into an exhausted soil of Santander de Quilichao, Cauca, Colombia[a].

Green manure incorporated	dw (t/ha)	Quantity (kg/ha) of nutrient contributed to the soil							
		TN	FN	AN	P	K	Ca	Mg	S
Zornia latifolia	2.83	63.4	39.5	23.9	4.2	23.2	16.4	8.8	5.7
Pueraria phaseoloides	2.68	84.4	37.5	46.9	5.6	36.7	18.5	8.3	5.6
Arachis pintoi	1.30	30.4	18.2	12.2	2.2	11.3	21.8	8.5	3.1
Macroptilium gracile	1.28	40.8	17.9	22.9	2.8	16.1	10.1	4.7	2.7
Centrosema acutifolium	2.70	75.6	37.8	37.8	4.6	28.1	19.7	6.8	6.2
Desmodium ovalifolium	3.00	50.4	42.0	8.4	4.2	22.5	18.9	8.4	5.4
Paspalum sp.	3.50[b]	39.2	49.0	-9.8	4.9	21.7	16.1	3.9	3.2

a. Green manures planted on the same exhausted plot and left in the soil for 2 consecutive years before being incorporated. Cassava cv. CM 507-37 was then planted at 6 months. TN = total nitrogen; FN = nitrogen fixed in humus (Torres 1981); AN = nitrogen available to the plant.
b. Various cuts at the site.

SOURCE: Cadavid L (1995).

Table 6-19. Dry matter (DM) production of various green manures (GM) and the effect of their incorporation on the soil and cassava yield (cv. M Col 1684). Cassava was cultivated with chemical fertilizer[1] applications or without them, at the CIAT–Quilichao station, cropping years 1983/84 and 1984/85.

Green manure treatment	GM DM (t/ha)	Fertility of soil in 1983[2]				Fertility of soil in 1984[3]		Fresh-root yield[4] (t/ha)			
		pH	OM (%)	P (ppm)	K (meq/100 g)	P (ppm)	K (meq/100 g)	1983/84		1984/85	
								No fert.	With fertil.	No fert.	With fertil.
1. No GM	—	4.1	5.5	3.8	0.10	3.6	0.08	16.9 c[6]	31.9 abcd	13.6 b	31.4 bcd
2. Cowpea	0.45[5]	4.0	5.5	5.2	0.12	5.5	0.08	18.9 bc	26.5 cd	19.5 ab	32.2 abcd
3. Groundnut	1.75[5]	4.1	5.9	5.1	0.14	6.2	0.09	29.3 a	39.0 a	24.6 a	30.0 cd
4. Guandul	1.95	4.1	6.0	4.6	0.13	6.6	0.07	28.6	33.8 abc	18.8 ab	38.9 a
5. Velvetbean	1.95	4.1	5.6	5.5	0.12	5.8	0.08	19.9 bc	23.6 d	18.9 ab	31.9 abcd
6. *Zornia latifolia*	0.55	4.1	5.6	5.2	0.12	5.1	0.07	24.1 abc	41.1 a	22.3 ab	28.6 d
7. *Centrosema pubescens*	0.90	4.1	5.9	4.6	0.11	5.9	0.08	25.1 abc	36.7 ab	15.2 ab	40.0 a
8. *Indigofera hirsuta*	1.90	4.1	5.8	5.5	0.13	6.7	0.08	25.7 ab	29.7 bcd	12.6 b	34.8 abcd
9. *Pueraria phaseoloides*	1.00	4.1	5.6	7.7	0.15	5.4	0.08	26.9 ab	40.4 a	13.7 b	37.3 abc
Average								23.9 b	33.6 a	17.7 b	33.9 a
F test:								Effect of fertil. **		Effect of fertil. *	
								Effect of GM **		Effect of GM NS	
								Fertil. × GM NS		Fertil. × GM **	

1. Application: 500 kg/ha of fertilizer 10–30–10 ($N–P_2O_5–K_2O$) in two cassava crops; DM = dry matter; OM = organic matter.
2. Before planting the first cassava crop in 1983; average of treatments with fertilizer application and without it.
3. Before planting a second cassava crop in 1984; average of treatments with fertilizer application and without it.
4. Values in a row followed by the same letter are not significantly different according to Duncan's Multiple Range Test at 5%; fertil. = fertilizer application.
5. Residual effect of green manures planted in 1983 on cassava yield obtained in 1984/85.
6. Additional yield: 520 kg/ha of groundnut and 420 kg/ha of guandul (measured as dry grain without pods).

SOURCE: Howeler et al. (2000).

Table 6-20. Dry matter (DM) production of some native green manures and their effect as mulch (EM) on soil fertility, and on yield of cassava cv. M Ven 25 cultivated with fertilizer application[a] and without it in a sandy soil, Media Luna, North Coast Region, Colombia, 1984/85.

Green manure treatment	DM of GM (t/ha)	EM (at time of planting cassava) on:						EM (2 months after planting cassava) on:						Fresh-root yield (t/ha)	
		pH	OM (%)	P (ppm)	Cations (meq/100 g S)			Macronutrients (ppm)		Cations (meq/100 g S)				No fertil.	With fertil.
					Ca	Mg	K	NH_4-N	NO_3-N	P	Ca	Mg	K		
1. No green manure	—	5.2	0.70	6.4	0.43	0.11	0.04	3.5	1.5	5.7	0.40	0.10	0.03	19.5	34.3
2. Native weeds	4.73	5.5	0.82	4.6	0.54	0.18	0.06	4.9	2.4	4.7	0.64	0.22	0.05	34.4	30.7
3. Cowpea	2.93	5.3	0.77	5.9	0.52	0.16	0.07	3.1	1.7	5.6	0.48	0.15	0.04	27.6	32.5
4. Groundnut	6.56	5.3	0.97	6.1	0.45	0.13	0.07	3.3	2.1	5.7	0.50	0.17	0.05	32.0	24.8
5. Guandul	3.93	5.1	1.15	8.4	0.54	0.17	0.07	3.3	1.9	6.8	0.47	0.15	0.04	30.2	29.7
6. Velvetbean	2.50	5.5	0.80	5.1	0.47	0.13	0.05	3.3	2.1	6.3	0.45	0.13	0.03	31.9	34.8
7. *Juncea crotalaria*	1.71	5.3	0.85	5.7	0.46	0.13	0.06	3.4	1.7	4.8	0.50	0.15	0.04	24.6	32.6
8. *Canavalia ensiformis*	3.29	5.0	0.85	8.0	0.56	0.17	0.09	4.6	2.6	7.3	0.71	0.20	0.06	34.0	32.9
9. *Indigofera hirsuta*	6.00	5.2	0.82	6.1	0.49	0.14	0.06	3.3	2.5	5.4	0.46	0.14	0.04	30.9	34.8
Average														29.4	32.3

a. Fertilizer application with 500 kg/ha of 15–15–15.
SOURCE: Howeler et al. (2000).

Table 6-21. Use of green manures for cassava in soils of Santander de Quilichao, Cauca, Colombia.

Green manure	Leaf analysis (%)			dw (t/ha) per cut:[a]				Cumulative dw (t/ha)
	N	P	K	1	2	3	4	
Styzolobium spp.	2.16	0.24	1.10	4.9	3.1	1.3	NP	9.3
Cajanus cajan	1.48	0.20	0.55	2.9	1.2	0.6	—	4.7
Indigofera hirsuta	1.93	0.20	0.70	6.0	4.2	2.4	0.6	13.2
Pueraria phaseoloides	2.27	0.37	1.60	4.0	2.8	1.8	2.1	10.7
Zornia latifolia	1.65	0.22	0.78	4.0	4.4	2.5	0.4	11.3
Stylosanthes guianensis	1.54	0.22	1.38	2.6	2.8	1.9	2.3	9.6
Macroptilium glacile	1.62	0.27	0.83	0.9	2.7	1.1	0.4	5.1
Codariocalyx gyroides	1.32	0.15	0.88	3.1	5.5	2.7	2.7	14.0
Groundnut cv. ICA Tatui	1.74	0.15	0.87	1.0	2.4	2.7	NS	6.1
Desmodium ovalifolium	1.32	0.17	0.60	3.7	6.4	3.6	5.9	19.6
Cowpea cv. TVX 1193 059	1.29	0.18	0.98	0.3	2.3	2.6	NP	5.2
Canavalia sp.	2.60	0.25	1.71	6.8	1.1	1.2	—	9.1
Brachiaria humidicola	1.12	0.13	0.32	9.6	14.4	3.7	8.1	35.8

a. Cuts: 1 = 6 months after planting (MAP); 2 = 11 MAP; 3 = 14 MAP; 4 = 19 MAP; in cuts 1 and 2, planting was repeated three times; NP = green manure not planted.

SOURCE: Cadavid L (1995).

Biomass production can be recycled this way, corresponding to about 8% and 9% of final yield (the entire plant) of the plants, with or without chemical fertilizer application, respectively. Figure 6-11 shows the allocation of the average nutrient contents in fallen leaves and petioles of cv. CM 523-7 in a soil at Quilichao, Cauca, during 10 months of growth.

The nutrients that most contribute to these plant organs are Ca and N. Magnesium and K contribute intermediate contents, whereas the poorest contributions came from S and P (Figure 6-11). In itself, only the accumulation of nutrients in these two organs represents the recovery of a very high nutrient loss from the soil. It would be difficult to recover if no adequate maintenance fertilizer applications were to be made.

It is clear, however, that, in the final harvest, no account is ever taken of the contribution of all the accumulated nutrients in fallen leaves and petioles during the development cycle, or in leaves and petioles contributed by the plant during harvest, which, on being returned to the soil, contribute nutrients to the soil and plant through recycling.

Howeler and Cadavid L (1983) suggest that a good part of the N removed of the soil can be returned to the same soil by incorporating leaves and stems. CIAT (1981) states that considerable amounts of this nutrient are returned to the soil through leaves fallen during the cassava's growing cycle.

The use of mulch and the nutrients contributed are directly related to microbial activity, rapid decomposition over time, mineralization rate, nutrient losses to water activity, and other inherent soil factors.

References

Burbano H. 1989. Las enmiendas orgánicas en el suelo: una visión sobre sus componentes orgánicos. Universidad de Nariño, Pasto, Colombia. p 386–422.

Cadavid L LF. 1987. El problema de la erosión en los suelos de Mondomo, Cauca, Colombia, dedicados al cultivo de la yuca y sus posibles soluciones. Faculty of Agricultural Sciences of the Universidad Nacional de Colombia–Palmira. 129 p.

Cadavid L LF. 1988. Efecto de la fertilización y humedad relativa sobre la absorción y distribución de nutrimentos en yuca (*Manihot esculenta* Crantz). MSc thesis. Faculty of Agricultural Sciences of the Universidad Nacional de Colombia–Palmira. 200 p.

Cadavid L LF. 1990. Investigaciones realizadas para la conservación de los suelos de ladera. Suelos Ecuat 20(1):136–144.

Cadavid L LF. 1995. Utilización de abonos verdes en suelos dedicados a la siembra de yuca (*Manihot esculenta* Crantz). Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 17 p.

Cadavid L LF. 1997. Manejo productivo de suelos de ladera cultivados con yuca (*Manihot esculenta* Crantz). In: Fertilidad del suelo y su potencial productivo: fundamentos para la interpretación de análisis de suelos, plantas y aguas para riego. Proc Seminar on Fertilidad del suelo y su potencial productivo, held at Palmira, Colombia, 1995. Sociedad Colombiana de la Ciencia del Suelo (SCCS), Bogotá, DC, Colombia. p 134–143.

Cadavid L LF; Acosta A; El-Sharkawy M. 1993. Manejo de un suelo arenoso en Pivijay, Magdalena, dedicado a la producción de yuca (*Manihot esculenta* Crantz). Suelos Ecuat 23(1/2):155–161.

Cadavid L LF; Acosta A; El-Sharkawy MA. 1995. Efecto de preparación, mulch y abonamiento en el cultivo de la yuca (*Manihot esculenta* Crantz) en suelos arenosos de Colombia. Suelos Ecuat 25:7–10.

Cadavid L LF; El-Sharkawy MA; Acosta A; Sánchez T. 1998. Long-term effects of mulch, fertilization and tillage on cassava grown in sandy soils in northern Colombia. Field Crops Res 57:45–56.

CIAT (Centro Internacional de Agricultura Tropical). 1981. Utilización de la yuca. In: Programa de Yuca, Informe Anual 1981. Cali, Colombia. p 231–250.

Cobo QL. 1998. Diseño, construcción y evaluación de un minisimulador portátil de lluvia para estudios de susceptibilidad a erosión de laderas. Thesis. Faculty of Agricultural Engineering of the Universidad del Valle and the Universidad Nacional de Colombia–Palmira. 64 p.

Gnahoua G; Kabrah Y. 1988. Cassava yield trend and the dynamics of soil chemical parameters in Southeastern Côte d'Ivoire. In: VIII Symposium of the International Society for Tropical Root Crops, held in Bangkok, Thailand. p 237–242.

Howeler RH. 1984. Prácticas de conservación de suelos para cultivos anuales. In: Howeler RH, ed. Manejo y conservación de suelos de ladera. Proc Seminar on Manejo y conservación de suelos, held in Cali, Colombia. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. p 77–93.

Howeler RH. 1986. El control de la erosión con prácticas agronómicas sencillas. Suelos Ecuat 16(1):70–84.

Howeler RH. 2001. Nutrient input and losses in cassava-based cropping system: examples from Vietnam and Thailand. Paper presented at the Workshop on "Nutrient Balances for Sustainable Production and Natural Resource Management in Southeast Asia", held in Bangkok, Thailand, February 2001. Centro Internacional de Agricultura Tropical (CIAT); Regional Cassava Office of the Department of Agriculture, Chatuchak, Bangkok. 30 p.

Howeler RH; Cadavid L LF. 1982. El cultivo de la yuca con conservación del suelo en la región de Mondomo. 7 p. (Multicopy.)

Howeler RH; Cadavid L LF. 1983. Accumulation and distribution of dry matter and nutrients during a 12-month cycle of cassava. Field Crops Res 7:123–139.

Howeler RH; Cadavid L LF. 1984. Prácticas de conservación de suelos para producción de yuca en ladera. Suelos Ecuat 14(1):303–310.

Howeler RH; El-Sharkawy MA; Cadavid L LF. 2000. The use of grain and forage legumes for soil fertility maintenance and erosion control in cassava in Colombia. 30 p.

Ortiz M AP. 1986. Colombia, sus gentes y regiones: La erosión. Instituto Geográfico Agustín Codazzi, (IGAC). Bogotá, Colombia. p 16-39.

Prager M; Angel S DI. 1989. Contribución de los abonos verdes al mejoramiento de la calidad de los suelos. Centro Latinoamericano de Tecnología y Educación Rural, Cali, Colombia. 45 p.

Ruppenthal M. 1995. Soil conservation in Andean cropping systems: soil erosion and crop productivity in traditional and forage-legume based cassava cropping systems in the South Colombian Andes. Margraf Verlag, Weikersheim, Germany. 110 p.

Torres E. 1981. Manual de conservación de suelos agrícolas. Editorial Diana, Mexico. p 123–135.

CHAPTER 7

Weed Control in Cassava

Fernando Calle and Hernán Ceballos[1]

Weed control in cassava has been studied relatively little. Given its hardiness, this crop was believed to tolerate competition from weeds without undue harm. However, in Colombia, the presence of weeds during the first 60 days of the crop's cycle was observed to reduce yields by about 50%, compared with cassava that was free of weeds throughout the cropping cycle.

Weeds pose a significant problem to most cash crops and, particularly to cassava. Weeds tend to determine a plant's development and its later yields. The importance of weeds to food production and their control is clearly documented and supported by the literature. To achieve economically viable production, losses caused by weeds must be adequately controlled. This is very important for both the productivity of high-yielding genetic materials and the development of technology packages. For cassava, this problem is of such a magnitude that it sometimes represents 30% or more of production costs.

Control Methods

In cassava, as in other crops, control must be systematic and integrated. Different options exist for controlling competing plants, whether cultural, manual, mechanized, chemical, or combinations among these approaches. No single control method exists that adapts to all the problems (CIAT 1973, 1976, 1979; Doll and Piedrahita 1973, 1976; López and Leinher 1980; Rodríguez 1989; Carvalho 1990; Marcano et al. 1995; Quiñones and Moreno 1995; Baéz et al. 1998; Girón and Alfonzo 2000; Rosenstein 2001).

Cultural control

This method groups specific practices that enable the crop to be more competitive with weeds. Among the most significant agronomic practices of this control system are correct selection of cultivars, use of good quality "seed" or stakes, optimal planting density, and crop protection.

Manual control

As a consequence of the cassava plant's slow initial growth, several passes of weeding must be carried out, using manual implements, until the crop's canopy closes completely and limits weed development by reducing the availability of light. This method is used in small plantings where labor is available and inexpensive.

Mechanized control

This method is usually employed in combination with manual or chemical control. It consists of using tools, such as cultivators, rotaries, or agricultural hooks, pulled by tractors or animals that pass between the rows and furrows. It starts 15 to 30 days after the crop is planted and continues for as long as crop cover allows it.

Chemical control

This control involves the use of preemergent herbicides, which prevent weeds growing for 45 to 50 days, while the cassava canopy is still open. Because chemical control is usually insufficient for the period of cassava development, the farmer must conduct later weeding activities. Critical shortages of labor and its high cost mean that, currently, chemical control, because of its advantages, becomes a practical

1. Agronomist and Breeder, respectively, Cassava Program, CIAT, Cali, Colombia.
E-mails: f.calle@cgiar.org and h.ceballos@cgiar.org

and economical option, particularly for large cassava plantations.

Available herbicides. For the chemical control of weeds in cassava crops, several products, with preemergent or postemergent action, can be easily obtained on the local market. Their selectivity, with respect to the crop, ranges from medium to high (Table 7-1).

Selecting the herbicide. The diversity of weed populations that become established in the fields is the result of agricultural history. To correctly select the preemergent herbicides, the predominant weeds must be identified before the soil is prepared. Knowing which herbicides control what weeds is also necessary. Weeds that escape the action of preemergent herbicides can be controlled by applying postemergent herbicides. Farmers who do not apply control treatments to their crops frequently confront dense weed infestations.

Integrating Control Methods, Direct Seeding, and Herbicide Tolerance

Cassava is one crop for which the integration of weed control methods is highly necessary, given that its slow initial growth allows weeds to develop vigorously. Preemergent herbicides usually control weeds for only 45 to 50 days, at the end of which the cassava canopy is still not closed. Hence, additional weed control becomes necessary, whether by applying postemergent herbicides or weeding manually.

Direct planting of crops into mulches without inversion plowing provides many advantages that are particularly relevant for cassava and the consequences of climate change. Perhaps the most immediate advantage is reduced production costs. Moreover, direct planting can also reduce the detrimental effects of cassava cultivation can have on the environment. For example, the soil surface is not exposed to the environment while a sufficient mulch of dead and/or

Table 7-1. Herbicides, and their combinations, for controlling weeds in cassava crops.

Product		Characteristics			
Commercial name	Technical name	Selectivity[a]	Time of application[b]	Dose of commercial product/ha	Type of weeds controlled
Karmex	Diuron	M	Pre	2.0–3.0 kg	Broadleaves
Lazo	Alachlor	H	Pre	3.0–4.0 L	Grasses
Cotoran	Fluometuron	M	Pre	4.0–5.0 L	Broadleaves
Goal	Oxyfluorfen	M	Pre	2.0–4.0 L	Broadleaves, grasses
Sencor	Metribuzin	M	Pre	1.0–1.5 L	Grasses
Afalon	Linuron	M	Pre	2.0–3.0 kg	Broadleaves, grasses
Treflan	Trifluralin	H	IBP	2.5–3.5 L	Broadleaves, grasses
Dual	Metolachlor	H	Pre	3.0–4.0 L	Grasses
Roundup	Glyphosate	Non-selective	Post	2.0–3.0 L	Broadleaves, grasses
Basta	Glufosinate	Non-selective	Post	1.0–3.0 L	Broadleaves, grasses
Fusilade	Fluazifop	H	Post	1.0–3.0 L	Grasses
Gramoxone	Paraquat	Non-selective	Post	2.0–3.0 L	Broadleaves, grasses
Karmex + Lazo		M	Pre	1.0–1.5 + 1.5–2.0	Broadleaves, grasses
Cotoran + Lazo		M	Pre	1.0–2.5 + 1.5–2.0	Broadleaves, grasses
Goal + Lazo		M	Pre	1.0–2.0 + 1.5–2.0	Broadleaves, grasses
Afalon + Lazo		M	Pre	1.0–1.5 + 1.5–2.0	Broadleaves, grasses
Karmex + Dual		M	Pre	1.0–1.5 + 1.5–2.0	Broadleaves, grasses
Cotoran + Dual		M	Pre	1.0–2.5 + 1.5–2.0	Broadleaves, grasses
Goal + Dual		M	Pre	1.0–2.0 + 1.5–2.0	Broadleaves, grasses
Afalon + Dual		M	Pre	1.0–1.5 + 1.5–2.0	Broadleaves, grasses

a. Smaller doses in lighter soils; M = medium; H = high selectivity.

b. Pre, Post = preemergent and postemergent, respectively; see also text; IBP = incorporated before planting.

live vegetation protects it. This key approach to reducing soil erosion may increase as rainfall becomes more intense in the world's cassava-growing regions.

Mulches may also increase water-use efficiency, as run-offs are fewer and more water infiltrates into the soil, where it remains for longer periods because of reduced evaporation from the soil surface. Nutrients may also be more efficiently used and retained. Soil structure can progressively improve under such minimal tillage systems.

However, a major drawback of direct planting is the frequently unmanageable weed problem. As desirable as direct planting is, in practice, it has developed quickly only where herbicide-tolerant crops are available. In 2008, herbicide-tolerant crops of soybean, maize, canola, cotton, and alfalfa occupied 79 million hectares or about two-thirds of the global biotech crop area of 125 million hectares, the total area on which biotech crops are grown (ISAAA 2008). These data refer to plants that are genetically transformed to tolerate herbicides, particularly glyphosate.

Genetic transformation is also feasible for cassava (see Chapter 21, *Biotechnology for Cassava*, this volume). The first evidence of somatic embryos and transgenic cassava was reported between 1993 and 1995 (Sarria et al. 1995, 2000) for tolerance of the herbicide glufosinate-ammonium (Figure 7-1). Since then, several projects on transgenic cassava have been developed (Taylor et al. 2004), including reduced cyanogenic potential (Siritunga et al. 2004; Jørgensen et al. 2005); starch quantity and quality (Raemakers et al. 2005; Ihemere et al. 2006); increased carotenoid content in roots (Chavarriaga et al. 2009); and leaf retention (Zhang and Gruissem 2004). The silencing of specific genes through RNA interference has also been demonstrated (Jørgensen et al. 2005).

Other alternatives exploit natural or induced variation for herbicide tolerance in different crops (Sherman et al. 1996; Tan et al. 2005, 2006; Tan and Bowe 2008). In most cases, tolerance of imidazolinones arises from changes in the gene codifying for acetohydroxy acid synthase (AHAS). Resistance against cyclohexanedione, found in maize, is regulated by acetyl-CoA carboxylase, and that against triazine originates in the *psbA* gene, which is related to photosynthesis (Tan et al. 2005, 2006). These discoveries have led to the development of herbicide tolerance in different crops such as maize, rice, wheat, canola, sunflower, lentils, sugar beet, cotton, soybean, lettuce, tomato, and tobacco.

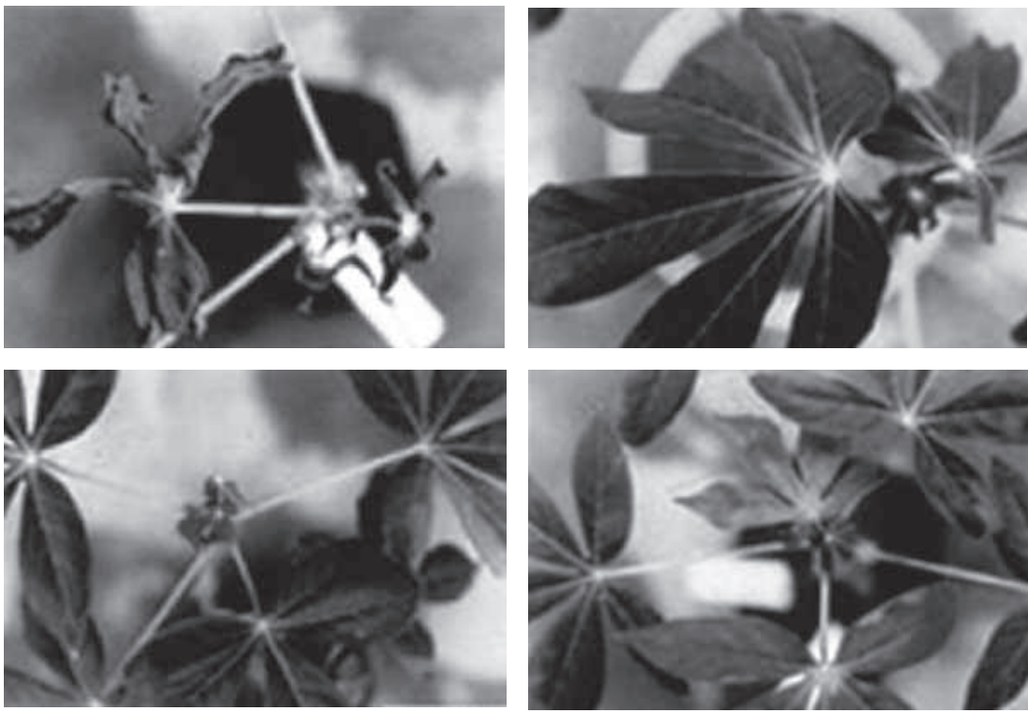


Figure 7-1. Genetically transformed cassava resistant to the herbicide Basta® (glufosinate-ammonium). This work was carried out for purely research purposes, as commercial exploitation of this product was not permitted.

Tolerance of herbicides can be achieved mostly through one of three mechanisms: (a) resistance at the herbicide's site of action; (b) metabolic detoxification of the herbicide; and (c) preventing the herbicide access from having to its site of action (Sherman et al. 1996). These considerations are relevant because, in some cases, tolerance of herbicides can assume a dominant or semi-dominant gene action, in addition to the more common recessive behavior. Maternal effects have also been reported (Tan and Bowe 2008). The most relevant examples of herbicide-tolerant crops are for imidazolinone (i.e., CLEARFIELD®), glyphosate (i.e., Roundup Ready®), and glufosinate (i.e., LibertyLink®) products. Tolerance of Roundup Ready® is based, so far, solely on genetic transformation.

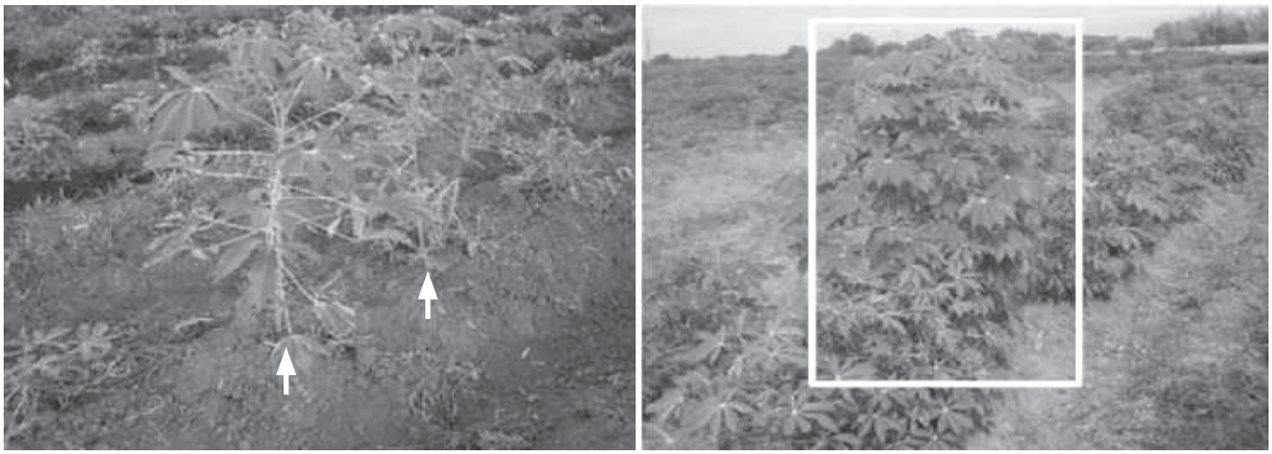
CIAT has initiated two aggressive approaches to identifying herbicide tolerance in cassava. The first approach, which induces self-pollinating cassava germplasm to produce S_1 genotypes, can expose recessive sources of tolerance to herbicides. The genotypes thus produced can then be subjected to different herbicides to detect phenotypes expressing tolerance. The second approach is through the use of molecular markers for the application of TILLING or EcoTILLING (Till et al. 2003; Guang-Xi et al. 2007). This approach is greatly facilitated by clearly understanding the genes that must be mutated, and the recent availability of the sequenced cassava genome.

The evaluation of partially inbred cassava materials started in 2009. A total of 700 cloned S_1 genotypes were evaluated in the field. Each genotype was represented by 12 plants, which had been planted in six different blocks in the field (two plants per genotype in each block). Each block was treated with commercial doses of the following herbicides: 2,4-D (Anikilamina®); glyphosate (Roundup®); imidazolinone (Plateau®); sulfonylurea (Ally®); glufosinate-ammonium (Basta®; Finale®); and atrazine. Although results are still preliminary, at least one genotype appears to have obvious tolerance of glufosinate-ammonium. Figure 7-2 illustrates clear differences in vigor of these two plants, compared with related S_1 genotypes.

References

Baéz J; Antequera R; Ramos J; Gutiérrez W; Medrano C. 1998. Densidad de siembra y control de malezas en el cultivo de la yuca (*Manihot esculenta* Crantz) en siembra directa bajo las condiciones de la planicie de Maracaibo. Rev Fac Agron Univ Zulia (Venez) 15(5):429–438.

Carvalho JEB de. 1990. Controle de plantas daninhas em mandioca. Centro Nacional de Pesquisa de Mandioca e Fruticultura (CNPMF), Cruz das Almas, BA, Brazil. 38 p.



December 1 January 18

Figure 7-2. Examples of an S_1 genotype (represented by two plants and highlighted by white arrows) with tolerance of glufosinate-ammonium. This genotype is surrounded by other, related, S_1 genotypes. The difference in vigor and absence of typical damage in the growing tip on applying the herbicide strongly suggests that this genotype tolerates the herbicide. The photographs were taken at two different ages of the plant.

Chavarriaga P; Beltrán J; Ladino J; Vacca O; López D; García M; Prías M; Oarra S; Al-Babili S; Beyer P; Tohme J. 2009. Combining biotechnology, molecular genetics and breeding to improve the content of carotenes in cassava roots. In: Proc 15th Triennial Symposium of the International Society of Tropical Root Crops, held in Lima, Peru, 2–6 November. Centro Internacional de la Papa (CIP), Lima, Peru. p 63–64.

CIAT (Centro Internacional de Agricultura Tropical). 1973. Informe anual 1972. Cali, Colombia. p 75–80.

CIAT (Centro Internacional de Agricultura Tropical). 1976. Informe anual 1975. Cali, Colombia. 63 p.

CIAT (Centro Internacional de Agricultura Tropical). 1979. Manejo y control de las malezas en el cultivo de la yuca—Guía de estudio para ser usada como complemento de la unidad audiotutorial sobre el mismo tema. Cali, Colombia. 36 p.

Doll J; Piedrahita W. 1973. Effect of time of weeding and plant population on the growth and yield of cassava. Paper presented at the Third International Symposium of Tropical Root Crops, Ibadan, Nigeria. 13 p. (Multicopied.)

Doll J; Piedrahita W. 1976. Métodos de control de malezas en yuca. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 12 p.

Girón C; Alfonzo E. 2000. Manejo integrado de malezas en yuca. Agron Trop (Maracay) 50(1):31–40.

Guang-Xi W; Tan M-K; Rakshit S; Saitoh H; Terauchi R; Imaizumi T; Ohsako T; Tominaga T. 2007. Discovery of single-nucleotide mutations in acetolactate synthase genes by Eco-TILLING. Pestic Biochem Physiol 88:143–148.

Ihemere U; Arias-Garzón D; Lawrence S; Sayre R. 2006. Genetic modification of cassava for enhanced starch production. Plant Biotechnol J 4:453–465.

ISAAA (International Service for the Acquisition of Agri-biotech Applications). 2008. Global Status of Commercialized Biotech/GM Crops: 2008.

Jørgensen K; Bak S; Busk PK; Sørensen C; Olsen CE; Puonti-Kaerlas J; Møller BL. 2005. Cassava plants with a depleted cyanogenic glucoside content in leaves and tubers: distribution of cyanogenic glucosides, their site of synthesis and transport, and blockage of the biosynthesis by RNA interference technology. Plant Physiol 139:363–374.

López J; Leinher DE. 1980. Control químico de malezas en policultivos con yuca (*Manihot esculenta* Crantz). Rev Comalfi 7(1/2):19–28.

Marcano JJ; Paredes F; Segovia P. 1995. Control de malezas en yuca. FONAIAP Divulg (Venez) 49:39–40.

Quiñones V; Moreno N. 1995. Control de malezas en yuca en Barinas, Venezuela. Agron Trop (Maracay) 45(1):85–94.

Raemakers K; Schreuder M; Suurs L; Furrer-Verhorst H; Vincken JP: de Vetten N; Jacobsen E; Visser RGF. 2005. Improved cassava starch by antisense inhibition of granule-bound starch synthase, I. Mol Breed 16:163–172.

Rodríguez R. 1989. Lucha contra las malezas en el cultivo de la yuca (*Manihot esculenta* Crantz). Ciencia Téc Agric Ser Prot Plantas (Cuba) 12(1):91–109.

Rosenstein E. 2001. Diccionario de especialidades agroquímicas: Sección semillas, 11 ed. Editorial PLM, Bogotá, DC, Colombia. p 2–10.

Sarria R; Torres E; Balcázar M; Destefano-Beltrán L; Roca WM. 1995. Progress in *Agrobacterium*-mediated transformation of cassava (*Manihot esculenta* Crantz). In: Proc Second International Scientific Meeting of the Cassava Biotechnology Network, held in Bogor, Indonesia, 22–26 August 1994. Working Document No. 150. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. p 241–244.

Sarria R; Torres E; Angel F; Chavarriaga P; Roca WM. 2000. Transgenic plants of cassava (*Manihot esculenta*) with resistance to Basta obtained by *Agrobacterium*-mediated transformation. Plant Cell Rep 19:339–344.

Sherman TD; Vaughn KC; Duke SO. 1996. Mechanisms of action and resistance to herbicides. In: Duke SO, ed. Herbicide resistant crops. CRC Press, Boca Ratón, FL, USA. p 13–35.

Siritunga D; Arias-Garzón D; White W; Sayre R. 2004. Over-expression of hydroxynitrile lyase in transgenic cassava roots accelerates cyanogenesis and food detoxification. Plant Biotechnol J 2:37–44.

Tan SY; Bowe S. 2008. Developing herbicide-tolerant crops from mutations. In: Proceedings FAO/IAEA International Symposium on Induced Mutations in Plants, held in Vienna, Austria, 12–15 August. p 134.

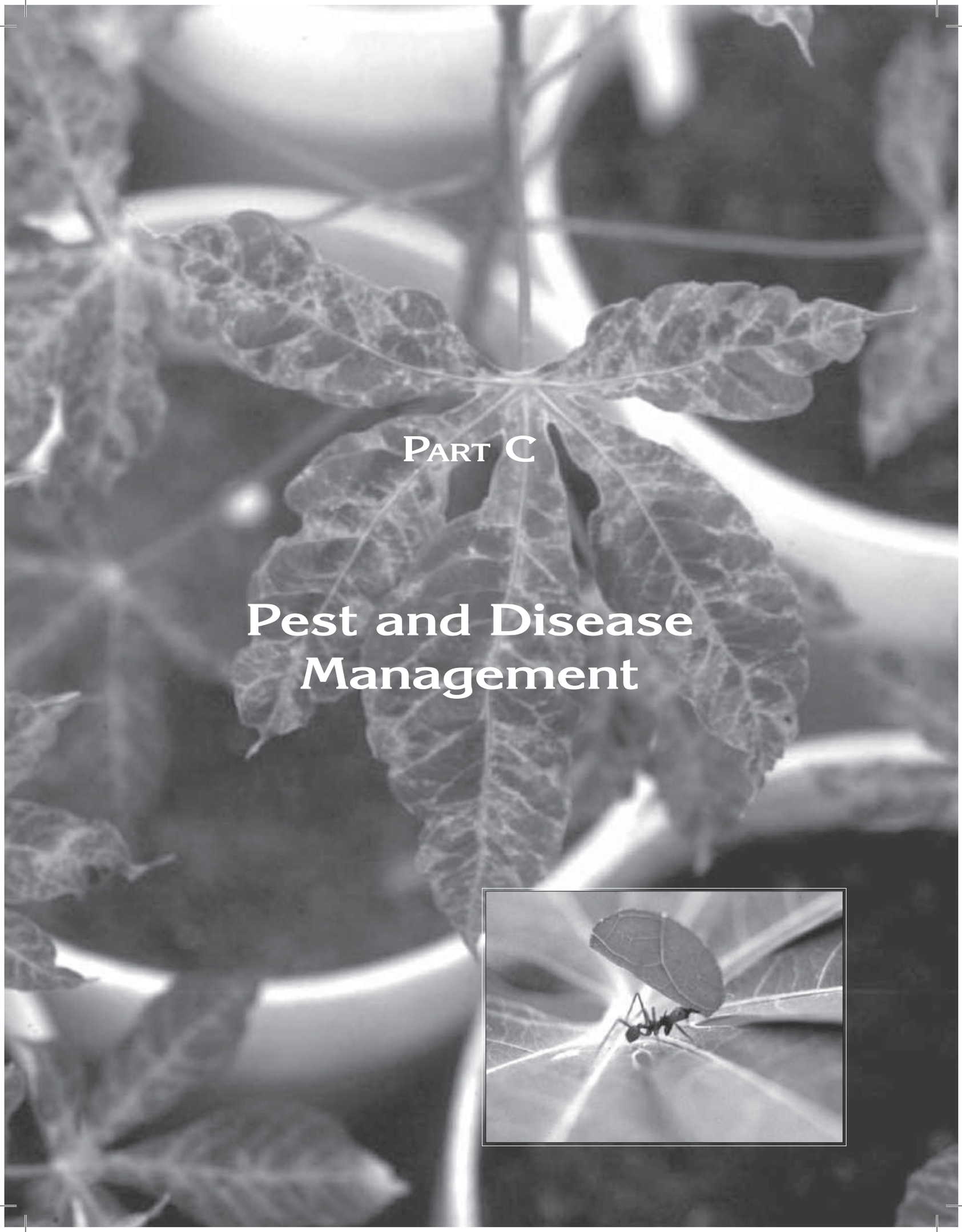
Tan S; Evans RR; Dahmer ML; Singh BK; Shaner DL. 2005. Imidazolinone-tolerant crops: history, current status and future. Pest Manage Sci 61:246–257.

Tan S; Evans R; Singh B. 2006. Herbicidal inhibitors of amino acid biosynthesis and herbicide-tolerant crops. Amino Acids 30:195–204.

Taylor N; Chavarriaga P; Raemarkers K; Siritunga D; Zhang P. 2004. Development and application of transgenic technologies in cassava. Plant Mol Biol 56:671–688.

Till BJ; Reynolds SH; Greene EA; Codomo CA; Enns LC; Johnson JE; Burtner C; Odden AR; Young K; Taylor NE; Henikoff JG; Comai L; Henikoff S. 2003. Large-scale discovery of induced point mutations with high-throughput TILLING. Genome Res 13:524–530.

Zhang P; Gruissem W. 2004. Extension of cassava leaf life by autoregulatory inhibition of senescence. Paper presented at the Sixth International Scientific Meeting of the Cassava Biotechnology Network, held in Cali, Colombia, 8–14 March 2004.



Part C

Pest and Disease Management

CHAPTER 8

Cassava Diseases

Elizabeth Álvarez[1], *Germán Alberto Llano*[2], *and Juan Fernando Mejía*[3]

World production of cassava roots was estimated at 233 million tons in 2008. Africa was the largest producer with 118 million tons on almost 12 million hectares, followed by Asia with 78.7 million tons on 3.97 million ha. Cassava (*Manihot esculenta* Crantz) is a significant staple, providing a basic daily source of dietary energy for almost one billion people in 105 countries. It also has numerous agroindustrial uses. Cassava grows on marginal lands, tolerates drought, and can grow in low-fertility soils. Cassava is also the most inexpensive source of starch that exists, being used in more than 300 industrial products (FAOSTAT, 2010).

Cassava is still widely cultivated under traditional management. This suggests that large numbers of farmers may be ignorant of the crop's diseases and their integrated management. Hence, several diseases threaten the sustainability of cassava production and its profitability. The principal diseases attacking the crop are:

Cassava bacterial blight (CBB[4]; *Xanthomonas axonopodis* pv. *manihotis* or *Xam*)
Phytophthora root rots (PRR; *Phytophthora* spp.)
Superelongation disease (SED; *Sphaceloma manihoticola*)
Cassava frogskin disease (CFSD; *Candidatus* phytoplasma, Cfdp of the 16SrIII-L and rpIII-H subgroups)
Cassava mosaic disease (CMD; begomovirus complex)
Cassava brown streak disease (CBSD; an ipomovirus)
Brown leaf spot (*Cercosporidium henningsii*)
Diffuse leaf spot (*Cercospora vicosae*)
White leaf spot (*Phaeoramularia manihotis*)
Anthracnose (*Colletotrichum* spp.)

1. Plant Pathologist, Cassava Program, CIAT, Cali, Colombia. E-mail: e.alvarez@cgiar.org
2. Agronomist Consultant, Cali, Colombia. E-mail: germanlln@yahoo.com
3. Research Associate, Plant Pathology, Cassava Program, CIAT. Currently Doctoral Candidate, Plant Pathology, Università di Bologna, Bologna, Italy. E-mail: juan_fmejia@yahoo.es; juanfernando.mejiad2@studio.unibo.it
4. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Diseases Caused by Fungi

Superelongation disease (*Elsinoe brasiliensis*)

Importance. Superelongation disease (SED) attacks susceptible cultivars, especially during the rainy seasons. Damage caused by SED is highly variable, depending on the level of cultivar resistance, climatic conditions, concentration of the initial inoculum, and the degree of contamination of planting materials (Álvarez and Llano 2002).

Losses can exceed 80% of total production in young crops, whereas significant losses do not occur in crops that are more than 6 months old. In Colombia, SED is found in the Eastern Plains, Atlantic Coast, and inter-Andean valleys. The disease is acute in agroecological areas with annual mean temperatures of 28 °C and annual precipitation of more than 1500 mm. In the greenhouse, 8 h of misting at temperatures of 25 to 30 °C was sufficient to cause an outbreak, indicating how easily the pathogen develops in the field (Mejía 2001).

Distribution. Superelongation disease was first observed by Bitancour and Jenkins in 1950, on *Manihot glaziovii* Muell.-Arg. in Brazil and Nicaragua and on *M. esculenta* in the Dominican Republic and Guatemala. The disease has since been reported (in order of reporting year) in Costa Rica (Larios and Moreno 1976), Colombia (Lozano and Booth 1979), Mexico (Rodríguez 1979), Cuba (Pino 1980), Venezuela (Rondón and

Aponte 1981), the Dominican Republic (Sosa 1992), Barbados, Panama (Chávez 1992; Zeigler 2000), Brazil (where it is restricted to the western regions of the country) (Álvarez et al. 2003d), and Trinidad and Tobago (Reeder et al. 2008). At the end of 2008, the disease was detected in Thailand (E Álvarez 2008, pers. comm.). The disease appears to be unknown in Africa.

Symptoms and epidemiology. The characteristic symptom of this disease is the exaggerated lengthening of stem internodes (Zeigler et al. 1980), creating thin and weak stems. Diseased plants are much taller and/or weaker and spindlier than healthy ones. In green sections of stems, and in petioles and leaves, deformations develop in associations with cankers. The lens-shaped cankers often have dark margins and are variable in size. In leaves, cankers are found on the underside, along the primary or secondary nervures. In stems, they may be more diffuse. Frequently, young leaves curl, and do not develop fully nor do the leaf blades expand completely. Leaves also develop irregular white spots (Figure 8-1). Sometimes partial or total death of leaves occurs, resulting in considerable defoliation. Dieback of the plant may also occur.

The disease spreads from one place to another through the use of infected stakes. The principal focuses of infection frequently constitute the shoots originating from residues of old plants left in the field after harvest. The disease spreads rapidly during the rainy season. This rapid dissemination is believed to occur through the formation of spores in the cankers. These spores can survive for more than 6 months in infected plants and are carried by rain and wind.

Etiology. Superelongation disease is caused by the fungus *Elsinoe brasiliensis*, which initially grows on the epidermis of the host and, after penetration, grows in the intercellular spaces in tissues of the epidermis and cortex. The fungus produces gibberellins, which promote the exaggerated growth in the plant's internodes. Gibberellins, as suggested by previous studies for other pathogens (Muromtsev and Globus 1975), play an essential role in the fungus's nutrition. The fungus, which has a low production of hydrolytic enzymes, uses this hormone to obtain sugars from the plant, promoting, at the molecular level, hydrolysis of carbohydrates with greater mass (Mejía 2001).

According to Álvarez and Molina (2000), the pathogen's genetic diversity in Colombia is broad, presenting differences among isolates within a single location and between locations. Isolates from the Atlantic Coast, Eastern Plains, and inter-Andean valleys of Colombia and from central and southern Brazil comprise two evolutionary units, with each unit relating to its respective country (Álvarez et al, 2001).

For gene 18S rRNA, obtained from two isolates of *E. brasiliensis*, the sequencing of a region involving ITS1 and ITS2 was reported to GenBank (accessions AY739018 and AY739019; CIAT 2004).

Host range. *Elsinoe brasiliensis* and *Sphaceloma* species (the asexual state), which both attack cassava, have a wide range of Euphorbiaceae hosts, including *Euphorbia brasiliensis* L., *E. hypericifolia* L., *Jatropha aconitifolia* Muell. var. *papaya* Arbelaez, *J. curcas* L., *Manihot carthaginensis* Muell., *M. esculenta*, and *M. glaziovii*. These hosts are cosmopolitan weeds and widely cultivated ornamentals.

Many regions in Africa and Asia have climatic conditions that closely resemble to those of the Eastern Plains, Atlantic Coast, and inter-Andean valleys of

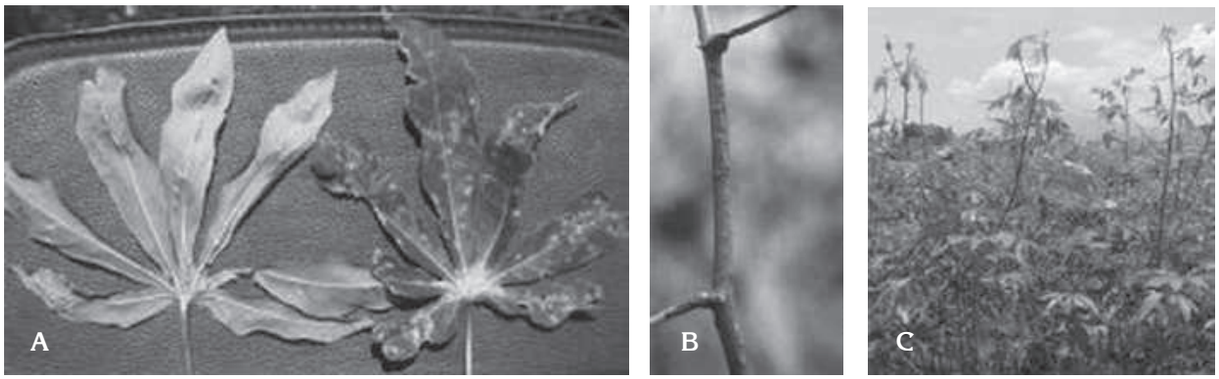


Figure 8-1. Symptoms of superelongation disease in cassava: **(A)** cankers on leaves, **(B)** cankers on petioles and stem, and **(C)** elongated stem.

Colombia, where the pathogen causes considerable losses. These African and Asian regions therefore face the danger that the pathogen will be introduced through planting materials of ornamentals such as *Jatropha* spp. L., which are not necessarily restricted by the same sanitary regulations as cassava.

Because the host range is broad, completely eradicating the pathogen is impossible and a certain amount of sufficient inoculum will be present throughout the year. In Brazil, the weed *Euphorbia heterophylla* L. was shown to be host to strains of *Elsinoe brasiliensis* that were highly pathogenic to cassava (Álvarez et al. 2003d). Furthermore, the genetically very variable hosts are also able to maintain a variable population of the pathogen (Zeigler 2000).

Integrated disease management. The use of healthy seed, obtained from disease-free plants or from plants derived from meristem culture, comprises a tool that may be sufficient to maintain disease-free crops. However, one preventive method for eradicating the pathogen is to immerse infected stakes for 10 min in captafol at 4.8 g/L of active ingredient (a.i.). When symptoms are observed in the field, foliar spraying should be carried out with difenoconazole at 0.07 cc/ha, followed by crop rotation with grasses.

In areas where the pathogen is endemic, planting should be carried out during periods with the least precipitation (CIAT 2003b). Infected plants (cassava or other Euphorbiaceae hosts) should be destroyed as soon as they are identified. The best way to eliminate this material is to pull up infected plants and burn them *in situ* (Zeigler 2000).

Varietal resistance. The selection of resistant varieties is perhaps the best alternative for controlling SED. Between 1995 and 2007, CIAT evaluated about 6400 genotypes at Villavicencio (Colombia) and found 257 with resistance to SED. On-farm evaluations at Sincelejo (Sucre, Colombia) showed the following as resistant: M Ven 25 and CM 4843-1, followed by ICA Catumare, ICA Cebucán, ICA Negrita, Vergara (CM 6438-14), and CM 4574-7 (CIAT 2001, 2002b, 2003a).

Pathogenic races of *E. brasiliensis* exist and are of high genetic variability. While they should be taken into account when improving resistance to SED (Álvarez and Molina 2000; Álvarez et al. 2003d), they are not thought to pose serious constraints to varietal improvement (Zeigler 2000).

Biological control. Spraying with suspensions of *Pseudomonas putida* considerably reduced the severity of damage caused by SED, thereby significantly increasing cassava yields (CIAT 1985).

Brown leaf spot (*Cercospora henningsii*)

Importance. Brown leaf spot has a broad geographical distribution, being found in Asia, North America, Africa, and Latin America. It attacks naturally *M. esculenta*, *M. glaziovii*, and *M. piauhynsis* Ule (Ferdinando et al. 1968; Golato and Meossi 1966; Powell 1972). In India, *Cercospora henningsii* is an important pathogen, causing severe defoliation (Edison 2002).

Symptoms and epidemiology. Symptoms in cassava leaves are characterized by leaf spots visible on both sides. On the leaves' upper surface, uniform brown spots appear, with defined and dark margins. On the leaves' undersurface, the lesions have less-defined margins and, towards the center, the brown spots have a gray-olive background because of the presence of the fungus's conidiophores and conidia. As these circular lesions grow, from 3 to 12 mm in diameter, they take up an irregular angular form, their expansion being limited by the leaves' major veins (Figure 8-2).

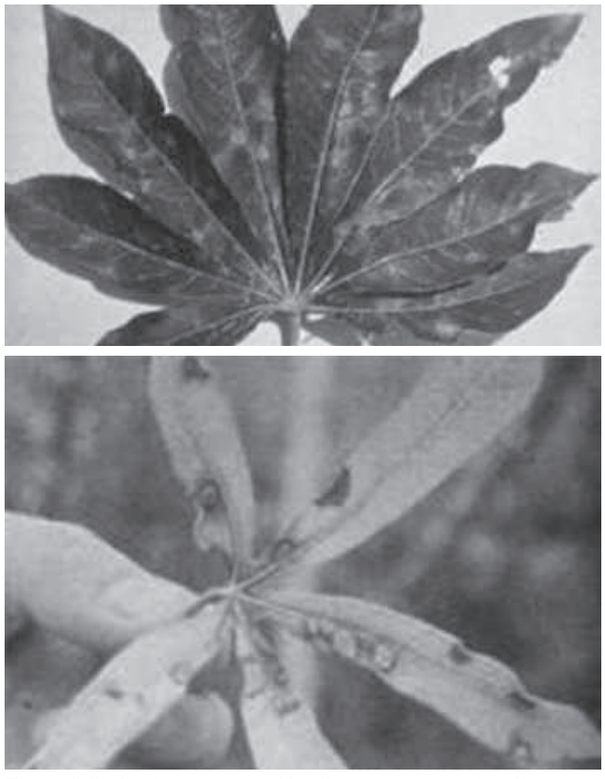


Figure 8-2. Leaf spots caused by *Cercospora henningsii*.

The veins found within the necrotic area are black. Sometimes, depending on how susceptible the variety is, an undefined yellow halo or discolored area can be observed around the lesions. As the disease progresses, infected leaves become yellow and dry before falling off, possibly because of toxic substances secreted by the pathogen. Susceptible varieties may undergo severe, or even total, defoliation during the hot rainy season.

When wind or rain carry conidia that have dropped from wounds of infected tissues towards leaves of a new planting, primary infections occur. If environmental humidity is sufficiently high, the conidia will germinate, producing branched germinal tubes that frequently anastomose (Chevaugeon 1956; Viégas 1941).

When lesions mature, stromata appear from which conidiophores emerge. Secondary cycles of the disease are repeated throughout the rainy season, when wind or rain carries conidia to new susceptible tissues of the plant. The fungus survives the dry season in old lesions, frequently those of fallen leaves. It renews activity with the advent of the rainy season and growth of new leaves in the host.

Chevaugeon (1956) observed that, in a cassava plant, the lower leaves are more susceptible than the youngest leaves. However, certain susceptible species (e.g., *M. carthaginensis* Muell.) and *M. esculenta* cultivars can be severely attacked. Severe symptoms have been observed in young leaves, petioles, and even fruits of *M. carthaginensis*. Although plants "hardened" by unfavorable conditions appear more resistant, no significant differences in susceptibility were found between plants growing in fertile soils and those growing in poor soils (Chevaugeon 1956).

Etiology. *Cercospora henningsii,* causal agent of the disease, grows in the intercellular spaces of leaf tissues, producing stromata from which conidiophores are produced in dense fascicles. The conidiophores are pale olive brown, semi-transparent, with uniform width and color, and non-branching. Sometimes, black perithecia appear, disseminated in the necrotic tissue of leaf spots and on the leaves' upper surface (Powell 1972). The perfect state of *C. henningsii* is *Mycosphaerella manihotis* (Ghesquière 1932; Chevaugeon 1956).

Management and control. To reduce the severity of infection, recommended cultural practices include reducing excess humidity during planting (Golato and Meossi 1966). Fungicides based on copper oxide and copper oxychloride, suspended in mineral oil, and applied at 12 L/ha also provide good chemical control (Golato and Meossi 1966). The best control over the disease can be achieved by using resistant varieties. Significant differences in varietal resistance have been found in Africa (Chevaugeon 1956; Umanah 1970), Brazil (Viégas 1941), and the extensive collection of cassava varieties held at CIAT, Colombia (CIAT 1972).

Diffuse leaf spot (*Cercospora vicosae*)

Importance. This disease is found where brown leaf spot predominates, that is, in the hot cassava-growing areas of Brazil and Colombia (CIAT 1972; Viégas 1941). The pathogen causes severe defoliation in susceptible cultivars but, in Colombia, does not cause heavy crop losses.

Symptoms and epidemiology. This disease is characterized by the presence of large leaf spots, with undefined margins. Each spot may cover one fifth, or more, of the leaf lobe. On the leaves' upper surfaces, the spots are uniformly brown, whereas, on the lower surfaces, spots also have grayish centers caused by the presence of the fungus's conidia and conidiophores. The spots' general appearance is similar to that of the spots induced by *Phoma* sp., although lesions induced by the latter have concentric rings on the leaves' upper surfaces (Figure 8-3).

Defoliation may occur in susceptible cultivars, being more severe at the end of the rainy season and/or vegetative cycle. As the disease progresses, leaves become yellow and dry before falling off.

Symptoms of this disease can be confused with those of cassava bacterial blight (CBB; see below), except that the blight lesions are noticeably aqueous.

Figure 8-3. Leaf spots caused by *Cercospora vicosae* in a cassava leaf.

Etiology. The fungus does not form stromata but sporulates abundantly. The conidiophores are reddish dark brown (Chupp 1953). The fungus has been recorded as a pathogen occurring only on *Manihot* spp. Mill. As its incidence on a single plant or in a given planting is very low and apparently confined to the plant's lower leaves, its importance is relatively less.

Management and control.

- Planting with healthy and resistant cultivars
- Using cultural practices that reduce humidity during planting

White leaf spot (*Phaeoramularia manihotis*)

Importance. This fungus is commonly found in the cold humid cassava-growing regions of Asia, America, North America, tropical Africa, and Latin America (Castaño 1969; Chevaugeon 1956; CIAT 1972). In these areas, the pathogen may cause considerable defoliation in susceptible varieties of *M. esculenta*, the only known host species (Chevaugeon 1956; Viégas 1941).

Symptoms and epidemiology. Leaf spots caused by *P. manihotis* are smaller, with a different color, to those induced by *C. henningsii*. They vary from circular to angular, with diameters of usually 1 to 7 mm. They are normally white, but sometimes yellowish brown. Lesions are sunken on both sides, to half of the thickness of a healthy leaf blade. On the lower leaf surface, the white spots can be distinguished but they frequently have diffusely colored margins, which sometimes appear as brown-violet irregular lines, surrounded by brown or yellowish halos. The spots' centers have a velvety grayish aspect during the pathogen's fruiting (Figure 8-4).

The fungus penetrates the host through stomatal cavities and then invades the host's tissues through the intercellular spaces. When leaf spots reach 5 to 7 mm in diameter, a stroma is formed, which produces conidiophores. The disease's secondary cycles are repeated throughout the rainy season as conidia are dispersed by wind or rain splash. The fungus survives the dry season in old infected tissues and renews activity at the beginning of the rainy season and with the host's new growth.

Etiology. *Phaeoramularia manihotis*, the causal agent, forms thin stromata in lesions on leaves. The stromata produce conidiophores in loose fascicles that emerge through the stromata and are usually olive brown (Powell 1972).

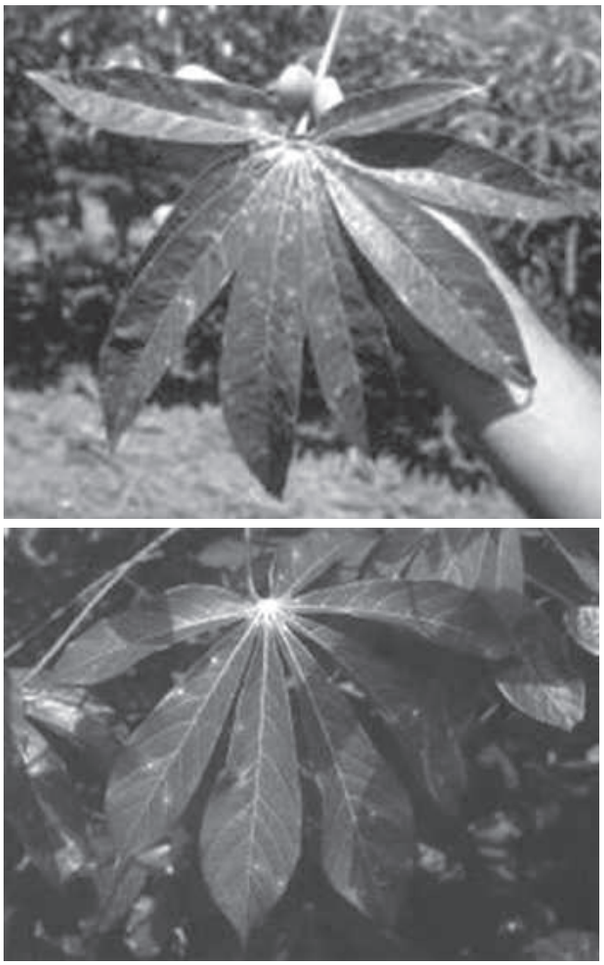


Figure 8-4. Leaf spots caused by *Phaeoramularia manihotis*.

White leaf spot is very similar to brown leaf spot. However, brown spot usually occurs in warm but not humid areas, whereas white spot appears in cold humid areas. These differences in their geographical distribution are also observed in Africa and Latin America, and are probably the result of different responses of the respective causal agents to temperatures and humidity. The optimal temperature for germinating *C. henningsii* conidia is 39 °C, with a maximum temperature of 43 °C. For *P. manihotis*, these temperatures are, respectively, 33 and 43 °C (Chevaugeon 1956).

Management and control. The control measures recommended for this disease are similar to those for brown leaf spot. Specifically resistant varieties are unknown, but field studies suggest they exist (JC Lozano 1979, unpublished data).

Concentric ring leaf spot (*Phoma* spp.)

Importance. This fungal disease, caused by *Phoma* spp., usually appears in the cold cassava-growing areas of Colombia (CIAT 1972), Brazil (Viégas 1943a), Philippines, tropical Africa, and India (Ferdinando et al. 1968). According to Edison (2002), this disease is an emerging problem in certain areas where cassava cultivation is intensive. During the rainy season and when the temperature is below 22 °C, the disease may cause severe defoliation in susceptible varieties and almost always produces stem dieback.

Symptoms and epidemiology. The disease is characterized by the presence of large dark brown leaf spots, with usually undefined margins. These lesions are commonly found at leaf points, margins of leaf lobes, or along the central vein or other secondary veins. Initially, lesions appear as concentric rings of brown pycnidia on the leaf's upper surface (Figure 8-5). These rings are not found on old injuries because the rain drags away mature pycnidia. In these cases, the spots are uniformly brown, and are very similar to those caused by *Cercospora vicosae*. On the lower leaf surfaces, very few pycnidia occur. Hence, lesions are uniformly brown.

Under conditions of high relative humidity, lesions may be covered by braid-like chains of grayish-brown hyphae. On the lower leaf surfaces, the nervures within the lesions become necrotic, forming black bands that emerge from the spots. These spots grow, causing leaf blight. The fungus invades the infected leaf and then the petiole, which becomes dark brown as it necroses. Leaves wilt and then fall, resulting in severe defoliation in susceptible cultivars. These cultivars may present dieback during epiphytotes and even total plant death. Necrotic stems become dark brown and frequently appear covered with pycnidia.

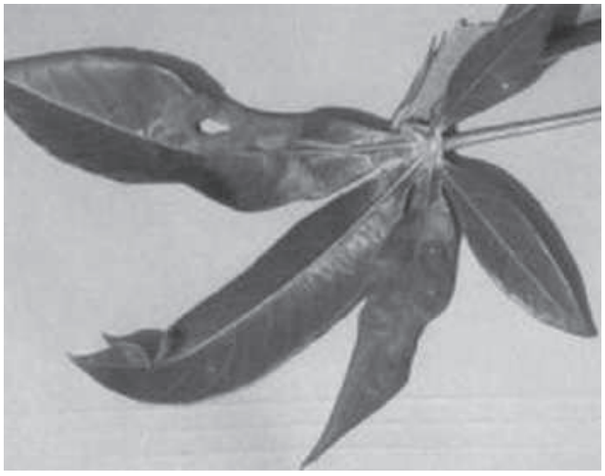


Figure 8-5. Leaf spots caused by *Phoma* sp. in cassava.

Field studies suggest that the more mature lower leaves may be more resistant than the young upper leaves. However, total defoliation, accompanied by partial or total dieback, has been observed in susceptible cultivars.

Favorable conditions for the germination of fungal spores occur at temperatures between 20 and 25 °C. With artificial inoculation, infection is only achieved when inoculated plants are kept for 48 h at less than 24 °C and with 100% relative humidity (JC Lozano 1979, unpublished data). Under field conditions, disease always occurs during the rainy season and in areas where the temperature is less than 22 °C.

The fungus's survival mechanism during dry hot periods is unknown. Viégas (1943b) suggested that the fungus may produce its sexual state on infected stems and leaf residues. However, this has not yet been observed or recorded.

Etiology. The causal agent produces numerous, spherical, dark brown pycnidia, either individually or in small clusters, on surfaces of leaves or stems. Pycnidia measure 100–170 μm in diameter, their walls are formed by polyhedral cells; and their ostiole measures 15–20 μm. Conidiophores are short and hyaline, producing small conidia (15–20 μm) that are unicellular and ovoid or elongated (Ferdinando et al. 1968; Viégas 1943a). On Lima-bean agar, the fungus forms pycnidia in profuse quantities, appearing in concentric rings.

Management and control. To date, no measures of control exist for the disease, even though it causes heavy losses in areas where environmental conditions are propitious for its development. Although no reports exist on varietal resistance, in the field in Colombia, resistance has been observed in naturally infected plantings. Chemical treatments such as carbendazim (3 g/L a.i.) and benomyl (0.6 g/L a.i.) during the rainy season may be equally effective in those areas where the disease is endemic.

Cassava ash (*Oidium manihotis*)

Importance. This disease was first recorded in Africa in 1913 (Saccardo 1913) and has since appeared in Latin America (CIAT 1972; Viégas 1943a) and Asia (Park 1934). The disease is characterized by the presence of yellowish undefined spots on *M. esculenta*

leaves. Although it is widely disseminated and frequently occurs during the dry season, the disease is considered to be of minor importance as it usually attacks only the lower leaves, in which it induces some necrosis.

Symptoms and epidemiology. The first symptoms of disease are characterized by the appearance of a white mycelium that grows on the leaf surface (Figure 8-6). The fungus penetrates the host cells, using haustoria. The infected cells become chlorotic and form undefined yellowish lesions. Within these yellowish areas, pale brown necrotic areas frequently appear. These are angular in shape and of different sizes. In some cassava varieties, the disease stops in the state of yellowish undefined lesions, which then may become confused with those induced by insects and mites.

Fully developed mature leaves seem to be most susceptible to pathogenic attack, although the young leaves of some varieties may also present symptoms. The disease commonly appears during the dry season and in warm areas.

Etiology. The sexual state of the causal agent, *Oidium manihotis*, is *Erysiphe manihotis* (Ferdinando et al. 1968). The fungus's mycelium is white, producing numerous haustoria on the host's epidermis. Conidiophores rest in an erect position. They are simple, with the upper parts both longer and wider, as they form the conidia. Conidia are oval or cylindrical, unicellular, hyaline, and measure 12–20 × 20–40 μm. They are produced in basipetal chains (Ferdinando et al. 1968; Saccardo 1913; Viégas 1943b).

Management and control. Although specific control of the disease is considered unnecessary, observations suggest that resistant varieties exist (CIAT 1972). Ferdinando et al. (1968) suggest that spraying with sulfur-based compounds can control the disease.

Figure 8-6. Cassava ash symptoms, caused by *Oidium* sp.

Cassava anthracnose (*Glomerella manihotis*)

Although cassava anthracnose has been known for a long time, it has been considered of minor importance. It is characterized by the presence of sunken leaf spots, 10 mm in diameter, that are similar to those caused by *C. henningsii*. The latter, however, appear towards the base of leaves, thus causing their total death.

The pathogen also causes young stems to wilt and induces cankers on mature stems (Irvine 1969) (Figure 8-7). New leaves, produced at the beginning of the rainy season, are the most susceptible. The disease tends to disappear when the dry season begins (Irvine 1969). This finding agrees with results obtained from artificial inoculations with an aqueous suspension of spores from the pathogen. Inoculation is successful if incubation is at 100% relative humidity for 60 h. The fungus will stop invading plant tissue when relative humidity drops to 70% (CIAT 1972). The insect *Pseudotheraptus devastans* Distant is associated with the disease (Fokunang et al. 2000), contributing to the pathogen's dissemination and increasing the severity of symptoms.

The organism causing this disease has been variously called *Glomerella manihotis*, *Colletotrichum manihotis* (Vanderweyen 1962), *Gloeosporium manihotis* (Bouriquet 1946), and *Glomerella cingulata* (Irvine 1969). All these names possibly refer to one species, but this hypothesis is yet to be confirmed.

Stem anthracnose caused by a *Colletotrichum* sp. was recorded in Nigeria (IITA 1972). Green portions of

Figure 8-7. Leaves and stem show cankers caused by *Glomerella manihotis*.

the stems presented shallow oval depressions that were pale brown, but with a point of normal green tissue in the center. In the ligneous portions of the stems, lesions were round, swollen, and in bands, forming deep cankers on the epidermis and cortex, and sometimes deforming the stem. Its importance is unknown but its prevalence, occurrence, and dissemination are considerable. In Asia stem anthracnose was recorded in Thailand (E Álvarez 2009, pers. comm.) (Figure 8-8).

Figure 8-8. Disease symptoms observed on cassava stems.

Cassava rust (*Uromyces* spp.)

Importance. Although recorded in Brazil and Colombia, this disease is considered to be of minor importance. It appears at the end of dry periods, sometimes causing a type of shoot proliferation in stem apices (Normanha 1970).

Symptoms and epidemiology. Infection is characterized by pustule formation on leaf veins, petioles, or green branches (Figure 8-9). Pustules are light to dark brown, depending on their age or class of fungal fructification. Mature pustules are readily parasitized by the fungus *Darluca filum*. They are sometimes surrounded by chlorotic halos and, usually, induce deformation of affected parts. Wind is the principal dissemination agent.

Etiology. In cassava, several species of rust pathogens have been recorded in different parts of the world. However, its incidence and severity are low. Some species of rust appear to occur only where temperatures are moderate and rainfall is high. Other species predominate during hot dry seasons.

Stem rots

In many cassava-growing areas, continuous cassava planting is not possible and stakes must be stored for later propagation. Stored stakes are attacked by three diseases that induce necrosis (CIAT 1972). These diseases considerably reduce stake viability, directly and indirectly, by increasing dehydration and causing necrosis.

Although the three different causal agents have been recognized, the diseases these induce are not

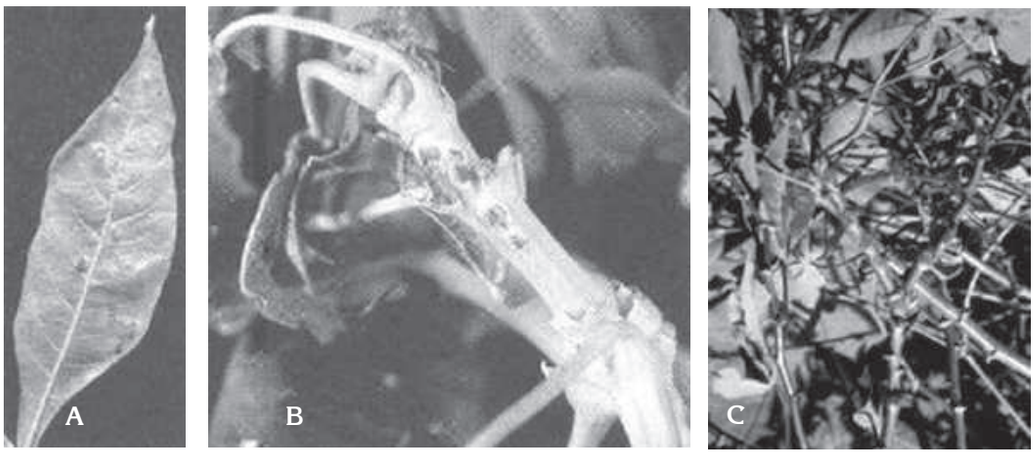


Figure 8-9. Symptoms of cassava rust characterized by pustule formation on **(A)** leaf, and **(B)** and **(C)** stems.

clearly differentiated in most cases. Macroscopically, the diseases look similar, particularly during their first developmental stages. Furthermore, more than one causal agent may be present, creating a syndrome.

The three diseases causing stem rots are stem necrosis caused by *Glomerella cingulata*, dry stem and root rot caused by *Diplodia* sp., and necrosis caused by an unidentified Basidiomycete (Lozano and Booth 1979).

Stem necrosis (*Glomerella cingulata*)

Importance. This disease is the most common of the three that induce rots or necrosis in stored cassava stakes. It also attacks residues of old stems left in cassava plantings.

Symptoms. Necrosis of stored stakes appears first at the ends and then progresses slowly towards the middle, before disseminating to all stakes (Figure 8-10). The disease occurs as a black discoloration of vascular bundles. It then develops surface blisters that later break, exposing groups of black perithecia in well-developed stromata.

Etiology. The causal organism appears to be *Glomerella cingulata* (Commonwealth Mycological Institute 1979, pers. comm.). Ascospores are hyaline, unicellular, and slightly curved. Infection probably occurs through wounds and is favored by high environmental relative humidity.

The relationship between this fungus and *Colletotrichum* sp., which causes anthracnose in cassava, has not still been determined. For example, the appearance of two types of symptoms may be due to two different states of the same agent rather than of two agents.

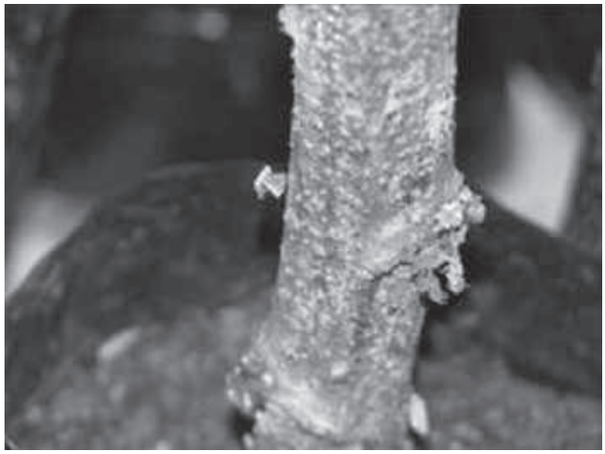


Figure 8-10. Necrosis caused by *Glomerella cingulata* in cassava stakes.

Dry rot of stem and root (*Diplodia* sp.)

Importance. This disease attacks stored cassava planting materials and residue stems left in the field. Its occurrence is not as common as necrosis caused by *Glomerella* spp.

Symptoms and epidemiology. The disease has two phases. The first is when root rot starts when soils are infested or when stakes from diseased plants are used. Symptoms, similar to those induced by root pathogens, consist in sudden plant death caused by root deterioration.

The second phase includes stem rot caused by systemic invasion of the fungus from the roots or by penetration through wounds. The disease is characterized by black discoloration and necrosis of the vascular bundles, which extend from the infection sites, that is, wounds in the stem. In the epidermis, they appear as blisters under which the stem's internal tissues are discolored black or dark brown. The blisters break, showing confluent masses of black pycnidia (Figure 8-11). Gum may be excreted, and partial or total wilting occurs. Dieback may also occur.

The pathogen disseminates across great distances through stakes from infected plantings. Within the same crop, dissemination is by wind and rain during fungal fructifications, use of infested tools and irrigation water, and land preparation for later plantings.

Etiology. The causal agent of dry rot of stem and root is *Diplodia manihotis*. In both the host and laboratory cultures, this organism produces pycnidia

Figure 8-11. Stem rot in a stake infected by *Diplodia* sp.

that erupt through the stem or root surface, becoming confluent, stromal, and ostiolate. The conidiophores are short and simple, producing dark two-cell conidia that are slightly elongated on reaching maturity. Infection is believed to occur through wounds, and is favored by high environmental relative humidity.

Management and control. To control the disease, the cassava crop should be rotated with nonsusceptible crops such as maize or sorghum, particularly when incidence is more than 3%. Planting stakes from healthy crops should be used and tools disinfected. Planting materials should be selected and handled carefully both before and after storage. Only viable cuttings or buds should be planted. One recommendation is to immerse cuttings in a solution of captan (3 g/L) and benomyl (3 g/L) for 5 min. Captan may be replaced by copper oxychloride.

Root rots

Root rots in cassava are important where soils are poorly drained or where excessively rainy seasons occur. In early growth, many microorganisms are capable of inducing not only root rots in young cassava plants, but also in the storage roots of mature plants. Although several root diseases have been reported, little information exists about them. Not even the symptoms are well described.

Usually, infection kills young plants at germination or shortly afterwards. Infection in plants older than 4 months may result in partial or total wilt, depending on whether the root rot is soft or dry. Once invaded by one or more primary pathogens, infected roots may be invaded by a wide spectrum of other microorganisms. These are usually the otherwise weak saprophytic parasites, which become capable of degrading root tissues and masking the identity of the primary causal agent. The resulting root rots therefore appear to have the same syndrome of symptoms.

Pathogens causing root rots include *Phytophthora* spp., *Fusarium* sp., *Scytalidium lignicola, Rosellinia* spp., *Sclerotium* sp., and *Fomes lignosus* (Ferdinando et al. 1968; Jennings 1970; Pereira 1998; Viégas 1955).

Some of these diseases often develop when cassava is planted immediately after woody crops such as coffee. Soils of such crops are infested with pathogens that attack ligneous plants such as cassava. These pathogens may be fungi or bacteria that cause root deterioration, either as the crop grows or after harvest when roots are stored.

Control measures for these diseases are similar, the best comprising cultural practices such as good drainage, selection of loose-textured soils, crop rotation, early harvest, and avoiding soils prone to flooding. Treatments with fungicides may help establish the crop, preventing root rots from attacking during the crop's first months. Ridomil® (2.5 kg/ha), applied to the soil, and foliar applications of Alliette® (0.4 kg/ha) have shown good results. Fungicides based on plant extracts, oils, and cytokinins help control soil fungi, while offering a nonpolluting organic alternative. Resistant varieties have also been reported (Castaño 1953; CIAT 1998; Drummond and Gonçalves 1957; Fassi 1957; Müller and De Carneiro 1970; Sánchez 1998).

Root rot or "black rot" (*Rosellinia* spp.)

Importance. This disease has been reported in many cassava-growing regions with heavy, poorly drained soils that have a high content of organic matter. It is also found in cassava crops planted after forest crops or ligneous perennial species (Castaño 1953; Viégas 1955). The disease has also been called "black rot" because of the characteristic black color of infected tissues and root cankers.

In Colombia, dry rots are found in the Coffee Belt and in crops planted where coffee, cacao, or *guamo* (a shade tree used in coffee plantations) had previously been grown.

Symptoms and epidemiology. Initially, the root epidermis is covered with white rhizomorphs that later become black (Figure 8-12). Internally, infected tissues of bulked roots are slightly discolored and exude liquid on pressure. The black mycelial bundles penetrate the tissues, where they grow, forming small cavities that contain mycelium of an off-white color. The infected roots have a characteristic odor of decaying wood.

Etiology. *Rosellinia necatrix*, the perithecial state of *Dematophora necatrix*, is the causal agent of this disease (Castaño 1953; Viégas 1955). This fungus induces root rot in other ligneous and herbaceous plants (Castaño 1953; Viégas 1955). However, very little information is available on the epidemiology of

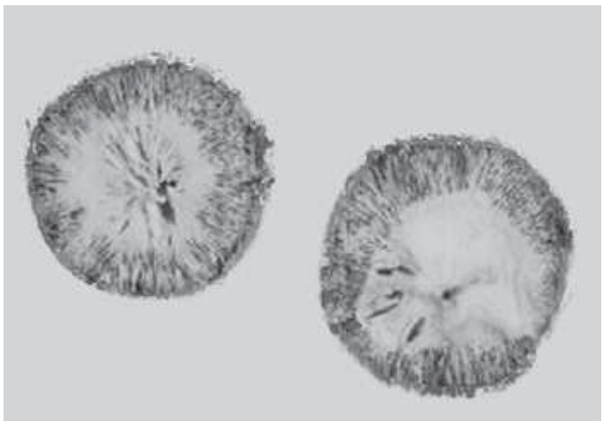


Figure 8-12. Rot caused by *Rosellinia necatrix* in cassava roots.

the fungus in cassava. Its sexual state is generally believed to occur only very rarely (Castaño 1953). Other *Rosellinia* species also attack cassava.

Management and control. Although the disease has not been reported in young plants, the recommendation is still to avoid selecting planting materials from infected crops.

- Rotate with grasses whenever the incidence of plant death or root rot reaches 3%.
- Eliminate infected cassava residues and/or litter from perennial trees (e.g., trunks and decaying branches).
- Plant in loose-textured soils.
- Improve soil drainage.
- Treat by solarization, exposing the soil to the sun for 3 months.
- Chemical control with Topsin (thiophanate-methyl) at 2 g/L of commercial product and applied to the soil before planting.
- Applications of Sincocin (plant extract) to the soil at 1 L/ha are recommended. Stakes may also be immersed in a solution of the product at 1%.

Root rot (*Sclerotium rolfsii*)

This disease commonly occurs in young stakes and mature roots, covering affected parts with a cottony mat. It has been reported only in Latin America (CIAT 1972; Ferdinando et al. 1968). The white mycelium, which is found in infected roots or towards the base of stems, is also disseminated through the soil. This mycelium can, sometimes, penetrate roots through wounds, causing subsequent rot. Although it is rarely lethal to young plants, this fungus may cause a high incidence of root necrosis in a plant.

The disease is caused by *Sclerotium rolfsii*, a common soil organism but a weak pathogen. It has a white mycelium of cottony appearance. It also produces numerous round sclerotia, which characteristically form in the host or laboratory cultures.

Cottony cassava rot (*Fomes lignosus*)

Although this disease is known in Latin America, it is currently of minor importance. The disease is identified by the presence of a mass of white mycelium under the cortex of bulked roots and by the presence of white mycelial threads that look like cotton fibers covering part or all the epidermis of infected roots to the base of stems. Internally, the infected tissues look dehydrated and have a characteristic odor of decaying wood. Young plants may become infected and sometimes suffer sudden wilting, defoliation, and root necrosis.

The organism causing the disease is *Fomes lignosus* (IITA 1972; Jennings 1970).

Diseases Caused by Pseudo-fungi

Root rots (*Phytophthora* spp.)

Importance. Root rots are a very common problem in cassava production, causing yield losses that may be as high as 80% of total production.

Distribution. Root rot caused by *Phytophthora* spp. affect cassava in different agroecological areas in Africa (Fassi 1957), tropical America (Müller and De Carneiro 1970), and India (Johnson and Palaniswami 1999). In Nigeria, Cameroon, and Benin, the pathogens causing root diseases of economic importance include *Sclerotium rolfsii*, *Botryodiplodia theobromae*, *Fomes lignosus*, *Rosellinia necatrix, Rhizoctonia solani, Phytophthora* spp., and *Fusarium* spp. (Hillocks and Wydra 2002).

Recent reports mention that cassava rots may cause losses between 5% and sometimes 100% in Latin America, Asia, and Africa, specifically, Colombia, Brazil (W Fukuda and C Fukuda 1996, EMBRAPA, Brazil; F Takatsu 1996, University of Brasília, Brazil, pers. comm.), Cuba (M Folgueras 2002, INIVIT, pers.

comm.), Mexico (LF Cadavid 2005, CLAYUCA, pers. comm.), India (J George 2004, CTCRI, pers. comm.), Uganda (W Serubombwe 2003, NARO, pers. comm.), Nigeria, Kenya, Indonesia, Ghana, Ecuador and probably in many other countries.

In Asia, root rots have recently been described in the Nondindang District, Buriram Province, Khonburi District, Nakhon Ratchasima Province (Figure 8-13)—areas characterized by loam sandy soil. The genotypes showing symptoms are Rayong 5, Kasetsart 50, and Huay Bong 60 (E Álvarez 2009, pers. comm.). The disease was also observed at the Rayong Field Crop Research Center, affecting genotype Huay Bong 80 (Figure 8-14). Cassava root rots have also been observed in Vietnam.

In India, *Phytophthora palmivora* is emerging as a serious threat to cassava in several industrial areas of Tamil Nadu, where it is endemic. Crop losses are as high as 50%. Differential reaction of cassava varieties to infection by *Phytophthora* was observed (Edison 2002).

Symptoms and epidemiology. *Phytophthora drechsleri* macerates the root parenchyma, causing a

Figure 8-14. Cassava root rot symptoms observed in Rayong and at the Thai Tapioca Development Institute (TTDI) in Huay Bong, Nakhon Ratchasima Province.

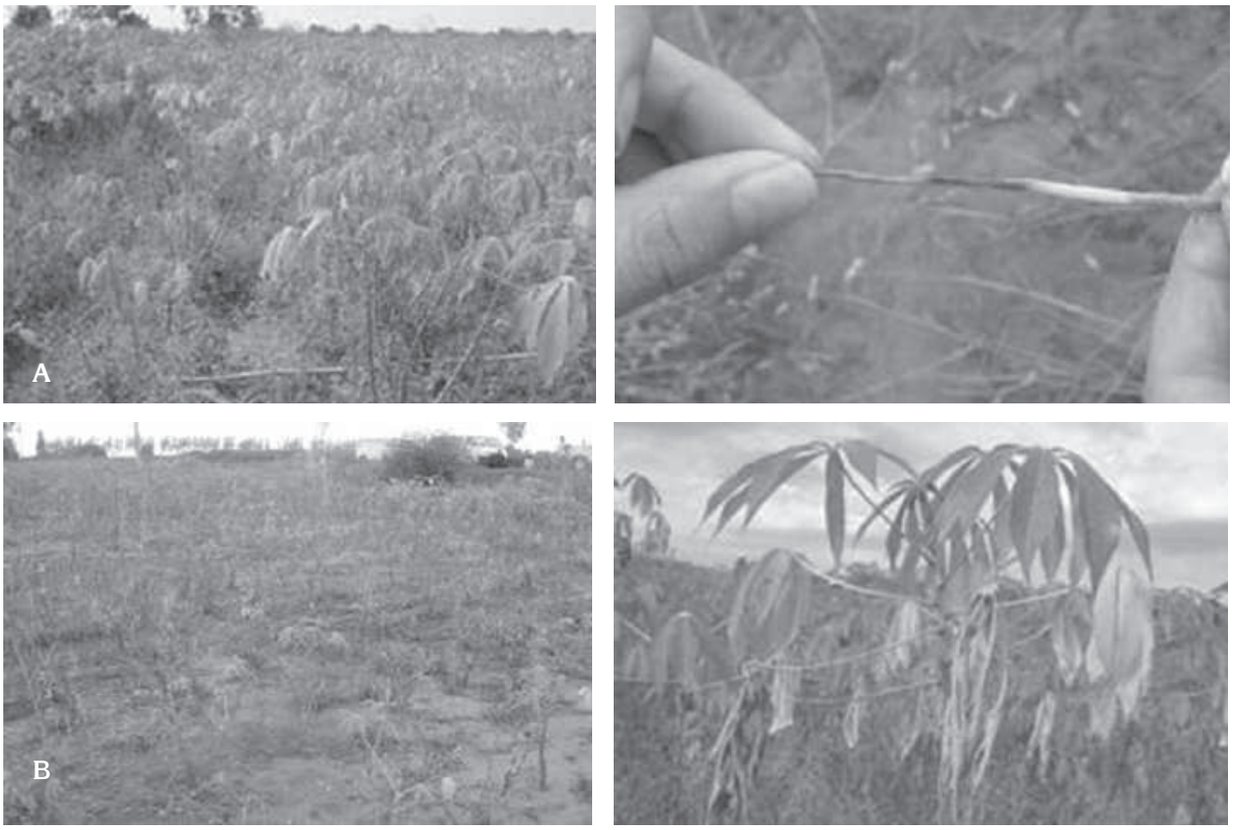


Figure 8-13. Cassava plants showing symptoms of root rot and wilting in **(A)** Buriram Province and **(B)** Nakhon Ratchasima Province, Thailand.

penetrating odor and changing root color to cream (Figure 8-15A). *P. tropicalis* has been isolated from crops in Colombia (Figure 8-15B). In the State of Sergipe (Brazil), in 1976–1979, *P. drechsleri* was found to cause rot in the neck and roots, irreversible wilting of aerial parts, and defoliation (Souza Filho and Tupinamba 1979) (Figure 8-15C). In contrast, *P. nicotianae* var. *nicotianae* shows little pepstatin activity. The odor is mild, with brown discoloration (Soto et al. 1988). Root attack by *P. drechsleri* leads to leaves falling and branch tips drying up before the plant dies (Figuereido and Albuquerque 1970). *Phytophthora nicotianae* also causes a similar leaf blight in cassava (Erwin and Ribeiro 1996; Lima et al. 1993).

Etiology. Farmers widely believe that root rots are caused by excess water in the soil. However, a study conducted in different edaphoclimatic areas of Colombia showed that different *Phytophthora* spp. are the major cause of cassava root rots (Sánchez 1998). Other pathogens also causing root rots include:

Fomes lignosus
Sclerotium rolfsii
Armillariella mellea
Fusarium spp.
Rhizoctonia sp.
Rhizopus sp.
Rosellinia necatrix (Lozano and Booth 1979)
Pythium chamaehyphon (GenBank accession AY745748; CIAT 2004)

Eleven species of *Phytophthora* have been reported as causing root rot. These are:

P. arecae (Coleman) Pethybridge (Álvarez et al. 1997c)
P. capsici Leonian (Lima et al. 1993)
P. citricola (CIAT 1999, 2000)
P. cryptogea Pethybr. & Lafferty
P. drechsleri Tucker (Figueiredo and Albuquerque 1970; Muller and De Carneiro 1970)
P. erythroseptica Pethybridge (Fassi 1957)
P. meadii (Barragán and Álvarez 1998)
P. melonis (GenBank accession AY 739021; CIAT 2000, 2004)
P. nicotianae Breda de Haan var. *nicotinae* (Dastur) (Soto et al. 1988)
P. palmivora (Johnson and Palaniswami 1999; (Álvarez and Llano 2002)
P. tropicalis (GenBank accession AY 739022; CIAT 2000, 2004).

The genetic diversity of these pathogens is broad and was determined through studies in Colombia with 80 isolates obtained from roots, young stems, and soils from 19 municipalities. These studies included the pathogen's pathogenicity, virulence, morphology, and molecular analysis of the internal transcribed spacer (ITS) region of the pathogen's ribosomal DNA. Eleven genetic groups were identified through PCR-RFLP (Álvarez et al. 1997a, 1997c, 2000; Sánchez 1998). *Phytophthora tropicalis* was identified through sequencing of the ITS region of ribosomal DNA and isoenzymes, showing it to be genetically similar to *P. capsici* (CIAT 2000). The isolate was obtained from cassava roots in Barcelona, Quindío; *P. palmivora* was isolated from cassava roots at CIAT, Valle del Cauca.

Integrated disease management. The integrated management of root rots includes the use of varietal resistance and/or cultural practices.

Figure 8-15. Root rots **(A** and **B)** and plant wilt **(C)** caused by *Phytophthora* spp.

Varietal resistance. A principal tool for managing root rots caused by various *Phytophthora* species is the use of varietal resistance. Various examples exist of the successful adoption of cassava clones resistant to *Phytophthora* spp. In 1990, the Brazilian Agricultural Research Corporation (Embrapa) and the Agricultural Research Center for the Humid Tropics (CPATU) released two cassava clones resistant to root rots: cvs. Mae Joana (IM-175) and Zolhudinha (IM-158). Both clones came from the State of Amazonas and are planted in the várzea ecosystem (a type of floodplains) of northern Brazil. The adoption of these clones, together with the application of appropriate cultural practices, increased root yields by more than 80% in this region (Lozano 1991b).

High yields and resistance to root rot caused by *P. drechsleri* were obtained in clones MD-33 and Pao (Mendonça et al. 2003). Pereira (1998) reported resistance to *P. drechsleri* in seven cultivars from a group of 31 evaluated. Barragán and Álvarez (1998) reported 15 resistant genotypes from a group of 60 elite genotypes evaluated. In 2003, Llano et al. reported six individuals from a family of 126 individuals, with high resistance to *P. tropicalis, P. palmivora*, and *P. melonis*. Although harvesting roots 14 months after planting resulted in increased yield, it also demonstrated a higher incidence of root rots, thus showing that root rot incidence varies according to clones and harvest time.

In a participatory research study, indigenous communities of the Colombian Amazon adopted cassava clones resistant to *Phytophthora* spp. (Llano and Álvarez 2008; Llano et al. 2001). These clones were selected in the laboratory (harvested roots) and greenhouse (stems) from 700 genotypes provided by Embrapa and CIAT.

To obtain reliable information on the genetics of such a complex disease, Takatsu and Fukuda (1990) concluded that standardized methods were needed for inoculating and evaluating resistance to each cassava root rot pathogen. CIAT and the National University of Colombia–Palmira identified cassava clones resistant to *P. nicotianae* var. *nicotianae* by first inoculating bulked roots of plants that were 10 to 12 months old. They then added a suspension of the fungus to a nutritive solution in which 45-day-old seedlings were growing. The roots of seedlings were colonized by the pathogen. The inoculated roots were evaluated in terms of the percentage of the pathogen's colonization of cortical and parenchymatous tissues.

Inoculated bulked roots demonstrated variation in the severity of symptoms, depending on whether they came from resistant or susceptible clones. The inoculation method was easier to carry out, less expensive, and with faster results than the seedling method. No correlation was found between the two inoculation methods (López and Lozano 1992).

Cassava seedlings planted in soil were also evaluated. The soil had previously been inoculated with a suspension of each of zoospores, oospores, or chlamydospores applied separately (Lima et al. 1993). Each inoculum type caused wilt and seedling death.

In 1995, Lima and Takatsu (1995) published the reactions of 13 cassava clones that had been stem-inoculated with three isolates of *P. drechsleri* in the greenhouse. The isolate with the most virulence was inoculated into roots in the field. To inoculate roots without harvesting them, inoculum was deposited in a small wound. The correlation between inoculated plants in the screenhouse and roots inoculated in the field was +0.24.

In other studies (Loke 2004), several biochemical and morphological markers, and leaf resistance were identified for preselecting clones for resistance to *P. tropicalis* in cassava populations, based on (1) reduced area of the parenchyma with the presence of scopoletin in roots after harvest; (2) a high relationship between iron and manganese; and (3) resistance in leaves 72 h after inoculation. Scopoletin is a coumarin that is found in very low concentrations in fresh roots but which increases considerably after harvest. This substance is easy to quantify in roots, using ultraviolet light, and is related to the cassava root's susceptibility to postharvest physiological deterioration.

Loke (2004) also demonstrated the benefits of using an index of resistance to *P. tropicalis* that includes molecular markers. The objective of this index is to select genotypes with durable resistance, based on a large diversity of resistance or defense mechanisms.

Several studies to identify the genetic base of resistance to *Phytophthora* have been conducted. For 25 cassava clones, a correlation of +0.31 was observed between resistance during penetration (in the peel, both epidermis and subepidermis) and after penetration (in the parenchyma). This finding indicated that these forms of resistance are moderately associated (Corredor 2005; Loke 2004). Alvarez et al. (2003c),

Llano et al. (2004), and Loke (2004) evaluated the cassava K family (150 F_1 individuals from the cross TMS 30572 × CM 2177-2), inoculating root fragments. Nineteen QTLs were identified as associated with resistance to different species of *Phytophthora* and *Pythium*, three of which explained between 8.3% and 11% of phenotypic variance.

Those QTLs that were expressed were also found to vary from one cropping cycle to another, depending on prevailing environmental conditions. Minor genes were demonstrated as controlling resistance to *P. tropicalis, P. melonis*, and *P. palmivora*, with a high genotype × environment interaction existing. Although the population showed differences within its genetic base for resistance to *Phytophthora*, levels of resistance were not sufficiently high for use in improvement programs. Hence, identifying contrasting parents for the disease would be useful, as well as developing new populations for determining QTLs (Llano et al. 2004; Loke et al. 2004).

To identify genomic sequences in cassava that are homologous with genes of resistance to diseases of different plant species, two cassava families were evaluated for their resistance to *P. tropicalis* (GenBank accession AY 739022), *P. melonis* (GenBank accession AY 739021), and *P. palmivora*, all causal agents of root rot. Two strategies were used to search for genes for resistance: (1) hybridization with probes for maize and rice, using RFLP; and (2) amplifying conserved regions of DNA, using the degenerate primers NBS and Pto kinase. Three cassava clones resistant to *P. tropicalis* and *P. palmivora* were used, obtaining clones that were sequenced and homologized with known genes of resistance.

With hybridization, cassava demonstrated very low homology with the monocotyledon genes tested. Twenty-eight NBS and 2 Pto kinase clones were obtained, of which 14 showed homologous sequence with resistance gene analogs (RGAs) and NBS-LRR (GenBank accessions: AY730038, AY730040, AY730041, AY737490, AY745762, AY745763, AY745764, AY745765, AY745766, AY745767, AY745768, AY745769, AY745770, and AY745771). Four of these showed an open reading framework (ORF) with conserved motifs in the nucleotide-binding site (NBS) region, which means they were considered to be RGAs. Altogether, three classes of RGAs were identified, none of which showed association with resistance to *Phytophthora* (Llano et al. 2004).

Cultural practices. The best cultural practices for the integrated management of root rots are summarized below:

- Selecting an appropriate, well-drained, and moderately deep soil. If the land is flat and soils are clayey, planting should be done on ridges.
- To catalyze resistance, fertilizers should be applied in drench form, using potassium sources, and/or as foliar sprays, using potassium phosphites.
- If rot incidence reaches 3%, the cassava crop should be rotated with grasses, at least once a year.
- Eradicating diseased plants by removing infected roots from the field and burning them.
- Selecting healthy plants to obtain clean seed. Where the farming area is infested, then stakes should be treated with metalaxyl at 0.3 g/L a.i.
- Treating stakes in hot water at 49 °C for 49 min is an alternative to chemical treatment (Álvarez et al. 2003b).

Immersing stakes in a suspension of *Trichoderma harzianum* and *T. viride* at 2.5×10^8 spores/L, and later applying the same suspension in drench form (CIAT 2006, 2007). Biological control of rots with isolates of *T. harzianum* and *T. viride* is promising (Bedoya et al. 2000; CIAT 2006, 2007; Edison 2002). Field trials in different agroecological zones of Colombia have shown that soil inoculated with strains of these types of *Trichoderma* will increase cassava yield (CIAT 2001, 2006, 2007). Isolates of *Trichoderma* spp. were selected on the basis of *in vitro* antagonism, production of secondary metabolites that inhibit *Phytophthora* spp., and bioassays in screenhouses.

To identify practices of disease management that are feasible for indigenous communities in the northwestern region of the Amazon (Colombia), participatory research trials were established, with the women farmers making the evaluations. Soil amendments were incorporated. These were ash, organic matter (dry leaves), and a 1:1 mixture of both materials. Dosage was 200 g/plant. Cassava was also associated with cowpea (*Vigna unguiculata*), and stakes selected from the middle part of healthy plants.

In these trials, cassava yield increased by 446% with applications of the ash and organic matter mixture. Where only ash was used, yield increased by 272%. Stake selection increased yield by 366%. Compared with traditional management, these practices reduced root rots by 100% (incorporation of the ash and organic matter mixture), 99% (association with cowpea), 94.2% (ash only), and 89.7% (stake selection) (Llano and Álvarez 2008).

Other Causal Agents of Cassava Rots

Other fungal root rots

Other fungal species can induce root rots in cassava plants at different growth stages, but little information is available on these diseases and their importance. These root rots are caused by:

Armillariella mellea, which attacks both the stem base and roots of mature plants (Arraudeau 1967; CIAT 1972)
Phaeolus manihotis (Heim 1931)
Lasiodiplodia theobromae (Vanderweyen 1962)
Pythium sp. (CIAT 1972)
Fusarium sp. (CIAT 1972)
Clitocybe tabescens (Arraudeau 1967)
Sphaceloma manihoticola (Bitancourt and Jenkins 1950)
Rhizopus spp. (Majunder et al. 1956)
Rhizoctonia sp. (Gonçalves and Franco 1941)
Aspergillus spp. (Clerck and Caurie 1968)
Nattrassia mangiferae (*Scytalidium* sp.); *Verticillium* sp.; and *Rigidoporus* sp.

Bacterial root rots

Some bacterial species belonging to the *Bacillus*, *Erwinia*, and *Corynebacterium* genera are also believed to cause soft rots and/or fermentation in bulked cassava roots (Akinrele 1964; Averre 1967). Symptoms of these soft rots are similar and are frequently accompanied by fermentation. These agents probably penetrate roots through wounds produced by farmers during cultivation or by animals, insects, or fungi. They are frequently accompanied by other saprophytic microorganisms that help advance deterioration.

The causal agent of cassava bacterial blight (see below) can also induce necrosis, discoloration, and dry rot in the vascular tissues of infected roots (Lozano 1973; Lozano and Sequeira 1974).

Cassava heart rot

This physiological disorder damages bulked roots (Averre 1967). It occurs in moist and poorly drained soils in which roots present a dry internal necrosis that extends irregularly from the center to cortical tissues. This disorder is observed in only 10%–20% of the roots of an infected plant. The larger and thicker roots are believed to be the most susceptible.

Postharvest physiological deterioration (PPD)

The cause of cassava roots' rapid deterioration after harvest is unknown, whether it results from physiological or pathological effects, or a combination of the two. Numerous microorganisms have nevertheless been isolated from deteriorated roots, with several being known to cause discoloration and rot.

Bacterial Diseases

Cassava bacterial blight (*Xanthomonas axonopodis* pv. *manihotis*)

Importance. Cassava bacterial blight (CBB) is regarded as one of the most limiting diseases of cassava production, as it can cause total crop loss in affected areas.

During the 1960s and 1970s, this disease caused major damage to the cassava crop. However, the application of integrated management programs, introduction of quarantine measures in some countries, and identification and planting of resistant varieties have led to its satisfactory control (Hillocks and Wydra 2002; Lozano 1986).

Distribution. Cassava bacterial blight has been known in Latin America since 1912, when it was reported in Brazil (Kemp 2000). It spread to the cassava-growing regions of Africa and Asia in the 1970s (Boher and Verdier 1994; Bradbury 1986). In Latin America, the disease has been reported from most of the cassava-growing regions of Bolivia, Brazil, Colombia, Cuba, the Dominican Republic, Mexico, Panama, Trinidad and Tobago, and Venezuela (Cajar 1981; Fukuda 1992; Languidey 1981; Lozano and Sequeira 1974; Rajnauth and Pegus 1988; Rodríguez 1979; Rodríguez 1992; Sosa 1992; Trujillo et al. 1982).

In Asia, CBB has been observed during the rainy season in Thailand (Figure 8-16) as well as in many other countries but it is seldom very severe (E Álvarez

Figure 8-16. Cassava bacterial blight (CBB) symptoms observed on cassava leaves of cv. Rayong 5 in Thailand.

2009, pers. comm.). The disease was first observed in Taiwan before 1945 (Leu 1976), and has since been reported from Malaysia, Indonesia, Thailand (Booth and Lozano 1978; E Álvarez and AC Bellotti 2009, pers. comm.), Vietnam (E Álvarez and AC Bellotti 2009, pers. comm.) and India (Cherian and Mathew 1981). In Africa, the disease causes severe epidemics (Hillocks and Wydra 2002), and appears in the following countries (in order of reporting year): Nigeria (Williams et al. 1973), Zaire (Maraite and Meyer 1975), Ghana (Doku and Lamptey 1977), Benin (Korang-Amoakoh and Oduro 1979, cited by Hillocks and Wydra 2002), the Democratic Republic of the Congo (Daniel et al. 1980), Côte d'Ivoire (Notteghem et al. 1980), Republic of South Africa (Manicom et al. 1981), Rwanda (Onyango and Mukunya 1982), Sudan (Kwaje 1984), Togo (Boher and Agboli 1992), Cameroon, Central African Republic, Tanzania, Kenya, and Burundi (Hillocks and Wydra 2002).

Symptoms and epidemiology. Symptoms characteristic of CBB are small, angular, aqueous-looking leaf spots found on the lower surface of the leaf blade. Or symptoms may be leaf blight or brown leaf burn, wilt, dieback, and a gummy exudation in infected young stems, petioles, and leaf spots (Figure 8-17). The vascular bundles of infected petioles and stems are also necrotic, appearing as bands of brown or black color. Symptoms occur 11 to 13 days after infection (Lozano and Booth 1979). Some susceptible varieties present dry and putrid spots around necrotic vascular bundles (Verdier 2002).

The bacterium disseminates widely through stakes from infected plants, from one cropping cycle to another, and from one area to another. Within the crop, the principal means of dispersal are water splash from rain and contaminated tools. The movement of people and animals within the crop, especially during or after rain, may also help disperse the pathogen (Lozano 1973).

Although the pathogen survives poorly in soil, this can be source of inoculum if it is contaminated, as well as irrigation water, although in reduced proportions. The bacterium can survive epiphytically on many weeds, which serve as sources of inoculum if control is

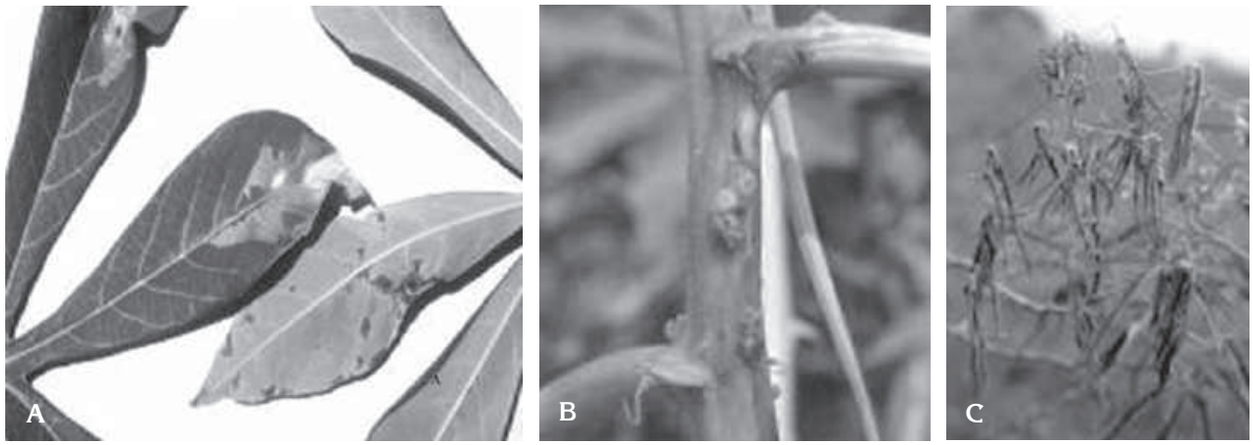


Figure 8-17. Symptoms of cassava bacterial blight, induced by the bacterium *Xanthomonas axonopodis* pv. *manihotis*: **(A)** angular leaf spots and leaf blight, **(B)** exudate on stem, and **(C)** plant wilt.

inadequate. Insects spread the disease over short distances.

The severity of CBB becomes greater when temperatures fluctuate widely between day and night. Hence, the disease is not important in areas of stable temperatures such as the Amazon Region, where the cloud cover does not permit marked fluctuations in temperatures.

Etiology. The causal organism, *Xanthomonas axonopodis* pv. *manihotis* (*Xam*), is a Gram-negative bacterium that is shaped like a slim cane. It is mobile by means of a polar flagellum. Its cells are not encapsulated, and the bacterium does not form spores.

The organism penetrates the host through stomas and wounds in the plant's epidermis. Infection is systemic, moving through the stems and petioles in xylem vessels and possibly also the phloem.

Xam can be detected, using the polymerase chain reaction (PCR), which amplifies a DNA fragment of 898 bp. This methodology permits detection to as low as 300 cfu/mL in leaves and stems infected by CBB (Verdier et al. 1998). When Verdier and Mosquera (1999) used the specific probe P898, they detected the bacterium in raw extracts of infected leaves and stems, and in cassava fruits and sexual seed. According to Verdier et al. (1993), pathogen diversity is narrow in Africa but broad in South America, cassava's center of origin.

Restrepo et al. (1996) reported that the diversity of the Colombian strains is very broad, at both pathogenic and genetic levels. Diversity is also high in Brazil (Restrepo et al. 1999) and Venezuela (Verdier et al. 1998).

Previous studies also revealed geographical differentiation among pathogen populations, according to ecozone. Evidence also exists of pathotypes moving within and between regions, probably because of movements of infected planting materials. In Colombia, analysis of pathogenic characteristics of *Xam* strains collected in three ecozones led to the definition of different pathotypes specific to each ecozone (Restrepo 1999).

An analysis, using the AFLP technique, of the genetic variability of 85 *Xam* isolates from Brazil, Colombia, Cuba, and Venezuela distinguished three groups: (1) a cluster at a similarity level of 0.6 and formed of isolates from different localities in Colombia; (2) a cluster at 0.7 and comprising 81% of the Venezuelan isolates included in this study, and 4 Brazilian isolates; and (3) a cluster at 0.4 and formed by most of the Brazilian isolates, 3 isolates from Venezuela, 1 from Cuba, and 3 from Colombia. In this last group, clustering below the 0.4 similarity level also occurred, indicating great genetic variability within the Brazilian sites, possibly related to the also high level of genetic diversity observed for the host plant (Sánchez et al. 1999). When new pathogen strains are introduced into a given area, the genetic diversity already found within the pathogen population is increased, thereby favoring the development of new pathotypes (Restrepo 1999).

Integrated disease management. To control the disease, integrated management should be carried out, involving varietal resistance, cultural practices, and biological control.

Varietal resistance. The genetic control of CBB is the most efficient and economic method for the farmer, but the cassava cropping cycle is long, with a very low production of planting materials. Hence, the time involved in producing resistant varieties is very long. At CIAT, resistant varieties are identified through evaluations in the Eastern Plains and the Atlantic Coast, where the disease is acute and endemic. They are also evaluated in the greenhouse, under controlled conditions, with temperatures at 30 °C and relative humidity at 95%.

In several greenhouse studies, plants of different cassava varieties were inoculated with 39 isolates from different regions of Colombia, Venezuela, and Brazil. Fifteen genotypes were identified as having high to intermediate resistance to CBB, scoring between 1.0 and 2.5 on a scale of severity from 1.0 to 5.0. These varieties included M Esc Fla 039, M Esc Fla 021, M Bra 383, M Col 2066, CM 3311-4, CM 7772-13, and SM 1779-8 (CIAT 1999, 2000, 2001, 2002b, 2003a).

Between 1995 and 2007, about 6400 cassava genotypes were evaluated in Villavicencio (Colombia) for their field resistance to CBB. Of these, 117 were identified as having partial resistance (CIAT 2001, 2002b, 2003a, 2006, 2007).

In a 10 × 10 diallelic study, carried out in Villavicencio, with 45 families and 30 plants per family, the cassava genotype CM 4574-7 was identified as having high general combination ability. Its progenies showed increased resistance to CBB and SED (Calle et al. 2005).

Tolerant varieties also exist such as M Bra 685, M Bra 886, ICA Catumare, ICA Cebucán, ICA Negrita, Vergara (CM 6438-14), CM 4574-7, and Chiroza. However, the disease has increased in severity in ICA Catumare, for which adequate selection of clean seed was not performed (Álvarez and Llano 2002). Several genotypes have also been identified as having resistance to several pathotypes of the bacterium (Álvarez et al. 1999).

Zinsou et al. (2004) recommended the cassava genotype TMS 30572 for farmers in Benin, because of its high yield and relatively stable resistance to CBB across different environments. Kpémoua (1995) showed that resistance to *Xam* is associated with the production of phenolic compounds and the reinforcement of cell walls in the vascular system during early infection.

To determine the genetic control of resistance, 150 F_1 individuals of the cross TMS 30572 × CM 2177-2 were inoculated with the pathogen and evaluated for resistance under controlled conditions in the greenhouse. Five different *Xam* strains from the world's major cassava-growing areas were used in the study. Genetic analysis identified six genomic regions that control resistance to all *Xam* strains. One region controlled >60% of resistance to each of the strains CIO-1 and CIO-136. Two regions accounted for >70% of resistance to strain CIO-84. Another 80% of resistance to strains CIO-136 and ORST X-27 could be explained by 3 loci for each strain (Jorge et al. 2000).

In three instances, the same genomic regions controlled resistance to two strains. A marker was obtained by Southern hybridization of a PCR amplification product from cassava, using heterologous primers designed from conserved regions of the *Xanthomonas* resistance gene in rice (*Xa21*). The region it marked accounted for 60% of phenotypic variance for resistance to strain CIO-136. A backcross population, derived from crossing members of the mapping population, has been developed and will provide more recombinations for fine mapping towards cloning resistance genes, and for studying intra-locus and inter-loci genetic interactions (Jorge et al. 2000).

A molecular genetic map of cassava was recently constructed from an F_1 cross of noninbred parents. RFLP, AFLP, EST, SSR markers were used to map resistance to CBB. The F_1 cross was evaluated with *Xam* strains under both field and greenhouse conditions. Nine quantitative trait loci (QTLs), located on linkage groups B, D, L, N, and X, explained the phenotypic variance of the crop's response to *Xam* in the greenhouse.

Jorge et al. (2001) reported eight QTLs associated with resistance to CBB, and found changes in the expression of QTLs from one cropping cycle to another in the field, which could be related to changes in the pathogen's population structure. A QTL, located in linkage group D, was conserved over two cropping cycles and in resistance evaluations in the greenhouse. In a previous study, Jorge et al. (2000) showed that 12 different QTLs control resistance to five *Xam* strains.

Hurtado et al. (2005) detected the molecular marker, microsatellite SSRY 65, that could select resistant genotypes in a cassava family corresponding to the cross CM 9208-13 × M Nga 19. Furthermore, the authors identified two RGAs of the NBS class through amplification with PCR, using two primers designed by Llano (2003). These RGAs could identify plant individuals that were resistant to the bacterium.

One approach to assessing cassava genetic diversity involves the structural analysis of genotypes resistant to CBB. Multiple correspondence analysis of AFLP data, using two primer combinations for cassava genotypes resistant and susceptible to two strains of *Xam,* elucidated the genetic structure of cassava germplasm resistant to CBB (Sánchez et al. 1999). Results revealed a random distribution of resistance or susceptibility, suggesting that resistance to CBB has arisen independently many times in cassava germplasm.

Phenolic compounds have been implicated in the resistance of cassava (*Manihot esculenta*) to xanthomonads. Cassava cultivars M Col 22 and CM 523-7 were inoculated with *Xam* and *X. cassavae*. CM 523-7 was susceptible to both pathogens, whereas M Col 22 was susceptible to *Xam* and resistant to *X. cassavae*. In the resistant interaction, no disease symptoms were observed in leaves. Bacterial growth was greatly reduced, and cell wall-bound peroxidase activity increased twofold, probably related to lignin deposition (Pereira et al. 2000).

Preformed putative defenses include copious latex production, which contains protease, ß-1,3 glucanase, and lysozyme activities. ESTs from a latex

cDNA library revealed a constitutive expression of many defense-related genes including chitinase, glucanase, and PAL. A cDNA-AFLP analysis of cassava leaves suffering a hypersensitive response to *Pseudomonas syringae* pv. *tomato* revealed that 78 genes, new to cassava, had expressed differentially. Homologs of a metalloprotease, glucanase, peroxidase, and ACC oxidase were all found to be upregulated. Pathogenicity determinants of *Xam* are being studied in the disruption of the *gum* biosynthesis gene (its EPS is produced copiously in plants) and the *pel* gene (pectate lyase appears as a single isoform) (Kemp et al. 2001).

RGAs were amplified as a means of elucidating the putative genes involved in cassava's defense response. For the cDNA-AFLP technique, of about 3600 cDNA fragments screened, 353 fragments were specific to a resistant variety. Sequence analyses showed significant homology with resistance genes, NPK-1 related proteins, senescence-related proteins, and other known proteins involved in disease resistance reactions.

Using degenerate primers, 12 classes of RGAs were identified in cassava. Screening a cassava cDNA library (root and leaf) with class-specific RGA probes also led to the identification of 16 expressed gene clones. Sequence analysis of clone L16 confirmed the constitutive expression of a protein that shares characteristics with previously reported resistance genes (Restrepo et al. 2001).

López et al. (2004a) identified 6046 unigenes and characterized a group of genes putatively involved in cassava's defense response to *Xam* infection. López et al. (2004b) identified the *RXam1* gene, homolog of *Xa21* from rice, in a 3600-bp DNA fragment. The gene is induced in the resistant variety (M Bra 685), 72 h after infection by *Xam*.

Cultural practices. The following practices are recommended:

- Use of healthy planting materials obtained from disease-free crops, plants derived from meristem culture, and by rooting buds and/or shoots

- Treating stakes by immersing them for 10 min in a solution of cupric fungicides such as copper oxychloride or Orthocide® (captan) at 3 to 6 g/L

- Immersion in extract of citrus fruit seeds (Lonlife®)

- Heat treatment of stakes (Álvarez et al. 2008; CIAT 2007), using hot water at 49 °C for 49 min. Incidence of CBB in untreated stakes was 37%, but dropped to 7% when treated with hot water. It dropped further to 0% when stakes were pretreated at 49 °C for 10 min 24 h before being treated with hot water for 5 h. Treatment with hot water did not, in practical terms, affect stake germination, reducing it by only 18% in the most prolonged treatment (Ramírez et al. 2000). The induction of enzymes that activate under stress conditions is probably responsible for conserving high stake germination, even after prolonged treatment in hot water.

Lozano (1986) also mentions the following practices for managing the disease:

- Planting at the end of rainy periods
- Crop rotation with grasses
- Planting barriers of maize to prevent dissemination by wind
- Improving soil drainage
- Weed control
- Fertilizers adapted mainly with sources of potassium
- Eradicating diseased plants
- Preventing the movement of people, machines, and animals from infected lots to healthy lots
- Eliminating infected materials after harvest by burning branches and stems
- Incorporating harvest residues into the soil

In field studies conducted in Benin and Togo by Wydra et al. (2001), locally and regionally well-adapted control measures for CBB were identified such as:

- Using locally preferred resistant varieties
- Intercropping with locally used crops
- Amending soils with local materials
- Fertilizer applications and recommendations on phytosanitary measures carried out to reduce disease

Complementary studies elucidated some mechanisms of resistance at the biochemical and genetic levels and molecular host-pathogen interactions.

New methods for detecting *Xanthomonas campestris* pv. *manihotis* (*Xcm*), using immunological and genetic techniques, were developed. Research results were partly verified under African conditions such as testing the cassava genome mapping population for reaction towards African strains to identify genetic markers and/or resistance related genes.

Biological control. Spraying with suspensions of *Pseudomonas putida* reduced the severity of damage caused by CBB, while cassava yields increased significantly (CIAT 1985). However, this practice has not been adapted for farming conditions.

Bacterial stem rot (*Erwinia carotovora* pv. *carotovora*)

Importance. This disease is important for the damage it does to the quality and germinability of planting stakes.

Symptoms. The disease is characterized by an aqueous and smelly stem rot or by medullary necrosis of the plant's ligneous parts (Figure 8-18). Infected plants show bud wilt. The stem's surfaces typically show perforations made by insects of the genus *Anastrepha* Schiner, which act as vectors for the bacterium. These orifices are easy to distinguish by the presence of dry latex, discharged as the stem is perforated. Diseased stakes used for planting will not germinate or they produce weak spindly plants, with a limited number of bulked roots (CIAT 1972).

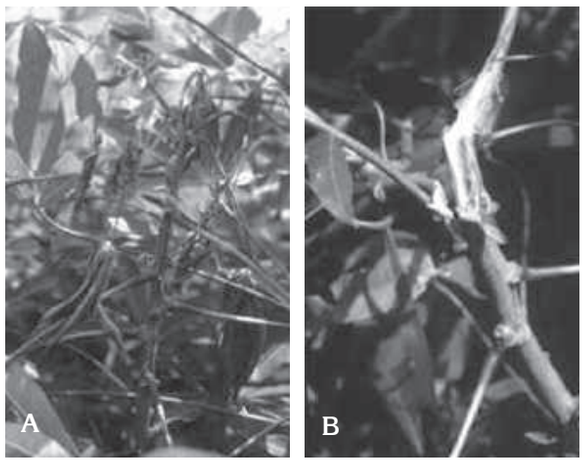


Figure 8-18. Symptoms caused by *Erwinia carotovora*: **(A)** wilt, and **(B)** damage to the medulla.

Management and control.
- Using healthy seed
- Planting with varieties resistant to the insect vector
- Burning infected stems

Bacterial stem gall (*Agrobacterium tumefaciens*)

Symptoms and epidemiology. This disease generally appears on the lower parts of stems in plants older than 6 months. Characteristic symptoms, found on stem nodes, are galls that often become very large, presenting a proliferation of buds on the epidermis (Figure 8-19). Infected plants may become weak and spindly, and in the early days of infection, suffer dieback to as far as major galls. A single plant could have several galls on a stem and even along lower branches (Lozano et al 1981).

The disease is usually initiated by infested soil being rain-splashed onto wounds caused by natural defoliation in stems of the plant's lower parts.

Management and control. Control is achieved through rotation with another crop when more than 3% of the planting is infected; disinfecting machetes with 2% sodium hypochlorite; always using planting stakes from healthy crops; and burning diseased materials within the crop (Lozano et al 1981).

Another bacterial disease is caused by *Erwinia herbicola*.

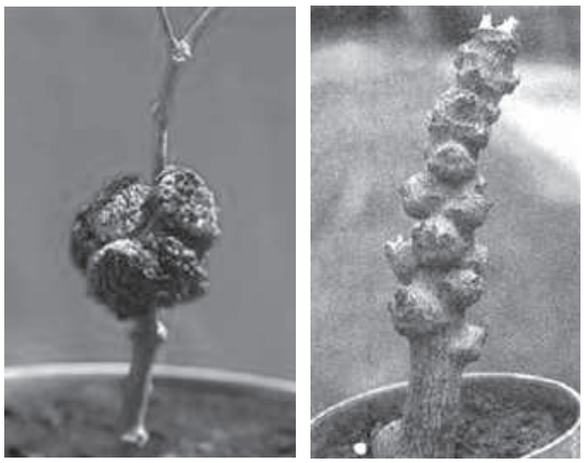


Figure 8-19. Galls on stem caused by *Agrobacterium tumefaciens*.

Diseases caused by '*Candidatus* Phytoplasmas'

(previously known as mycoplasma-like organisms or MLOs)

Cassava frogskin disease (*Ca.* phytoplasma, subgroup 16SrIII-L and rpIII-H)

Importance. Cassava frogskin disease (CFSD) is an economically important disease affecting cassava roots. It was reported for the first time in 1971, in the Department of Cauca, southern Colombia. Its origin appears to be the Amazon region of Brazil or Colombia (Pineda et al. 1983).

Frogskin disease directly affects root production, causing losses of 90% or more. Symptoms consist of small, longitudinal fissures distributed throughout the root. As roots increase in diameter, the fissures tend to heal, giving the injuries a lip form. The root cortex or epidermis appears cork-like and peels off easily. Depending on the severity of symptoms, the depth and number of lesions increase until the root becomes deformed (Álvarez et al. 2003a; Pineda et al. 1983).

Distribution. In the 1980s, the disease occurred in most cassava-growing regions of Colombia and has continually spread. It has now been reported in Brazil, Costa Rica, Panama, Peru, and Venezuela (Calvert and Cuervo 2002), as well as in Nicaragua and Honduras. In Venezuela, it was reported for the first time in the States of Barinas and Aragua, with incidences between 11.4% and 14.3%, in cassava stakes grafted with 'Secundina', a variety used to diagnose the disease (Chaparro and Trujillo 2001).

Symptoms and epidemiology. Frogskin mostly attacks cassava roots, reducing their diameter, but some varieties may also show symptoms in leaves such as mosaic, chlorosis, curling, and/or curvature in leaf margins (Figure 8-20A). However, these symptoms are difficult to distinguish under field conditions, and may be confused with damage from mites, thrips, viruses, and micronutrient deficiencies, or they can be masked when temperatures are >30 °C.

Characteristic CFSD symptoms in the roots include a woody aspect and the thick, cork-like peel, which is also fragile and opaque. The peel also presents lip-like slits that may join to create a net-like or honeycomb pattern (Figures 8-20B and 8-20C). When roots do not bulk adequately (Figure 20D), the stems tend to be thicker than normal. In contrast, the roots of healthy plants are well developed, with thin, brilliant, and flexible peel.

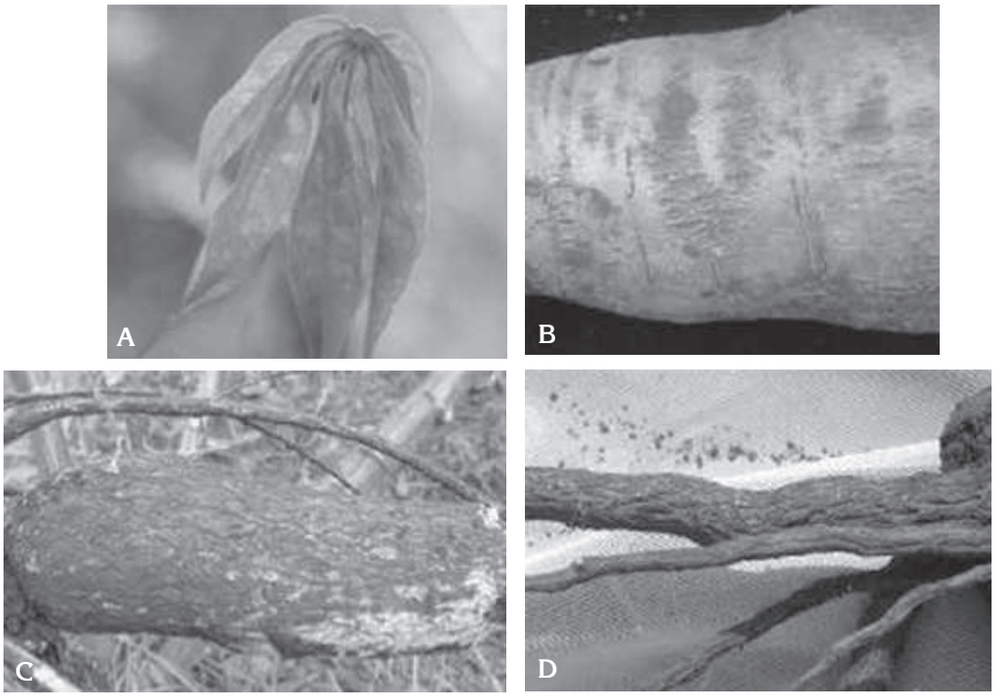


Figure 8-20. Symptoms of cassava frogskin disease in **(A)** leaves, **(B)** and **(C)** presence of lips in root, and (D) reduced root bulking.

Molecular tests, carried out on plants of cassava and pink vinca (*Catharanthus roseus* (L.) G. Don) after transmission trials with dodder (*Cuscuta* sp. L.), detected the presence of phytoplasmas associated with the 16SrIII group. Graft transmission could transfer phytoplasmas from infected to healthy plants (CIAT 2005).

Insects were collected to identify the vector or vectors of the phytoplasma causing the disease. A homology of 90% was found among sequenced fragments from tissue of the insect *Scaphytopius marginelineatus* Stål (Hemiptera: Auchenorrhyncha: Cicadellidae) and from tissues of two cassava varieties.

Etiology. The CFSD-associated phytoplasmas were identified as group 16SrIII strains by restriction fragment length polymorphism (RFLP) and sequence analyses of amplified rDNA products, and results were corroborated by PCRs employing group 16SrIII-specific rRNA gene or ribosomal protein (rp) gene primers. Collectively, RFLP analyses indicated that CFSD strains differed from all phytoplasmas described previously in group 16SrIII and, on this basis, the strains were tentatively assigned to new ribosomal and ribosomal protein subgroups 16SrIII-L and rpIII-H, respectively. This is the first molecular identification of a phytoplasma associated with CFSD in cassava in Colombia (Álvarez et al. 2009).

The phytoplasma was not detected in healthy plants from the same varieties harvested in disease-free fields. These results point towards the possible role played by phytoplasmas in this disease (Álvarez et al. 2003a; CIAT 2002a). The importance of the CFSD in cassava production systems has motivated other scientific groups at CIAT, such as the Virology group, to undertake efforts to understand the characteristics of the disease, its symptoms and its management practices.

Cuttings from CFSD-infected plants in the greenhouse were taken, and rooted in deionized water with different doses of chlortetracycline. Inhibition of leaf symptoms caused by CFSD was successful in two experiments when 50 ppm chlortetracycline were used, thus indicating that CFSD is not caused by a virus. Nested PCR also showed that phytoplasmas were present in leaves of infected plants when treated with 0 ppm tetracycline (CIAT 2003b).

Although the disease spreads mostly through infected stakes, the disease is believed to have insect vectors. Numerous homopteran species (e.g., planthoppers, tree hoppers, and froghoppers) were collected from cassava fields in 9 departments and 17 sites in Colombia. Three genera—*Scaphytopius fuliginosus* Osborn, *Empoasca* sp. Walsh, and *Stirellus bicolor* Van Duzee (Hemiptera: Cicadellidae)—were the most frequently collected. These three species are known vectors of viruses and phytoplasmas for other crops. Based on the evidence of high homology (80%) between insect and phytoplasma detected in cassava, *Sc. fuliginosus* appears to be a potential candidate as the vector for CFSD (CIAT 2003b). However, tests for transmission have not yet effectively confirmed this hypothesis. The whitefly (*Bemisia tuberculata*) is still associated with the disease transmission.

Integrated disease management. To date, the disease is managed principally by using stakes from healthy plants. Heat treatment, followed by meristem culture, has been used to obtain plants free of CFSD. Grafting with the susceptible variety Secundina is useful for monitoring the effectiveness of the heat treatment (Flor et al. 2001). Treating stakes at temperatures of more than 55 °C appears promising but needs adjusting to reduce losses by the consequent low germination of stakes.

Plantings with more than 10% of incidence (foliage, stakes, and roots) should be burned. Plant health surveillance and quarantine systems need to be strengthened to prevent the entry or mobilization of planting materials from areas with the disease.

Field and greenhouse studies carried out at CIAT have reported 30 genotypes with different levels of resistance. These findings were confirmed through the expression of leaf symptoms in grafts with variety Secundina (CIAT 2003b; Cuervo 2006). The use of tolerant varieties will be a useful tool in controlling this disease.

Witches' broom

Importance. This disease, known as *superbrotamiento* in Spanish, has been reported in Brazil, Venezuela, Mexico, and Peru (Figure 8-21). Although its incidence is not significant, the percentage of witches' broom in affected plantings is much higher than that of other diseases caused by American phytoplasmas. Crop losses can reach 80% (Lozano et al. 1981). In Asia a new cassava disease was observed at Quang Ngai, Vietnam (Figure 8-22). Typical

Figure 8-21. Symptoms of "*superbrotamiento*" in cassava. (Photo: B Pineda.)

symptoms similar to witches' broom are widespread in southern Vietnam, in Plangyao, Chacheoengsao, Thailand, and also in the Philippines (Figure 8-23). The disease may seriously affect yields and the availability of clean planting material.

Symptoms. Several symptomatologies exist:

1. Plants exhibit dwarfism and an exaggerated proliferation of buds. Sprouts have short internodes and small leaves, but do not show deformation or chlorosis.
2. Proliferation of weak spindly sprouts on the stakes.

Figure 8-23. Disease symptoms observed on cassava plants in the Philippines.

3. Stakes produce only a few dwarf and weak spindly sprouts that never reach normal size.
4. When the affected cassava is uprooted, the roots are thinner and smaller, with rough-textured skins, and drastically reduced starch content.

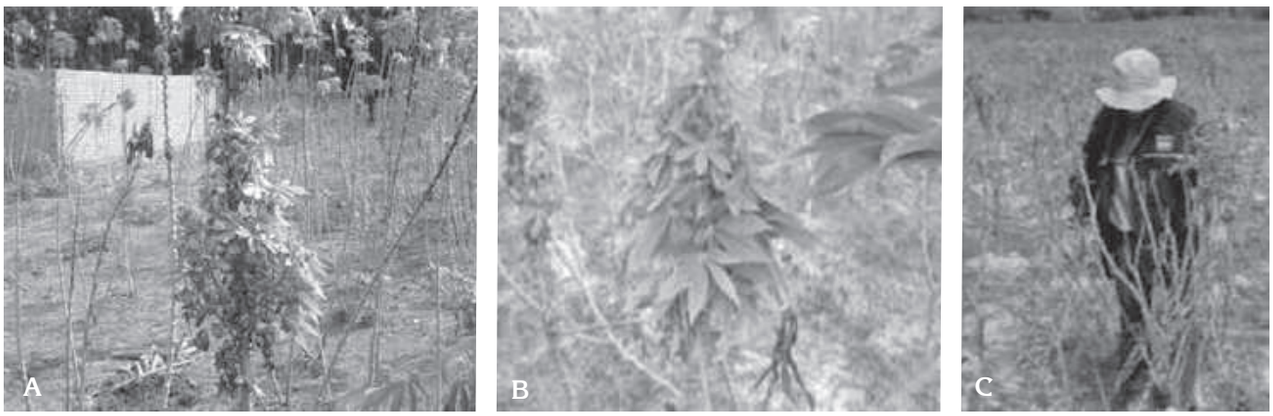


Figure 8-22. Cassava plants in Vietnam with exaggerated bud proliferation; **(A) (B)** shoot proliferation and/or usually **(C)** rachitic branches growing from a single stake; and shoots with short internodes and small leaves that show no deformation or chlorosis. (Photos: JF Mejía.)

The disease is transmitted mechanically and by the use of stakes from diseased plants (Lozano et al. 1981).

Etiology. The transmission of cassava phytoplasmas by *Cuscuta* sp. into pink vinca was 100% positive. Symptoms appeared 3 weeks after implanting the host parasite into pink vinca in growth chambers at 18–20 °C. No transmission was achieved with the insect *Scaphytopius fuliginosus*, even 3 months after exposure to feeding, whether cassava to cassava, cassava to vinca, or vinca to vinca (Valencia et al. 1993).

In Vietnam, disease recognition was carried out in the country's central and southern regions (Quang Ngai and Dong Nai provinces). Samples for diagnosing phytoplasmas were collected in southern Vietnam at Hung Loc Agricultural Research Center and from a farmer's plot in Dong Nai province, both sites about 60 km from Ho Chi Minh City. Phytoplasmas were detected in the samples collected in Thailand and Vietnam. Diagnosis results confirm the association of symptoms (high bud proliferation shoots with short internodes, and small leaves) with phytoplasmas.

Phytoplasmas were detected in roots, small leaves, and leaf veins showing symptoms. No phytoplasmas of the 16SrIII group (reported in America) were found in the samples from Thailand and Vietnam. However, only samples from eastern Thailand and southern Vietnam have been evaluated. These results need to be confirmed. Molecular tests based on the 16Sr gene indicated that differences exist between the phytoplasmas detected in eastern Thailand and southern Vietnam (E Álvarez, JF Mejía, and A Bertaccini 2009, pers. comm.).

Management. The use of healthy planting materials and the elimination of diseased plants in the field are recommended to prevent the disease (Lozano et al. 1981). The disease is reduced by selecting stakes from healthy plants and by restricting the movement of cassava planting stakes, especially from infected areas, and that of related species such as *Jatropha*. Varietal resistance also exists.

Antholysis

Importance. Antholysis in cassava was observed in crops in southwestern Colombia in 1981 by Jayasinghe et al. (1983), severely in some experimental clones. However, this disease does not have economic importance and is only sometimes observed.

Symptoms. The disease appears in the inflorescence, with a characteristic virescence in the petals, which, instead of being their normal pink, become green. Hypertrophy of the petals is later observed and they become structures similar to leaves (phyllody). The floral racemes lose their normal appearance and resemble sprouts, giving this syndrome its name "antholysis" (*antho* – flower; *lysis* – dissolve, loosen) (Figure 8-24).

Figure 8-24. Symptoms of antholysis in cassava: **(A)** healthy flower, **(B)** virescence, and **(C)** phyllody. (Photos: B Pineda.)

Infected flowers commonly exhibit a very swollen gynophore and develop internodes in the floral receptacle, a phenomenon known as apostasis. Furthermore, elongation of the receptacle occurs above the insertion of the pistil, with development of sprouts. Flower fertility is lost, resulting in nonfunctional flowers that abort prematurely. Affected plants do not present symptoms in other organs and, moreover, germination did not differ between infected and healthy stakes (Jayasinghe et al. 1983).

Etiology. By using an electron microscope, Jayasinghe et al. (1983) observed oval or spherical pleomorphic structures only in phloem tissues. Transmission is 100% by stakes. Under greenhouse conditions, symptoms of antholysis appear within 1 month of planting, contrasting with healthy plants, which take 5 months to flower.

Treatment with penicillin (500 to 1000 ppm) did not reduce symptoms, whereas tetracycline reduced antholysis by 90%. This sensitivity and detection by Dienes' stain confirmed that the causal agent is a phytoplasma (Jayasinghe et al. 1983).

Management. The disease is reduced by selecting stakes from healthy plants. Varietal resistance also exists.

References

To save space, the acronym "CIAT" is used instead of "Centro Internacional de Agricultura Tropical".

Akinrele IA. 1964. Fermentation of cassava. J Sci Food Agric 15:589–594.

Álvarez E; Llano GA. 2002. Enfermedades del cultivo de la yuca y métodos de control. In: Ospina B; Ceballos H, eds. La yuca en el tercer milenio: Sistemas modernos de producción, procesamiento, utilización y comercialización. CIAT, Cali, Colombia. p 131–147.

Álvarez E; Molina ML. 2000. Characterizing the *Sphaceloma* fungus, causal agent of superelongation disease in cassava. Plant Dis 84:423–428.

Álvarez E; Chacón MI; Loke JB; Sánchez NJ. 1997a. Genetic variation in strains of *Phytophthora* spp. affecting cassava. Phytopathology 87(6):S3–S4.

Álvarez E; Loke JB; Sánchez J; Bellotti A. 1997b. Progress in the characterization of *Phytophthora* isolates, the causal agent of root rots of cassava. American Phytopathological Society - Annual Meeting, 9–13 August, Rochester, NY, USA. Phytopathology 87(6):S4.

Álvarez E; Sánchez J; Chacón MI; Loke JB. 1997. Avances en la caracterización de aislamientos de *Phytophthora* spp. el agente causal de pudriciones de raíces en yuca. ASCOLFI Congress at the International Center for Tropical Agriculture (CIAT), Cali, Colombia. August 1.

Álvarez E; Cadena SF; Llano GA. 1999. Evaluación de resistencia de yuca a doce cepas de *Xanthomonas axonopodis* pv. *manihotis*. ASCOLFI Informa (Colombia) 25(4–6):57–59.

Álvarez E; Chacón MI; Sánchez NJ. 2000. DNA polymorphism and virulence variation of a *Phytophthora* population isolated from cassava *Manihot esculenta* Crantz. In: Carvalho LJCB; Thro AM; Duarte Vilarinhos A, eds. Proc IV International Scientific Meeting of the Cassava Biotechnology Network (CBN), held in Brasília, Brazil, 3–7 Nov 1998. National Research Center for Genetic Resources and Biotechnology (CENARGEN) of the Brazilian Agricultural Research Corporation (EMBRAPA); CBN, Brasília, Brazil. p 279–287.

Álvarez E; Mejía JF; Lozada T. 2001. Assessing virulence and genetic variability of *Sphaceloma manihoticola*, causal agent of superelongation in cassava (*Manihot esculenta*), in Brazil and Colombia, using RAMS and AFLP. Phytopathology 91:S101.

Álvarez E; Mejía JF; Loke JB; Hernández L; Llano GA. 2003a. Detecting the phytoplasma–frogskin disease association in cassava (*Manihot esculenta* Crantz) in Colombia. Phytopathology 93(6):S4. (Also presented as a poster at the APS annual meeting, held in Charlotte, NC, USA, 9–13 Aug 2003.)

Álvarez E; Loke JB; Llano GA. 2003b. Development of ecological practices to manage *Phytophthora* root rot of cassava (*Manihot esculenta*). Poster presented at the 8th International Congress of Plant Pathology (ICPP2003), held in Christchurch, New Zealand, 2–7 Feb 2003. Vol 2, p 133.

Álvarez E; Loke JB; Rivera S; Llano GA. 2003c. Genética de la resistencia a pudrición causada por *Phytophthora tropicalis* en dos poblaciones segregantes de yuca (*Manihot esculenta* Crantz). Fitopatol Colomb 26(2):61–66.

Álvarez E; Mejía JF; Valle TL. 2003d. Molecular and pathogenicity characterization of *Sphaceloma manihoticola* isolates from south central Brazil. Plant Dis 87(11):1322–1328.

Álvarez E, Mejía JF, Llano GA; Loke JB. 2008. Enfermedades limitantes de la yuca. Instituto Colombiano Agropecuario (ICA), Palmira, Colombia. 24 p.

Álvarez E; Mejía JF; Llano GA; Loke JB; Calari A; Duduk B; Bertaccini A. 2009. Detection and molecular characterization of phytoplasma associated with frogskin disease in cassava. Plant Dis 93:1139–1145.

Arraudeau M. 1967. Cassava in the Malagasy Republic: Research and results. In: Proc I Triennial Symposium of the International Society for Tropical Root Crops (ISTRC), held in Augustine, Trinidad, 1967. University of West Indies, Augustine, Trinidad. Vol 1(3), p 180–184.

Averre W. 1967. Vascular streaking of stored cassava roots. In: Proc I Triennial Symposium of the International Society for Tropical Root Crops (ISTRC), held in Augustine, Trinidad, 1967. University of West Indies, Augustine, Trinidad. Vol 2(4), p 31–35.

Barragán MI; Álvarez E. 1998. Identificación de fuentes de resistencia a la pudrición radical en yuca (*Manihot esculenta* Crantz). Ascolfi Informa (Colombia) 24(2):8–9.

Bedoya FA; Álvarez E; Loke JB. 2000. Selección *in vitro* de aislamientos de *Trichoderma* spp. para el control biológico de la pudrición radical en yuca. Fitopatol Colomb 23(2):65–67.

Bitancourt A; Jenkins AE. 1950. Estudos sobre as Miringinales. II. Vinte novas especies de *Elsinoaceas neatropicais*. Arq Inst Biol (Sao Paulo) 20:1–28.

Boher B; Agboli CA. 1992. La bacteriose vasculaire du manioc au Togo: Caracterisation du parasite, repartition geographique et sensibilite varietale. Agron Trop (Paris) 46(2):131–136.

Boher B; Verdier V. 1994. Cassava bacterial blight in Africa: the state of knowledge and implications for designing control strategies. Afr Crop Sci J 4:505–509.

Booth RH; Lozano JC. 1978. Cassava bacterial blight in South East Asia. Plant Dis Rep 62(6):529–530.

Bouriquet G. 1946. Les maladies du manioc a Madagascar. Bull Econ Madag (Tananarive) 65:198–237.

Bradbury JF. 1986. Guide to plant pathogenic bacteria. CAB International, Wallingford, UK. p. 332.

Cajar A. 1981. Inventario fitosanitario de la colección de clones de yuca (*Manihot esculenta* Crantz) en Calabacito, Veraguas, 1979. Publicación Miscelánea No. 4. Instituto de Investigacion Agropecuaria de Panamá (IDIAP), Santiago, Veraguas. Panama. 9 p.

Calvert LA; Cuervo M. 2002. Enfermedades virales de la yuca en América del Sur. In: Ospina B; Ceballos H, eds. La yuca en el tercer milenio: Sistemas modernos de producción, procesamiento utilización y comercialización. CIAT, Cali, Colombia. p 262–268.

Calvert LA.; Thresh JM. 2002. The viruses and virus diseases of cassava. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 237–260.

Calle F; Pérez JC; Gaitán W; Morante N; Ceballos H; Llano GA; Álvarez E. 2005. Diallel inheritance of relevant traits in cassava (*Manihot esculenta* Crantz) adapted to acid-soil savannas. Euphytica 144:177–186.

Castaño JJ. 1953. La llaga negra o podredumbre negra radicular de la yuca. Agric Trop (Colombia) 8:21–29.

Castaño JJ. 1969. Mancha foliar de *Cercospora caribae* en yuca (*Manihot utilissima* Pohl.) en la región de Barbosa (Antioquia). Agric Trop (Colombia) 25:327–329.

Chaparro EI; Trujillo G. 2001. First report of frog skin disease in cassava (*Manihot esculenta*) in Venezuela. Plant Dis 85(12):1285.

Chávez M. 1992. Mejoramiento de la yuca en Panamá. In: Iglesias CA; Fukuda W, eds. Memorias de la Reunión Panamericana de Fitomejoradores de Yuca 2, 1990, Documento de Trabajo No. 112. CIAT, Cali, Colombia. p 85–90.

Cherian MT; Mathew J. 1981. Influence of age of plants on cassava bacterial blight incidence and development of *Xanthomonas axonopodis* pv. *manihotis*. Agric Res J Kerala 19(1):116–117.

Chevaugeon J. 1956. Les maladies criptogamique du mandioc en Afrique Occidentale. Encycl Mycol 28:1–205.

Chupp C. 1953. A monograph of Cercospora. Cornell University, Ithaca, NY, USA. 667 p.

CIAT. 1972. Annual report. CIAT, Cali, Colombia. 192 p.

CIAT. 1985. Cassava Program. In: Annual report 1984. Cali, Colombia. 270 p.

CIAT. 1998. Improved cassava for the developing world—Annual report [of] Project IP-3. Cali, Colombia. p 19–30.

CIAT. 1999. Improved cassava for the developing world—Annual report [of] Project IP-3. Cali, Colombia. p 61–81.

CIAT. 2000. Improved cassava for the developing world—Annual report [of] Project IP-3. Cali, Colombia. p 123–154.

CIAT. 2001. Improved cassava for the developing world—Annual report [of] Project IP-3. Cali, Colombia. p 7.1–7.26.

CIAT. 2002a. Activity 1: Cassava and tropical fruit pathology. In: Integrated pest and disease management in major agroecosystems—Annual report [of] Project PE-1. Cali, Colombia. p 84, 182.

CIAT. 2002b. Improved cassava for the developing world—Annual report [of] Project IP-3. Cali, Colombia. p 7.1–7.80.

CIAT. 2003a. Improved cassava for the developing world—Annual report [of] Project IP-3. Cali, Colombia. p 7.1–7.55.

CIAT. 2003b. Integrated pest and disease management in major agroecosystems—Annual report [of] Project PE-1. Cali, Colombia. p 110, 141.

CIAT. 2004. Integrated pest and disease management in major agroecosystems—Annual report [of] Project PE-1. Cali, Colombia. p 11.1–11.61.

CIAT. 2005. Crop and agroecosystem health management—Annual report [of] Project PE-1. Cali, Colombia. p 51–53.

CIAT. 2006. Improved cassava for the developing world—Annual report [of] Project IP-3. Cali, Colombia. p 11.1–11.28.

CIAT. 2007. Improved cassava for the developing world—Annual report [of] Project SBA-2. Cali, Colombia. p 9.1–9.17.

Clerck GC; Caurie M. 1968. Biochemical changes caused by some *Aspergillus* species in root tubers of cassava (*Manihot esculenta* Crantz). Trop Sci 10:149–154.

Contreras N; Mireles M; Moreno N; Fernández S. 1991. Enfermedades fungosas y bacterianas que afectan el cultivo de la yuca en el Estado Barinas. Fonaiap Divulga No. 37. Fondo Nacional de Investigaciones Agropecuarias (FONAIAP), Maracay, Venezuela. 6 p.

Corredor JA. 2005. Evaluación de la asociación de características morfológicas y bioquímicas de la raíz de yuca (*Manihot esculenta* Crantz) con la resistencia a pudrición por *Phytophthora tropicalis* y al deterioro fisiológico poscosecha. Universidad de Caldas, Facultad de Ciencias Agropecuarias, Manizales, Colombia. 136 p.

Cuervo M. 2006. Caracterización molecular de algunos aislamientos del virus del cuero de sapo de yuca recolectados en diferentes zonas de Colombia. Dissertation for postgraduate course in agricultural sciences with emphasis in plant genetic resources. Universidad Nacional de Colombia, Palmira, Colombia. 71 p.

Daniel JF; Boher B; Nkouka N. 1980. Propagation de *Xanthomonas manihotis* transmis au manioc par des insectes, dans la Republique Populaire du Congo. In: Terry ER; Oduro KA; Caveness F, eds. Proc I First Triennial Roots Crops Symposium of the International Society for Tropical Root Crops (ISTRC)–Africa Branch, held in Ibadan, Nigeria, 8–12 Sep 1980. ISTRC, p 71–74

Davidse LC; Looijen D; Turkensteen LJ; Van Der Wal D. 1981. Occurrence of metalaxyl-resistant strains of *Phytophthora infestans* in the Netherlands. Eur Plant Prot Organ Bull 15:403–409.

Doku EV; Lamptey P. 1977. Control of cassava bacterial blight (*Xanthomonas manihotis*) in Ghana. In: Cassava bacterial blight: Report of an Interdisciplinary Workshop, held in Ottawa, CA. p 22.

Drummond OA; Goncalves RD. 1957. Apodrecimiento das hastes e raizes da mandioca. O Biológico 23:244–245.

Edison S. 2002. Plant protection problems in cassava in India. In: Howeler R, ed. Proc 7th Regional Cassava Workshop, held in Bangkok, Thailand, 28 Oct–1 Nov 2002. p 264–270.

El-Sharkawy MA; Cock JH; Lynam JK; Hernández AP. Cadavid L, LF. 1990. Relationships between biomass, root-yield and single-leaf photosynthesis in field-grown cassava. Field Crops Res 25(3–4):183–201.

Erwin DC; Ribeiro OK. 1996. *Phytophthora* diseases worldwide. APS Press, The American Phytopathological Society, St. Paul, Minnesota, USA. 562 p.

Essers SAJA; Bosveld M; Grift van der RM; Voragen AGJ. 1993. Studies on the quantification of specific cyanogens in cassava products and introduction of a new chromogen. J Sci Food Agric 63:287–296.

FAO (Food and Agriculture Organization of the United Nations). 2008. Yuca para la seguridad alimentaria y energética. (Available at www.fao.org/newsroom/eS/news/2008/1000899/index.html).

FAO (Food and Agriculture Organization of the United Nations). 2009. FAOSTAT Agriculture Data. (Available at http://apps.fao.org/).

FAO (Food and Agriculture Organization of the United Nations). 2010. FAOSTAT Agriculture Data. (Available at http://apps.fao.org/).

Fassi B. 1957. Premieres observationes sur una pourriture des racines du manioc causée par un *Phytophthora*. D. Information de LIEAC 6(15):16–17.

Ferdinando G; Tokeshi H; Carvalho PCT; Balmer E; Kimati H; Cardoso CON; Salgado CL. 1968. Manual de fitopatología, doencas das plantas e seu control. Biblioteca Agronómica, Ceres, Sâo Paulo, Brazil. 640 p.

Figueiredo MM; Alburquerque FCD. 1970. Podridão mole das raizes da mandioca (*Manihot esculenta*). Pesqui Agropecu Bras 5:389–393.

Flier WG; Bosch GBM van den; Turkensteen LJ. 2003. Stability of partial resistance in potato cultivars exposed to aggressive strains of *Phytophthora infestans*. Plant Pathol 3(52):326–337.

Flor N, Pineda B; Mafla G. 2001. CIAT cassava collection cleaned against "seedborne" diseases of quarantine importance. Poster presented at the Fifth Meeting of CBN-V, held in St. Louis, Missouri, USA, 4–9 Nov 2001.

Fokunang CN; Akem CN; Ikotun T; Dixon AGO; Tembe EA. 2000. Role of the insect vector *Pseudotheraptus devastans* in cassava anthracnose disease development. Eur J Plant Pathol 106:319–327.

Fregene M; Ángel F; Gómez R; Rodríguez F; Chavarriaga P; Roca W; Tohme J; Bonierbale M. 1997. A molecular genetic map of cassava (*Manihot esculenta* Crantz). Theor Appl Genet 95:431–441.

Fukuda W. 1992. Melhoramento de mandioca no Brasil. In: Iglesias CA; Fukuda W, eds. Memorias de la Reunión Panamericana de Fitomejoradores de Yuca 2, 1990. Documento de Trabajo No. 112. CIAT, Cali, Colombia. p 15–31.

García MC; Lamattina L; Cassia RO. 2001. Involvement of iron and ferritin in the potato–*Phytophthora infestans* interaction. Eur J Plant Pathol Bull 107:557–562.

Gees R; Holh HR. 1988. Cytological comparison of specific (Ra) and general resistance to late blight in potato leaf tissue. Phytopathology 78:350–357.

Gergely L. 2000. Study of foliage and tubers for susceptibility to potato blight of potato variety candidates. Novenyvedelem (Budapest, Hung.) 10(36):517–521.

Ghesquiere J. 1932. Sur la "mycosphaerellose" des feulles dy manioc. Bull Inst Royal Coll Belg 3:160–178.

Golato C; Meossi E. 1966. Una nuova malattis folgiare della manioca in Somalia. Riv Agric Subtrop Tropic 60:182–186.

Gómez KA; Gómez AA. 1984. Statistical procedures for agricultural research. John Wiley & Sons, Inc., New York. 333 p.

Gonçalves RD; Franco J. 1941. Rhizotoniose em mandioca e podridão das raizes (*Diplodia*) em tunque. O Biológico 7:360–361.

Heim R. 1931. Le *Phoeolus manihotis* sp. nov., parasite du manioc a Madagascar, et considération sur le genre *Phoeolus* Pat. Ann Cryptogam Exot 6:175–189.

Helms TC; Nelson BD; Goos RJ. 2002. Registration of 'Walsh' soybean. Crop Sci 42:1379–1380.

Hillocks RJ. 2002. Cassava in Africa. In Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 41–54.

Hillocks RJ; Wydra K. 2002. Bacterial, fungal and nematode diseases. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford UK. Colombia. p 261–280.

Hurtado PX; Álvarez E; Fregene M; Llano GA. 2005. Detección de marcadores microsatélites asociados con la resistencia a *Xanthomonas axonopodis* pv. *manihotis* en una familia de yuca (bc1). Fitopatol Colomb 28(2):81–86.

IITA (International Institute of Tropical Agriculture). 1972. Report of root, tuber and vegetable improvement Program. Ibadan, Nigeria. 48 p.

Irvine FR. 1969. Cassava (*Manihot utilissima*) in West African agriculture 2: West African crops. Oxford University Press, London, England. p 153–159.

Ivanov GE; Mertsedin RN. 1990. Zinc oxide improves potato tuber quality. Kartofel'-i-Ovoshchi 2:13–15.

Iwaro AD; Sreenivasan TN; Umaharan P. 1997. Foliar resistance to *Phytophthora palmivora* as an indicator of pod resistance in *Theobroma cacao*. Plant Dis 81:619–624.

Jaramillo G; Zapata G. 2002. Ficha técnica de clones industriales de yuca adaptados a las condiciones del norte del Cauca y sur del Valle. Paper prepared for the Intensive Course on Cassava Production, held at CIAT, 25–28 June 2002. CIAT, Cali, Colombia. 28 p.

Jayasinghe U; Pineda B; Lozano JC. 1983. Antólisis en yuca (*Manihot esculenta* Crantz), asociada con organismos similares a micoplasmas. Fitopatol Bras 9:051–057.

Jennings DL. 1970. Cassava in Africa. Field Crop Abstr 23:271–277.

Johnson I; Palaniswami A. 1999. *Phytophthora* tuber rot of cassava: a new record in India. J Mycol Plant Pathol 3(29):323–332.

Jorge V; Fregene M; Duque MC; Bonierbale MW; Tohme J; Verdier V. 2000. Genetic mapping of resistance to bacterial blight disease in cassava (*Manihot esculenta* Crantz). Theor Appl Genet 101(5-6):865–872.

Jorge V; Fregene M; Vélez CM; Duque MC; Tohme J; Verdier V. 2001. QTL analysis of field resistance to *Xanthomonas axonopodis* pv *manihotis* in cassava. Theor Appl Genet 102:564–571.

Kaitany R; Melakeberhan H; Bird GW; Safir G. 2000. Association of *Phytophthora sojae* with *Heterodera glycines* and nutrient stressed soybeans. Nematropica 30:193–199.

Kemp B. 2000. Cassava bacterial blight. [on line] University of Bath, UK. www.bath.ac.uk/~bspbk/cbb.html [accessed: Sept 2001].

Kemp BP; Beeching JR; Cooper RM. 2001. Pathogenicity and resistance in *Xanthomonas* blight of cassava. Poster presented at Fifth meeting CBN-V. Nov 4–9, 2001. St. Louis, Missouri. USA.

Kpémoua KE. 1995. Etude comparative du développement de *Xanthomonas campestris* pv *manihotis* chez des variétés de manioc sensibles et résistantes; approaches histologiques, ultrastructurales et cytochimiques des mécansmes de la pathogénèse. Dissertation. University of Nantes, France.

Kwaje SL. 1984. The occurrence of a new disease, *Xanthomonas manihotis* on cassava in the Sudan. Acta Hortic 143:421–426.

Languidey P. 1981. El añublo bacteriano de la yuca (*Manihot esculenta* Crantz). Instituto de Investigación Agrícola "El Vallecito". Universidad Gabriel René Moreno, Santa Cruz, Bolivia. n.p.

Larios JF; Moreno RA. 1976. Epidemiología de algunas enfermedades foliares de la yuca en diferentes sistemas de cultivo. I. Mildiú polvoso y roña. Turrialba 26(4):389–398.

Leu LS. 1976. Cassava bacterial blight in Taiwan. In: Proc 4th Symposium of the International Society for Tropical Root Crops (ISTRC), held in Cali, Colombia. International Development Research Centre (IDRC), Ottawa, Canada. p 175–179.

Levesque CA; Holley JD; Utkhede RS. 1993. Individual and combined effects of *Enterobacter aerogenes* and metalaxyl on apple tree growth and *Phytophthora* crown and root rot symptom development. Soil Biol Biochem 25(8):975–979.

Lima MF; Reifschneider F; Takatsu A. 1993. Virulência de isolados e métodos de inoculação de *Phytophthora drechsleri* e *P. capsici* em plântulas de mandioca. Hortic Bras 11(2):153–155.

Lima MF; Takatsu A. 1995. Reaction of cassava genotypes (*Manihot esculenta*) to *Phytophthora drechsleri*. Fitopatol Bras 20(3):406–415.

Llano GA. 2003. Identificación de genes análogos de resistencia a enfermedades en yuca (*Manihot esculenta* Crantz), y su relación con la resistencia a tres especies de *Phytophthora*. MSc thesis in Agricultural Sciencies, with emphasis in Plant Breeding. Universidad Nacional de Colombia, Palmira, Colombia. 122 p.

Llano GA; Álvarez E. 2008. Controlling cassava root rots with the participation of Tukano communities in the Mitú area of the Colombian Amazon. Gene Conserve 28:426–455.

Llano GA; Alvarez E, Muñoz JE; Fregene M. 2004. Identificación de genes análogos de resistencia a enfermedades en yuca (*Manihot esculenta* Crantz), y su relación con la resistencia a tres especies de *Phytophthora*. Acta Agron 53(1/2):15–24.

Llano R, GA; Álvarez E; Loke JB; Madriñán R; Restrepo JA; Mora JR. 2001. Evaluación de la adaptación de variedades de yuca con resistencia a *Phytophthora* spp., mediante investigación participativa en comunidades indígenas de Mitú (Vaupés, Colombia). Acta Agron (Colombia) 51(1/2):31–39.

Loke JB. 2004. Análisis genético de la resistencia de yuca (*Manihot esculenta* Crantz) a *Phytophthora tropicalis*, causante de pudrición radical. MSc thesis in Agricultural Sciences, with emphasis in Plant Breeding. Universidad Nacional de Colombia, Palmira, Colombia. 105 p.

Loke JB; Álvarez E; Vallejo FA; Marín J; Fregene M; Rivera S; Llano GA. 2004. Análisis de QTLs de la resistencia a pudrición de raíz causada por *Phytophthora tropicalis* en una población segregante de yuca (*Manihot esculenta* Crantz). Acta Agron 53(3/4):35–41.

Lopes EB. 1978. Danos causados pela podridão radicular induzida por *Phytophthora drechsleri* Tucker, em vinte e cinco cultivares de mandioca (*Manihot esculenta* Crantz) e recomendações de contrôle. Empresa Brasileira de Pesquisa Agropecuária, Piracicaba, SP, Brazil. 14 p.

Lopes EB; Matias EC. 1984. Contrôle varietal e cultural da podridão radicular da mandioca. Pesquisa em Andamento No. 7. Empresa Estadual de Pesquisa Agropecuária da Paraiba, João Pessoa, PB, Brazil.

Lopes EB; Matias EC; Aguiar Filho SP. 1978. Podridão de raizes na mandioca. Pesqui Agropecu Bras 13(4):45–50.

Lopes, EB; Melo GSD; Matias EC. 1984. Problemas fitossanitarios da mandioca (*Manihot esculenta* Crantz) na Paraiba, e recomendações de contrôle. Empresa Estadual de Pesquisa Agropecuária da Paraiba, Lagoa Seca, PB, Brazil. 15 p.

López C; Lozano T, JC. 1992. Evaluación sobre resistencia a *Phytophthora nicotianae* var. *nicotianae* en yuca (*Manihot esculenta* Crantz). Fitopatol Colomb 16(1/2):113–119.

López C; Jorge V; Mba C; Cortes D; Soto M; Restrepo S; Piégu B; Cooke R; Delseny M; Tohme J; Verdier V. 2004a. A catalogue of 6000 expressed genes in cassava: identification of genes implicated on cassava bacterial blight resistance and starch biosynthesis. In: Proc Sixth International Scientific Meeting of the Cassava Biotechnology Network (CBN), held in Cali, Colombia, 8–14 March 2004. CIAT, Cali, Colombia. p 120.

López C, Cooke R; Delseny M; Tohme J; Verdier V. 2004b. R-*Xam1* gen: A *Xa21* homologue associated to bacterial blight resistance in cassava. In: Proc Sixth International Scientific Meeting of the Cassava Biotechnology Network (CBN), held in Cali, Colombia, 8–14 March 2004. CIAT, Cali, Colombia. p 160.

Lozano JC. 1973. Bacterial blight of cassava in Central and South America: etiology, epidemiology and control. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 19 p.

Lozano JC. 1986. Cassava bacterial blight: a manageable disease. Plant Dis 70 (12):1089–1093.

Lozano JC. 1991a. Control integrado de enfermedades en yuca. Fitopatol Venez 4(2):30–36.

Lozano JC. 1991b. Primeros cultivares de mandioca resistentes a pudriciones radicales liberan en Brasil. Yuca Bol Inf 15(1):4–5.

Lozano JC; Booth RH. 1976. I Curso Intensivo Nacional de Mandioca: aspectos gerais, económicos e industriais. Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Centro Nacional de Pesquisa de Mandioca e Fruticultura, Cruz das Almas, BA, Brazil. 446 p.

Lozano JC; Booth RH. 1979. Enfermedades de la yuca. In: Curso de Producción de Yuca. CIAT, Cali, Colombia. p 163–216.

Lozano JC; Loke JB. 1994. Potential for biological control of *Phytophthora* root rot of cassava (*Manihot esculenta* Crantz) by *Trichoderma* spp. CIAT, Annual Report, 1994.

Lozano JC; Nolt B. 1994. Diseases of cassava (*Manihot esculenta* Crantz). In: Common names for plant diseases 1994. American Phytopathological Society, St. Paul, MN. p 36–37

Lozano JC; Sequeira L. 1974. Bacterial blight of cassava in Colombia: etiology (*Xanthomonas manihotis*). Phytopathol 64(1):83–88.

Lozano JC; Bellotti A; Reyes JA; Howeler R; Leihner D; Doll J. 1981. Problemas en cultivo de la yuca. CIAT, Cali, Colombia. 208 p.

Lozano T, JC; Cock JH; Castaño-Zapata J. 1978. Nuevos avances en el almacenamiento de yuca. Fitopatol Colomb 7(1):2–14

Lübberstedt T; Klein D; Melchinger AE. 1998. Comparative quantitative trait loci mapping of partial resistance to *Puccinia sorghi* across four populations of European flint maize. Phytopathol 88:1324–1329.

Majunder SK; Pingale S; Swaminathan M; Subrahmanyan V. 1956. Control of spoilage in fresh tapioca tubers. Bull Cent Food Technol Res Inst (Mysore) 5:108–109.

Manicom BQ; Becker MM; Deschodt D. 1981. First report of cassava bacterial blight in South Africa. Phytophilactica 13(4):195–196.

Maraite H; Meyer JA. 1975. *Xanthomonas manihotis* (Arthaut-Berthet) Starr, causal agent of bacterial wilt, blight and leaf spots of cassava in Zaire. PANS-Pest-Artic-News-Summ 21(1):27–37.

Mejía JF. 2001. Caracterización molecular y patogénica de aislamientos de *Sphaceloma manihoticola* provenientes de la región centro-sur de Brasil. Thesis, Universidad Nacional de Colombia, Palmira, Colombia.

Mendonca HA; Moura GDEM; Cunha ET. 2003. Avaliação de clones de mandioca em diferentes épocas de colheita no Estado do Acre. Pesqui Agropecu Bras 6(38):761–769.

Montaldo A. 1973. Vascular streaking of cassava root tuber. Tropical Sci 15:39–46.

Muller MF; De Carneiro FA. 1970. Podridão mole das raizes da mandioca (*Manihot esculenta*). Bol Tec Inst Pesqui Agropecu Bras 5:389–395.

Muromtsev G; Globus G. 1975. On the adaptability significance to phytopathogene *Gibberella fujikuroi* (Saw.) Wr. of the ability to synthesize gibberellins. In: Kurdev T, Ivanova I, Karanor E, eds. Proc Second International Symposium on Plant Growth Regulators. Bulgarian Academy of Sciences, Sofia. p 149–153.

Normanha SE. 1970. General aspects of cassava root production in Brazil. In: Proc 2nd International Symposium on Tropical Root and Tuber Crops, held in Honolulu and Kapaa, Kauai, Hawaii. University of Hawaii, Honolulu. Vol 1, p 61–63.

Notteghem JL; Chatenet M; Pouzet D. 1980. *Xanthomonas campestris* pv. *manihotis*, a cassava withering agent in the Ivory Coast. Agron Trop (Paris). 35(2):189–191.

Okey EN; Duncan EJ; Sirju-Charran G; Sreenivasan TN. 1996. Factors affecting the susceptibility of six cocoa clones to *Phytophthora palmivora* (Butl.) Butler bark canker in Trinidad. Plant Pathol 45(1):84. DOI:10.1046/j.1365–3059.1996.d01–94.

Oliveros B; Lozano JC; Booth RH. 1974. A *Phytophthora* root rot of cassava in Colombia. Plant Dis Rep 58(8):703–705.

Onyango DM; Mukunya DM. 1982. Distribution and importance of *Xanthomonas manihotis* and *X. cassavae* in East Africa. In: Proc of an IDRC workshop, "Root crops in Eastern Africa", held in Kigali, Rwanda, 23–27 Nov 1980.

Orf JH; Denny RL. 2000. Registration of 'MN1401' soybean. Crop Sci 40:1825.

Park M. 1934. Report of the work of the mycological division. In: Ceylon Administration Reports: Reports of the Director of Agriculture. p 125–133.

Pereira A. 1998. Reacão de genótipos de mandioca aos agentes causais de podridões radiculares *Phytophthora drechsleri*, *Fusarium* sp. e *Scytalidium lignicola*. MSc thesis. Universidade Federal da Bahia, Cruz das Almas, Brazil. 73 p.

Pereira LF; Goodwin PH; Erickson L. 2000. Peroxidase activity during susceptible and resistant interactions between cassava (*Manihot esculenta*) and *Xanthomonas axonopodis* pv. *manihotis* and *Xanthomonas cassavae*. J Phytopathol 148:575.

Pineda B, Jayasinghe UV; Lozano JC. 1983. La enfermedad cuero de sapo en yuca (*Manihot esculenta* Crantz). ASIAVA (Colombia) 4:10–12.

Pino JA. 1980. Estudio preliminar sobre la enfermedad superalargamiento de la yuca (*Sphaceloma* sp.) en clones de yuca (*Manihot esculenta*) en Cuba. Cienc Tec Agric: Viandas Hortal Granos 3(1):5–21.

Powell PW. 1972. The cercospora leaf spots of cassava. Tropical Root and Tuber Crops Newsletter 6:10–14.

Rajnauth G; Pegus JE. 1988. Studies on diseases of cassava and yam in Trinidad. In: Proc 1st Annual Seminar on Agricultural Research, held in Centeno, Trinidad and Tobago, 1–3 Oct 1987. Trinidad and Tobago. Vol 2, p 15–23.

Ram C; Tupinamba EA. 1986. Avaliação de resistencia de mandioca a podridão radicular. Pesquisa em Andamento No. 7, Empresa Brasileira de Pesquisa Agropecuária. Unidade de Execução de Pesquisa de Âmbito Estadual de Araçaju, Araçaju, SE, Brazil. 3 p.

Ramaswamy NM. 2001. Constraints and future strategies for sustainable productivity in cassava. Poster presented at the Fifth CBN Meeting, held in St. Louis, Missouri, USA, 4–9 Nov 2001.

Ramírez JA; Álvarez E; Marmolejo de la T F. 2000. Determinación *in vitro* de la sensibilidad térmica de cepas de *Xanthomonas axonopodis* pv *manihotis*, agente causal de la bacteriosis vascular de la yuca. Fitopatol Colomb 23(2):87–91.

Reeder R; Kelly PL; St. Hill AA; Ramnarine K. 2008. Superelongation disease, caused by *Elsinoe brasiliensis,* confirmed on cassava in Trinidad and Tobago. New Disease Reports. [on line]18. Available at www.bspp.org.uk/ndr/jan2009/2008-61.asp (accessed 27 Nov 2008).

Restrepo S. 1999. Etude de la structure des populations de *Xanthomonas axonopodis* pv. *manihotis* en Colombie. Dissertation. University of Paris VI, France.

Restrepo S; Mosquera GM; Vélez CM; López CE; Zuluaga P; González C; Chávez M; Santaella M; Suárez E; Jorge V; López A; Pineda R; García S; Ojeda S; Tohme J; Verdier V. 2001. Cassava bacterial blight: recent advances in the understanding and control of the disease. Poster presented at the Fifth CBN Meeting, held in St. Louis, Missouri, USA, 4–9 Nov 2001.

Restrepo S; Valle TL; Duque MC; Verdier V. 1999. Assessing genetic variability among Brazilian strains of *Xanthomonas axonopodis* pv. *manihotis* to restriction fragment length polymorphism and amplified fragment length polymorphism analyses. Can J Microbiol 45(9):754–763.

Restrepo S; Verdier V; Álvarez E. 1996. Variabilidad de *Xanthomonas campestris* pv. *manihotis* en Colombia. Ascolfi Inf 22(1):1–4.

Rickard JE. 1982. Investigation into post-harvest behavior of cassava roots and their response to wounding. Dissertation. University of London, London. 161 p.

Rodríguez A. 1979. El programa de yuca en el INIA. Yuca Boletín Informativo 7:13–14.

Rodríguez S. 1992. Mejoramiento genético de yuca en la República de Cuba. In: Iglesias CA, Fukuda W. Proc Segunda Reunión Panamericana de Fitomejoradores de Yuca. Documento de Trabajo No. 112. CIAT, Cali, Colombia. p 43–53.

Rondón A; Aponte A. 1981. Estudio de superalargamiento de la yuca y búsqueda de cultivares tolerantes a la enfermedad. Agron Trop 31(1-6):81–89.

Saccardo PA. 1913. Sylloge fungorum: omnium hucusque cognitorum. Typis Semin (Patavii, Italy) 22:1250.

Sánchez NJ. 1998. Caracterización de *Phytophthora* spp., agente causal de pudrición en raíz de yuca (*Manihot esculenta* Crantz) utilizando pruebas de patogenicidad y técnicas moleculares. Thesis. Universidad Nacional de Colombia, Santafé de Bogotá, Colombia. 205 p.

Sánchez G; Restrepo S; Duque M; Fregene M; Bonierbale M; Verdier V. 1999. AFLP assessment of cassava variability in cassava accessions (*Manihot esculenta*), resistant and susceptible to cassava bacterial blight (CBB). Genome 42:163–172.

Sosa M. 1992. Mejoramiento de la yuca en República Dominicana. In: Iglesias CA, Fukuda W. Proc Segunda Reunión Panamericana de Fitomejoradores de Yuca. Documento de Trabajo No. 112. CIAT, Cali, Colombia. p 99–105.

Soto L; Laberry R; Lozano JC. 1988. Características etiológicas de dos grupos de *Phytophthora* afectando la yuca en Brasil y en Colombia. In: Abstracts [of the] X Congreso de ASCOLFI, V Resúmenes ALF, and XXIX Reunión APS, held in Cali, Colombia, 10–14 July 1988. CD-ROM.

Souza Filho BF de; Tupinamba EA. 1979. Ocorrência da podridão mole das raizes de mandioca (*Manihot esculenta* Crantz) em Sergipe. Comunicado Técnico No. 04. Empresa Brasileira de Pesquisa Agropecuária. Unidade de Execução de Pesquisa de Âmbito Estadual de Quissama, Araçaju, SE, Brazil. 4 p.

Takatsu A; Fukuda S. 1990. Current status of cassava diseases in Brazil. In: Hahn SK; Caveness FE, eds. Integrated pest management for tropical root and tuber crops—Proc Workshop on the Global Status of and Prospects for Integrated Pest Management of Root and Tuber Crops in the Tropics, held in Ibadan, Nigeria, 1987. International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. p 127–131.

Trujillo GE; Subero LJ; Luciani J. 1982. Evaluación preliminar de algunos clones de yuca (*Manihot esculenta* Crantz), del banco de germoplasma de la UCV (Universidad Central de Venezuela) resistentes al añublo bacterial causado por *Xanthomonas axonopodis* pv. *manihotis*. Paper presented at the Seminario Nacional de Yuca, held in Maracay, Venezuela, 1–3 Dec 1980. Rev Fac Agron, Univ Cent Venez 31:231–239.

Umanah EE. 1970. Identification and cultivation of currently recommended improved cassava varieties. Memo of the Federal Department of Agricultural Research (Ibadan, Nigeria) 93:1–18.

Valencia M; Arroyabe JA, Laberry R; Lozano C. 1993. Estudio sobre transmisión del agente causal del superbrotamiento de la yuca (*Manihot esculenta* Crantz). Fitopatol Colomb 17(1):39–45.

Vanderweyen A. 1962. Maladies cryptogamiques. In: Précis des maladies et des insectes nuisibles dur les plantes cultives au Congo au Rwanda et au Burundi. Institut National pour l'Etude Agronomique du Congo, Brussels. p 471–480.

Verdier V. 2002. Bacteriosis vascular (o añublo bacteriano) de la yuca causada por *Xanthomonas axonopodis* pv. *manihotis*. In: Ospina B; Ceballos H, eds. La yuca en el tercer milenio: Sistemas modernos de producción, procesamiento, utilización y comercialización. CIAT, Cali, Colombia. p 148–159.

Verdier V; Mosquera G. 1999. Specific detection of *Xanthomonas axonopodis* pv. *manihotis* with a DNA hybridization probe. J Phytopathol 147(7/8):417–423.

Verdier V; Dongo P; Boher B. 1993. Assessment of genetic diversity among strains of *Xanthomonas campestris* pv. *manihotis*. J Gen Microbiol (UK) 139:2591–2601.

Verdier V; Restrepo S; Mosquera G; Duque MC; Gerstl A; Laberry R. 1998. The *Xanthomonas axonopodis* pv. *manihotis* population in Venezuela: its genetic and pathogenic variation. Plant Pathol 47:601–608.

Viégas AP. 1941. Manchas das folhas da mandioca producidas por cercosporas. Bragantia 1:233–248.

Viégas AP. 1943a. Alguns fungos da mandioca. I. Bragantia 3(1):1–17.

Viégas AP. 1943b. Alguns fungos da mandioca. II. Bragantia 3(2):20–29.

Viégas AP. 1955. A podridão das raizes da mandioca. Rev Agron (Porto Alegre, Brasil) 17:202–208.

Wheatley CC. 1982. Studies on cassava (*Manihot esculenta* Crantz) roots, post-harvest physiological deterioration. Dissertation. University of London. 246 p.

Wheatley CC; Schwabe WW. 1981. Scopoletin involvement in post-harvest physiological deterioration of cassava root (*Manihot esculenta* Crantz). J Exp Bot 36(166):783–791.

Wheatley CC; Lozano C; Gómez G. 1985. Deterioración poscosecha en raíces de yuca: investigación, producción y utilización. Documento de Trabajo No. 50. CIAT, Cali, Colombia. p 393–510.

Whiley AW; Pegg KG; Saranah JB; Langdom PW. 1987. Influence of *Phytophthora* root rot on mineral nutrient concentrations in avocado leaves. Aust J Exp Agric 27(1):173–177.

Williams RJ; Agboola SD; Schneider RW. 1973. Bacterial wilt of cassava in Nigeria. Plant Dis Rep 57(10): 824–827.

Wydra K; Ahohuendo B; Banito A; Cooper RMC; Dixon A; Kemp RB; Kpemoua K; Rudolph K; Witt F; Verdier V; Zinsou V. 2001. Adaptation and implementation of integrated control measures of cassava bacterial blight through collaborative research between European partners, IITA and NARS in Africa. Poster presented at the Fifth CBN meeting, held in St. Louis, Missouri, USA, 4–9 Nov 2001.

Zeigler R. 1982. The superelongation disease of cassava: pathogen taxonomy, gibberellin production and characteristics of host resistance. Dissertation. Cornell University, Ithaca, NY, USA. 133 p.

Zeigler RS. 2000. *Elsinoe brasiliensis*. In: Compilation of datasheets of quarantine pests for Eastern Africa. Commonwealth Agricultural Bureaux International, Wallingford, UK. 1151 p.

Zeigler RS; Powell LE; Thurston MD. 1980. Gibberellin A4 production by *Sphaceloma manihoticola,* causal agent of cassava superelongation disease. Phytopathol 70:589–593.

Zinsou V; Wydra K; Ahohuendo B; Hau B. 2004. Genotype x environment interactions in symptom development and yield of cassava genotypes in reaction to cassava bacterial blight. Dissertation. Institute of Plant Diseases and Plant Protection, University of Hannover, Germany.

CHAPTER 9

Cassava Bacterial Blight, Caused by *Xanthomonas axonopodis* pv. *manihotis*

Valérie Verdier[1], Camilo López[2], and Adriana Bernal[3]

Introduction

A limiting factor in cassava production is cassava bacterial blight (CBB)[4]. This disease is distributed extensively in Asia, Africa, and South America.

Losses caused by CBB vary greatly. If environmental conditions are favorable for disease development and if no agronomic practices are adopted to control it, losses may reach 100% in only two or three cropping cycles. The disease spreads from one area to another and from one growth cycle to the next mainly through the planting of infected stakes. Dissemination also occurs over small areas through tools, insects, and rain splash.

Disease severity depends very much on the cultivar, soil fertility, climate, and quantity of inoculum present in the area. Repeated cropping of highly susceptible varieties, without rotation, reduces soil fertility, which increases the crop's predisposition to the disease.

The causal agent of the disease is the bacterium *Xanthomonas axonopodis* pv. *manihotis* or *Xam*. This pathogen induces a wide range of symptoms. In Colombia, the disease was very destructive in 1971. Since then, its presence has been reported in the country's principal cassava-producing areas (Lozano 1986; Restrepo and Verdier 1997).

1. IRD, 911 Avenue Agropolis BP 64501, 34394 Montpellier Cedex 5, France. E-mail: valerie.verdier@ird.fr
2. Department of Biology, UN, Ciudad Universitaria, Bogotá, Colombia. E-mail: celopezc@unal.edu.co
3. Faculty of Sciences, Universidad de los Andes, Bogotá, Colombia. E mail: abernal@uniandes.edu.co
4. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Symptoms

Xam is a systemic pathogen and an epiphyte. It characteristically induces a combination of a wide range of symptoms, including angular spots in leaves, blight, wilt, exudates and lesions in stems, and death (Figure 9-1).

Infection begins with an epiphytic phase of the pathogen on leaves, which helps build inoculum. This,

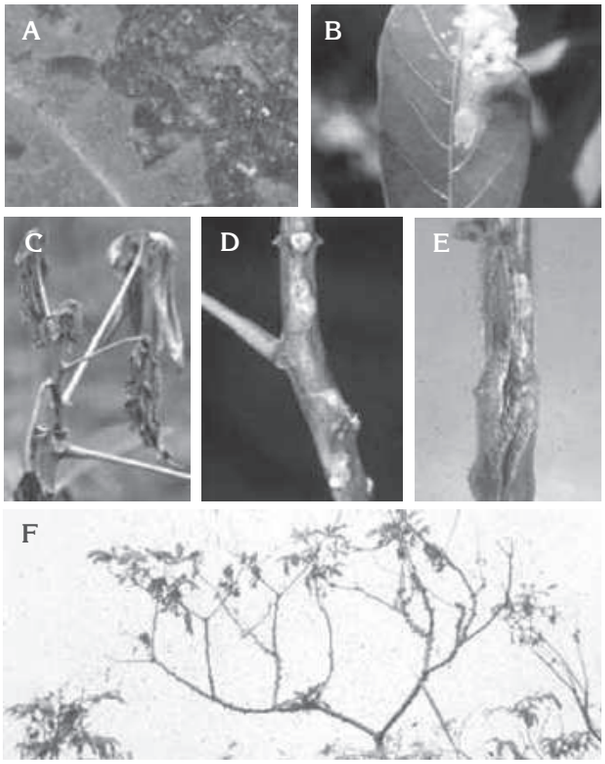


Figure 9-1. Symptoms caused by the bacterium *Xanthomonas axonopodis* pv. *manihotis* in cassava. **(A)** Angular spots; **(B)** blight; **(C)** wilt; **(D)** exudates on a stem; **(E)** deep lesions on a stem; **(F)** defoliation and plant death. (Photos by Bernard Boher.)

in its turn, significantly increases the probability of future infection through stomata and wounds. Leaf spots appear as moist, angular areas that are clearly distinguishable on the lower surface of leaves. The leaf blight is attributed to a toxin (3-methylthiopropionic acid) produced by *Xam*. The bacterium colonizes the intercellular spaces in leaf mesophyll and multiplies rapidly, producing large quantities of exopolysaccharide matrix. The leaf spots exude a yellowish and sticky substance that concentrates into drops, mainly on the lower side of leaves. These bacterial exudates are scattered to other plants by rain drops, which fall and splash, during the rainy season and, to a lesser extent, through insects. The pathogen multiplies and the consequent increased production of bacterial exudates blocks vascular tissues, leading to the leaves wilting.

Highly susceptible clones may be entirely defoliated. The bacterium enters the xylem vessels through lysis of cell walls in the tissue and multiplies rapidly in the vascular system, extending to all parts of the plant and producing death. Symptoms can also appear on fruits as wet areas and on the leaf sheath or in embryos. Seeds from infected fruits may be deformed and the germination rate is low. Roots of infected plants usually do not present symptoms, except in some susceptible varieties, which may then display dry and putrescent spots around necrosed vascular lines. This characteristic putrefaction is exclusive to vascular tissues, with other root tissues remaining normal.

Losses are usually correlated with the number of infected stakes used in planting. When plants are infected, their aerial parts may be completely destroyed. New shoots may develop from the stem, either above or below the soil surface. These young shoots are susceptible under extreme and rainy conditions, rapidly becoming infected. If the planting material is infected, any shoots it produces will wilt and quickly die.

Etiology

The causal agent of bacterial blight was renamed several times between 1912 and 1915. It was first called *Bacillus manihotis* Arthaud-Berthet and Bondar; and then called *Phytomonas manihotis* (Arthaud-Berthet and Bondar) Viegas. It was then renamed *Xanthomonas manihotis* (Arthaud-Berthet) Starr, and further *X. campestris* pv. *manihotis* Berthet and Bondar. In 1995 Vauterin et al. proposed the name *X. axonopodis* pv. *manihotis* (or *Xam*).

The bacterium grows in a medium containing sucrose, producing colonies without pigmentation. It is a Gram-negative rod, measuring 0.5 × 1.0 mm, and has a single polar flagellum. Except for the lack of pigmentation, most of its physiological and biochemical characteristics are typical of xanthomonads.

More than 90% of *Xam* strains evaluated hydrolyze Tween 60, Tween 80, and starch. They grow in the presence of 0.001% (w/v) of $Hg(NO_3)$, but not of 0.05% (w/v) of triphenyltetrazolium chloride or of 0.001% (w/v) of malachite green. They show βglucosidase activity, and form acid from melibiose but not from D-ribose or lactose. They grow in DL-glyceric acid, but not in mucic or saccharic acid, or ethane. They use L-threonine as their only source of nitrogen and are sensitive to 10 g of gentamicin and fusidic acid.

According to Restrepo and Verdier (1997), considerable variation was observed among *Xam* strains in terms of biochemical, physiological, serological, and genomic characters when analyzed, using either the restriction fragment length polymorphism (RFLP) or amplified fragment length polymorphism (AFLP) technique (Restrepo et al. 1999).

For characterization, different types of probes for *Xam* are being used by RFLP, whether genomic or plasmid. Universal probes such as ribotyping have also been used. The African *Xam* strains belong to one of five ribotypes identified in South America and, when using RFLP analyses with a plasmid probe, 14 different haplotypes can be distinguished. A high level of DNA polymorphism was detected in strains from South America (Restrepo and Verdier 1997).

In Colombia, *Xam* strains collected from three edaphoclimatic zones (ECZs) were geographically differentiated (Restrepo and Verdier 1997). The genetic diversity of *Xam* was shown to have a microgeographical distribution (Restrepo et al. 2000b).

Differences in virulence between *Xam* strains were described for the first time by Robbs et al. (1972). Such variation in virulence was also observed among strains from either Brazil or Africa. The speed at which differences in symptoms develop suggests variation in aggressiveness. In 1998, a total of 10 pathotypes were determined among *Xam* strains in Venezuela, using five cassava varieties as differentials (Verdier et al. 1998b). In 2000, a group of differential cassava varieties was proposed to differentiate the virulence of *Xam* in Colombia (Restrepo et al. 2000a). Different pathotypes

were identified within a group of strains representing the genetic diversity of *Xam* in Colombia.

Disease Cycle and Epidemiology

Infection begins with the multiplication of the pathogen as epiphyte, occurring usually near the stomata. Leaves are penetrated through stomatic openings or wounds. Twelve hours of high relative humidity suffice for bacterial establishment. The most appropriate temperature for infection is about 23 °C.

Apparently, the length of the photoperiod does not affect the bacterium's establishment. *Xam* is a vascular pathogen that establishes itself inside vessels after a preliminary phase of intercellular development in the mesophyll. If the bacterium invades lignified stems, it remains within the vascular tissues, where it can survive for up to 30 months. Host-pathogen interactions have been studied under controlled conditions, using histological and cytochemical methods.

Studies on the epiphytic phase of the disease are well documented, both in the field and *in vitro*. A cytochemical study of the development of an aggressive strain in a susceptible host showed that *Xam* degrades the middle lamella and cell wall (Boher et al. 1995). This suggests that the bacterium's lytic activity favors its intercellular progress and penetration of vascular bundles. The bacterial extracellular matrix (xanthan), produced in all phases of pathogenesis, is associated with the degradation of the host's parietal structures.

Seed can be infected by rain, mechanical inoculation, or translocation of the pathogen through xylem vessels. A high percentage of planting materials collected from crops infected with CBB carry the pathogen. However, they do not show symptoms, as the bacterium is latent in the embryo. Dormancy breaks shortly after germination. Although stakes germinate normally, symptoms can appear during stem and leaves development.

The use of infected stakes is the principal reason for the pathogen persisting from one growth cycle to the next. Another reason is the way it is dispersed over the land. The pathogen can disperse over short distances mainly through rain splash and contaminated tools. Tools used to harvest cassava are simultaneously used to cut stakes for the next plantings. Hence, the pathogen disseminates easily to healthy stakes taken from asymptomatic stems, which harbor the pathogen. Because wounds facilitate infection, the transit of people and animals through cassava fields, especially during or after rains, can help spread the pathogen.

Other potential sources of inoculum are soils or contaminated irrigation waters, although their role in infection is smaller, as the pathogen does not survive well in soil. In contrast, it survives as an epiphyte on many weed hosts that then serve as inoculum sources. Insects may also disseminate the bacterium, comprising as much as 10% of its dispersion over short distances.

During drought, disease development is reduced but the bacterium remains viable in plant tissues and exudates, providing sources of inoculum when the rainy season arrives.

Incidence of Disease

The amount of damage caused by CBB varies in different places of the world, but can be considerable. Crop losses can reach 30% when stakes are taken from infected materials to disease-free plots. If environmental conditions are favorable and control measures are not adopted, losses can reach 100% within three harvesting cycles.

When weak pathogens such as *Colletotrichum* spp. and *Choanephora cucurbitarum* invade tissues infected with CBB, the synergistic effect of these pathogens increases disease severity. Such combinations can produce losses of up to 90% of the first harvest.

At the beginning of the 1970s, CBB epidemics in the Democratic Republic of the Congo caused losses of the cassava crop (75%), with the total damage being compounded by the destruction of the leaves, which are rich in protein and therefore used in the diet. Famine developed, during which crop losses in central Africa were 80%. In 1974, an epidemic was reported in Minas Gerais, Brazil, causing losses of 50% in a planting of over 10,000 hectares.

Losses in other regions of America ranged between 5% and 40% in 1975. In Asia, losses have not been estimated, as the pathogen was introduced only recently, possibly in the mid-1960s. The disease is endemic in certain regions of America and Africa, where it causes significant losses. The blight is moderately important in Thailand and China, although, especially in China, its incidence has been increasing over the last 2 years.

Disease severity increases when day-to-night temperatures fluctuate widely from 15 to 30 °C. This explains the moderate to low severity of CBB in areas with relatively stable temperatures. This effect of temperature on the disease has helped researchers predict the relative importance of the disease in each region and to develop practical recommendations for its control.

Geographical Distribution in Colombia

The principal edaphoclimatic zones (ECZs) where cassava is cultivated in Colombia were visited between 1995 and 2000. An ECZ is defined according to climatic conditions; soil type; importance of the predominant ecosystem; and the crop's principal limitations, both biotic and abiotic:

- ECZ1 = subhumid tropical areas
- ECZ2 = acid-soil plains of the Colombian Eastern Plains
- ECZ5 = high-altitude Andes
- ECZ7 = semiarid area of the Guajira region

In each ECZ, different sites were visited and different plots were evaluated for the presence of bacterial blight. For each plot, at least 15 plants were randomly chosen and qualified according to a scale of 1 to 5, where 1 refers to an asymptomatic plant and 5 to a plant that died from CBB. Evaluations were made in optimal periods (rainy seasons) for observing symptoms. In each field, leaf or stem tissue was collected from plants infected by *Xam* to confirm the pathogen's presence.

In ECZ1 (North Coast), the disease incidence was severe on all farms or plots visited. The varieties most used were M Col 2215 ('Venezolana') and M Col 1505, which were found to be highly susceptible to CBB in greenhouse evaluations. In this ECZ, the climate is favorable for disease development and is a factor towards explaining the blight's incidence. Indeed, optimal conditions for CBB include alternate dry and rainy seasons, very high relative humidity, and significant differences between the maximum and minimum daily temperatures (Lozano and Sequiera 1974).

In ECZ2 (Eastern Plains), disease is severe. In ECZs 1 and 2, the widespread distribution of the pathogen can also be explained by the intensity with which cassava is cultivated in these areas and the length of time the pathogen has been present in the zones. However, the lack of available stakes encourages small farmers to exchange planting materials, which may be contaminated. Hence, variants of *Xam* are disseminated or introduced into regions where the CBB had not been previously detected.

In ECZ5 (high-altitude Andes), the disease is widespread. Geographically isolated from the other zones by mountains, CBB is conditioned for altitude, which permits the introduction of only a few cassava varieties. The genetic context of the host is therefore limited and, in certain plots (perhaps most), only the genotype 'Algodona'—a variety discovered by the region's small farmers—is found. Because of the uniform population, the pathogen does not exert pressure for change.

In ECZ7 (semiarid region of Guajira), the disease was not detected in the field, nor was the bacterium found in collected samples. Recently, the disease was detected as relatively severe in the Departments of Quindío and southern Valle del Cauca. Usually, plots in forest ecosystems are disease-free.

Resistance to *Xanthomonas axonopodis* pv. *manihotis*

Resistance to *Xam* by *Manihot esculenta* is characterized mainly by hypersensitivity at the vascular scale, and is not observed in leaves. In this case, response is more defensive than constituting real hypersensitivity.

Resistance to CBB is expressed as a gradual development of the disease in leaves and stems. Kpémoua et al. (1996) demonstrated that, in resistant varieties and on a cellular scale, osmophilic compounds accumulate in vacuoles, and cell walls in contact with the pathogen lignify rapidly. In addition, tylosis, which closes off vascular bundles, occurs rapidly. Phenols and reinforcements of structural barriers (lignin, callose, and suberin deposits) are also produced. Thus, a resistant variety impedes the bacterium's progress and no exudates are formed (Boher and Verdier 1994; Boher et al. 1995).

Overall, the same reactions are presented in the tissues of both susceptible and resistant varieties. The difference is that, in resistant varieties, reactions occur earlier and with greater intensity, so that the defensive response diminishes the extent of the disease (Kpémoua et al. 1996).

A very important characteristic is the increase in cells that produce phenols, found first in the phloem and then in the xylem of resistant varieties that have been infected. Phenol compounds are known to play a key role in plants' resistance to pathogens. Other compounds, including new lignins, are synthesized only after being induced by the bacterium. Applications of potassium fertilizer also increase resistance to *Xam*, probably because it improves lignification mechanisms in vascular tissues.

Evaluating resistance

Evaluation of resistance to CBB can be conducted at various levels, whether in the field or greenhouse, with seedlings and seeds, or in *in vitro* cultures. For field evaluations, the following scale of 1 to 5 is used (Figure 9-2), where:

1 = absence of symptoms
2 = angular spots only, no wilt
3 = extensive angular spots and leaf wilt, gum exudates in stems and petioles
4 = extensive angular spots, wilt, leaf defoliation, and drying of apical parts
5 = drying of apical parts and plant death

Plants are evaluated over three or four cycles and, in each cycle, four observations are made.

This type of evaluation is very useful in areas where disease pressure is high, which facilitates observation of disease development and progress. Furthermore, this type of evaluation does not require investment in inoculation materials or maintenance of plants under special conditions. In Colombia, such evaluation is practiced in the different ECZs where cassava is cultivated, such as the Eastern Plains, Atlantic Coast, and Andean Region. When inoculum presence is low, spraying can be carried out with local strains of the bacterium, together with sand or other abrasive material that wounds foliage and thus facilitates penetration by the pathogen.

Stems are inoculated 1 month after planting mature stakes. Bacterial isolates are made to grow on LPG agar medium 12 h before inoculation. To inoculate, a colony is taken from the bacterial culture, using the end of a needle or toothpick, directly out of the petri dish. With that same needle, the colony is introduced into the stem near the plant's apical parts, at about 10^8 cfu per puncture. According to the availability of material, 10 replications are made for each pair of bacterial isolate and cassava variety.

Observations are made at days 8, 15, and 30 after inoculation. Optimal conditions for disease development are 30 °C and a saturated relative humidity. Symptoms are scored on a scale of 1 to 5 (Figure 9-3), where:

1 = necrotic area around inoculation point
2 = exudate at the inoculation point
3 = wilting, regardless of quantity of exudate (one or two leaves)
4 = wilting of more than two leaves
5 = entire plant wilts

A categorical (i.e., quantifiable) appraisal can therefore be made of the observations.

A simple method of inoculating *in vitro* seedlings has been described (Verdier et al. 1990). It is carried out under sterilized conditions on 6-week-old seedlings. The inoculum is calibrated at 10^8 cfu/mL and is deposited, using a paintbrush, on the lower and upper surfaces of the first two leaves (i.e., the oldest). The plants are left in a climate chamber at 28 °C with a day-to-night ratio of 16/8 h.

Identifying genes for resistance

Resistance to CBB is believed to be polygenic and additively inherited, with a variation that ranges between 25% and 65% (Hahn et al. 1979). Differences between resistant and susceptible varieties are expressed as a variation in the rate of colonization by *Xam* and penetration of vascular tissues. Hence, resistance is considered to be quantitative (Kpémoua et al. 1996). Because of the quantitative nature of resistance, a strategy based on detecting quantitative trait loci (QTLs) was developed to use the available cassava genetic map to identify those genomic regions involved in resistance. These regions are also known as quantitative resistance loci or QRLs.

The cassava genetic map was developed through an intraspecific cross between TMS 30572 (an improved variety developed at IITA) and CM 2177-2 (an elite line from CIAT). To detect QRLs, five bacterial strains (CIO84, CIO1, CIO136, CIO295, and ORSTX27) were selected. They corresponded to different haplotypes from different geographical regions of the country, as according to Restrepo et al. (2004). Resistance was evaluated in an F_1 population under controlled conditions in the greenhouse. In all, 12 QRLs were detected, located in linkage groups B, C, D, G, L, N, and X, which explained 9%–27% of resistance (Jorge et al. 2000). Some QRLs were specific for

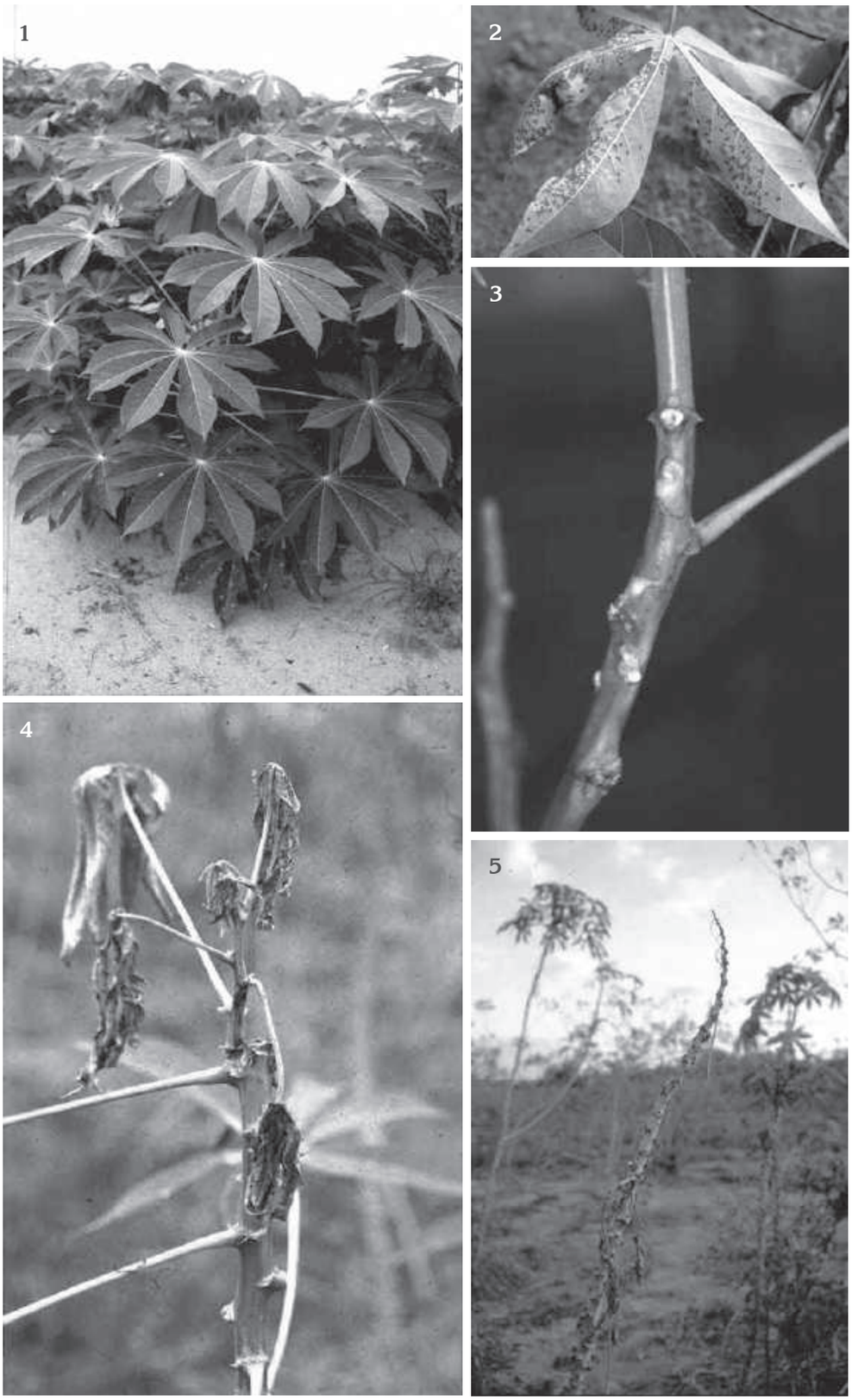


Figure 9-2. A scale of 1 to 5 is used in the field to evaluate symptoms of cassava bacterial blight (see text). (Photo 1 by Válerie Verdier; photos 2–5 by Bernard Boher.)

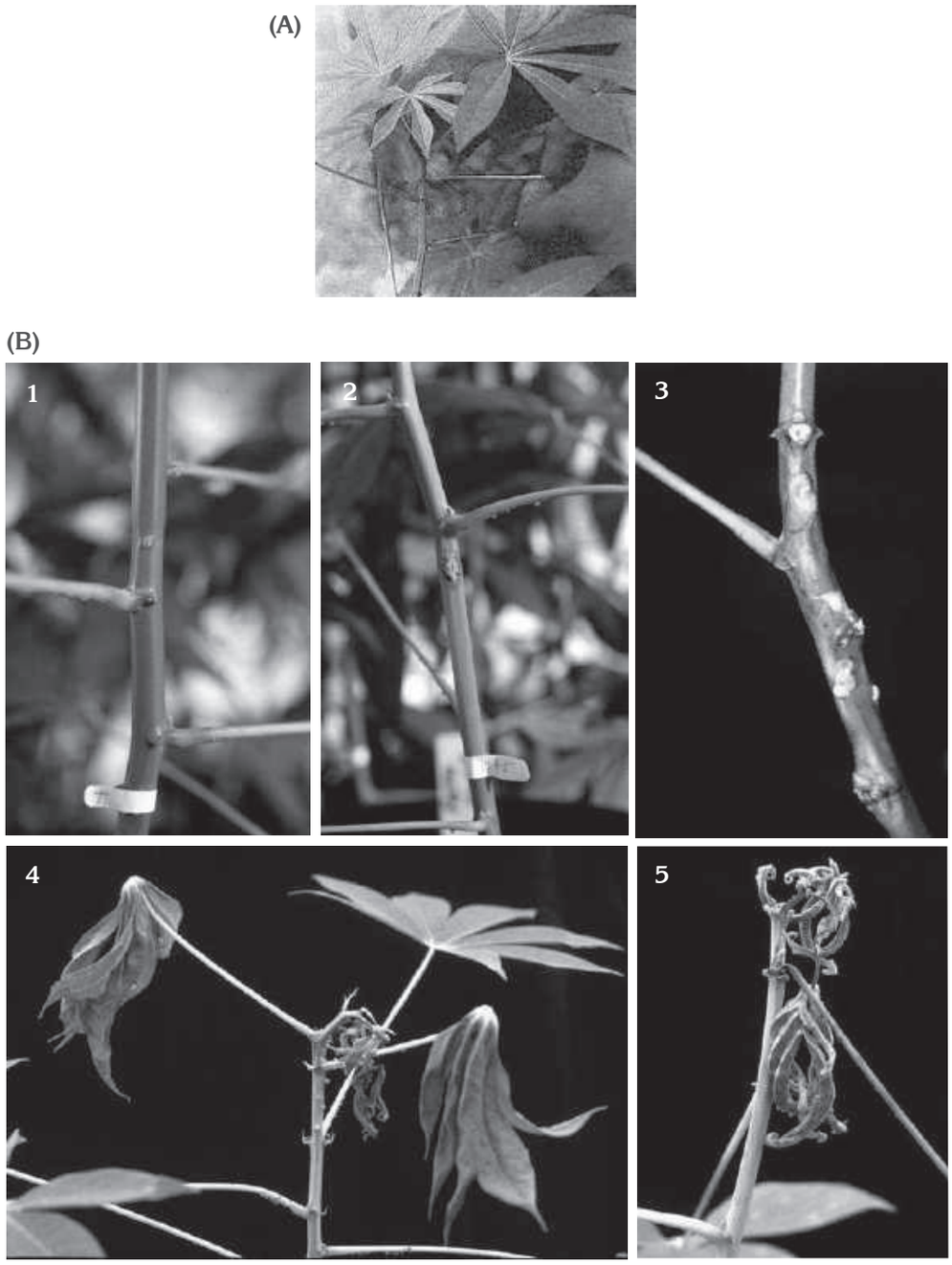


Figure 9-3. **(A)** Inoculating a stem; **(B)** a scale of 1 to 5 is used to evaluate symptoms in the greenhouse (see text). This technique is used to evaluate the resistance or susceptibility of a cassava variety to the pathogen. (Photos by Válerie Verdier.)

certain *Xam* strains, while others, mainly in linkage group D, were common to different *Xam* strains (Jorge et al. 2000).

Similarly, resistance to bacterial blight was evaluated in the field under high disease pressure for three consecutive production cycles (Jorge et al. 2001). Several QRLs were detected but a change was observed in the QRLs during the 2-year study. These changes correlated with the dynamics of *Xam* populations (Jorge et al. 2001). In particular, QRLs detected in linkage group D were observed as remaining constant over two production cycles. In the greenhouse, some QRLs were identified in this same linkage group. Certain analyses suggest that this region may have come from *Manihot glaziovii* (Jorge et al. 2001). Similarly and more recently, QRLs have also been identified for strains from Africa (Wydra et al. 2004).

Proteins for resistance to pathogens in different plant species possess conserved domains such as NBS, TIR, and LRR, which have been used to design degenerated primers and thus isolate resistance gene analogs (RGAs) (Meyers et al. 1999). This strategy was used to identify RGAs in cassava (López et al. 2003), including two of type TIR and 10 of type NBS. Analysis of a bacterial artificial chromosome (BAC) library enabled identification of low- or single-copy RGAs, as well as RGAs that are part of multigenic families (López et al. 2003). Mapping analyses located two BACs with NBS in linkage group E and four in linkage group J. In the latter group, the presence of a region with at least 15 NBS-type sequences could be established.

Unfortunately, to date, no QTLs associated with resistance have been identified in this region (López et al. 2003). More recently, additional data on QTLs associated with two *Xam* strains permitted identification of a new QTL associated with resistance to strain CIO151 in linkage group U (López et al. 2007). The marker responsible for this QTL corresponds to a BAC that contains an NBS-type RGA (B39P22). This QTL explains 62% of resistance, suggesting the presence of a major gene in this BAC clone. The gene is denominated as *RXam2* for "resistance to *Xam* 2".

Using primers generated from the resistance gene *Xa21* from rice, which confers resistance to *X. oryzae* pv. *oryzae*, led to the identification of a fragment of the cassava genome that presents a high degree of similarity with this gene. This fragment is related to a QTL that explains 13% of resistance to *Xam* strain CIO136 (Jorge et al. 2000). From a BAC clone, the complete gene has been sequenced and is called *RXam1* for "resistance to *Xam*" (López, 2004.). All these data suggest that the protein codified by the *RXam1* gene is implicated in resistance to strain CIO136.

Control

Losses caused by CBB can be reduced if a combination of agronomic practices and detection methods is used, together with varietal resistance. The measures described below have successfully reduced the incidence of CBB and has even eradicated the pathogen in some areas.

Cultural practices

Crop rotation controls the blight only if the stakes used to plant cassava are disease-free. All residues from infected plants should be buried, as the pathogen does not survive long in the soil. Or they may be removed and burned. An interval of 6 months between two cassava crops is sufficient to prevent transmission of the pathogen in the soil. Weeds must be carefully controlled, as the pathogen can survive as epiphytes for long periods. Rotating the cassava crop with maize or sorghum effectively reduces primary infection by CBB caused by rain splash. Four consecutive rotation cycles will reduce the incidence and severity of the disease to economically insignificant levels.

Losses can be reduced by changing planting times, especially in subtropical areas. Cassava is usually planted at the beginning of the rainy season, when conditions are also optimal for infection by and dispersal of the pathogen. But the crop can be planted towards the end of the rainy season, when environmental conditions are drier, thus reducing incidence of CBB. Disease-free planting materials are essential for maintaining the blight at low levels.

A method for producing stakes free of bacteria is to root infected or uninfected stakes in sterilized water and then collect the apical parts of shoots. This method is useful for cleaning infected clones or stakes. The pruning of aerial parts of infected plants sometimes helps reduce dispersal of the disease and secondary infection. The success of this method depends on the susceptibility of the variety and on the interval between initial infection and pruning. It is more successful with resistant and moderately resistant cassava varieties that are mildly infected.

Improving crop nutrition

Soil organic content can be improved by burying crop residues in small containers (which also restricts pathogen survival), applying dung, or alternating cassava with legumes. Potassium increases resistance to *Xam*, but small farmers find this fertilizer difficult to obtain.

Improving the quality of planting materials

Improved quality can be achieved by carefully selecting healthy stems from which stakes are obtained. However, farmers are not accustomed to selecting stakes according to this criterion. Nevertheless, they can be trained to recognize bacterial blight symptoms and thus choose clean stems or those with little contamination for new plantings. This practice is also recommended for the control of other cassava diseases. Healthy planting materials can also be produced in controlled multiplication sites, an

especially important measure in areas with low or medium disease pressure.

The production and distribution of high-quality stakes is essential, and has proven invaluable, for enhancing cassava production. This practice has been neglected in Colombia and should receive more attention.

The operation and management of these multiplication fields, which could be used to supply small farmers, is not still organized. Such sites would facilitate better control over crop health, improve distribution of new varieties, and better control the introduction of new pathogens and pests. Cassava seed beds for planting stakes should preferably be placed in forest areas, where CBB can be avoided.

Applying detection methods

Cassava pathogens and pests disseminate largely through the exchange of cassava stakes. Bacterial wilt was introduced this way into Africa and Asia. Many of the cassava pathogens, including CBB, can be also dispersed through botanical seed.

Planting materials and seeds should be collected only from healthy plants in crops that are presumably free of bacterial blight. These crops should be inspected more than once before collection, especially towards the middle and end of the rainy season when the blight tends to be more severe, to determine overall plant health. Any abnormal seed or stake should be discarded. To prevent dissemination of the bacterium and other pathogens through seed, seeds should be visually reviewed with considerable care and selected for density. They are then dried in heat.

Different methods exist for detecting *Xam* in accordance with international plant health quarantine. The PCR procedure is simple and takes 2 h (Verdier et al. 1998a). This method detects *Xam* at 300 cfu/mL in plant tissues. Because of its specificity and sensitivity, the method has considerable potential as a reliable procedure for detecting and identifying the CBB pathogen in infected plant tissue.

Nested PCR is also available for detecting *Xam* in cassava seed (Ojeda and Verdier 2000). Nested PCR increases sensitivity of detection and enables successful identification of the pathogen in seeds or embryos. A material can be evaluated in just one day.

Dot-blotting uses a DNA fragment that acts as a specific probe for a pathovar. This simple and specific method can detect *Xam* colonies recovered from plant tissues and also evaluate colonies of presumed *Xam* isolates (Verdier and Mosquera 1999). The pathogen's presence can be identified directly in cassava plant tissues (leaves, stakes, fruits, seeds, and embryos). Dot-blotting is a highly sensitive and fast technique that permits large-scale evaluation of stakes at relatively low cost and with little equipment. Viable bacteria can also be detected through plating in semiselective medium for *Xam* (Fessehaie et al. 1999).

Biological control

Pseudomonas putida strains, applied to leaves, can significantly reduce the number of angular spots per leaf and the number of leaves blighted per plant in susceptible cassava clones. In one study, cassava plants were impregnated by spraying with a solution of 1×10^9 cells per milliliter of beneficial bacteria in water four times per month during the rainy season, beginning one month after planting. Root production increased, on average, by 2.7 times. Although the use of these biocontrol agents looks promising for commercial plantings, more research is needed to determine if this practice is indeed recommendable.

Resistant varieties

The most appropriate and realistic method for controlling CBB is through host resistance. A certain number of adopted varieties possess considerable resistance to CBB and have remained so over many years. The genetic base of such resistance is currently limited, but should be expanded by using other *Manihot* species and natural hybrids of *M. esculenta* and *M. glaziovii,* and should be introduced, on a widespread basis, into locally adapted varieties.

Functional Genomics in Cassava

To identify genes that are expressed in response to *Xam* infection and other genes expressed in cassava plants, a strategy of generating expressed sequence tags (ESTs) was developed. These tags are short sequences that are generated from cDNA libraries, meaning that they correspond to genes that express under given conditions, which thus indicate their function. To obtain a wide range of genes, several types of cDNA libraries were constructed from different plant parts of different varieties that were either inoculated or

not inoculated with *Xam*. We generated 13,043 ESTs and assembled them into a unigene set of 5700 unique sequences, comprising 1875 contigs (overlapping sequences, involving 9218 ESTs) and 3825 unique sequences. These may represent about 10% to 20% of the genes present in cassava (López et al. 2004).

With this information, the first microarray of cassava was developed and used to study the kinetics of expression of these 5700 genes in response to infection by *Xam* (López et al. 2005). Genes were identified, whose expression varied significantly between plants inoculated with the pathogen and healthy plants (126 showed induction and 73 were repressed). The proportion of differentially expressed genes was low and constant for the first 48 h after inoculation but increased considerably by day 7 before dropping at day 15 after inoculation.

Of the genes expressed differentially, most showed similarity with proteins known to be important in plant protection against pathogens, for example, proteins implicated in the strengthening of cell walls or associated with oxidative stresses such as peroxidases, cationic peroxidases, and glutathione-S-transferase; or with protein degradation (proteases and ubiquitin), which are transcription factors responding to ethylene. The repressed genes found were basically genes that code for proteins involved in photosynthesis (López et al. 2005).

A group of 10 differentially expressed genes were studied, using real-time PCR. The pattern of expression (induction or repression) was conserved for all the genes, using both methods. The induced genes represented a group with high potential for being used in genetic improvement programs, once their functional validation was confirmed (López et al. 2005).

Comparative and functional genomics of *Xanthomonas axonopodis* pv. *manihotis*

Understanding the bacterium's pathogenicity strategies and the plant's natural defense strategies can help generate innovative control methods that target critical points in disease development. Recently, strategies of comparative and functional genomics have been used to accelerate the discovery of important genes for pathogenicity in this bacterium (Verdier et al. 2004). As a result, the genome of *Xam* strain CIO151 has been sequenced, using state-of-the-art technology (the 454 and Illumina sequencing systems, reviewed in Metzker 2005). Thousands of sequence fragments were assembled until tens of genomic fragments of the bacterium were obtained (Arrieta et al. 2011). These DNA fragments denote a genomic structure typical of a bacterium belonging to the *Xanthomonas* genus.

The bacterium has a genome of about 5 Mbp, with two operons of ribosomal RNA and more than 50 codifying regions for tRNAs (Arrieta et al. 2011). A phylogenomic study was developed, which used hundreds of genes that were shared between this and other *Xanthomonas* species that had also been sequenced. This study confirmed the phylogenetic proximity of *Xam* with closely studied bacteria such as *Xanthomonas axonopodis* pv. *citri* and *Xanthomonas euvesicatoria* (Rodríguez et al. 2011). *Xam*'s evolutionary proximity with other extensively studied bacteria enabled comparisons that facilitated the search for pathogenicity genes in *Xam*.

Among the important strategies used by phytopathogenic bacteria are the production of proteins for adhering to the host, synthesis of toxins, production of exopolysaccharides, and the secretion and translocation of proteins to the cytoplasm of the plant cell. In the genome of *Xam*, the following have so far been found (Arrieta et al. 2011):

- Eleven genes potentially associated with adhesion to surfaces
- Three clusters of genes potentially associated with the biosynthesis of toxins
- Two clusters that codify for type II secretion system, which secretes enzymes that degrade host components
- One cluster implicated in the biosynthesis of exopolysaccharide xanthan
- One cluster of genes for cellular signaling for quorum sensing
- One cluster that codes for type III secretion system

The last system, type III secretion system or TTSS, is perhaps the most important for pathogenicity in Gram-negative bacteria (Alfano and Collmer 2004). This system is highly conserved for the injection of effector proteins in the host's cytoplasm. Once inside, these effectors suppress the host's defenses and generally modify the host's physiology to benefit the pathogen. However, in a resistant host, these effectors are recognized by the plant's surveillance system. Thus, the set of effectors that a bacterium has determines whether it will cause disease in a plant with a given set of resistance genes. When these genes are absent, the pathogen can freely invade the host, as its effectors will then be fully virulent.

Each phytopathogenic bacterium is estimated to have 35 to 50 genes that codify for effector proteins (Alfano and Collmer 2004). In the *Xam* genome, more than 20 effectors have been found after comparison with other phytopathogenic bacteria of the *Xanthomonas* and *Pseudomonas* genera (Arrieta et al. 2011). Two of these genes were found to be associated with pathogenicity. One is *hpaF*, which is shared with many *Xanthomonas* bacteria and has previously been associated with virulence in *X. axonopodis* pv. *glycines* (Kim et al. 2003). The other is *pth*B (Castiblanco et al. unpublished data), which has been used extensively in population studies and which presents high sequence homology with genes of the TAL family (for "transcription activator-like" gene family) in *Xanthomonas*.

The TAL gene family contains a type of effector that is translocated by the TTSS to the cellular cytoplasm (Bonas et al. 1989), where it is directed to the nucleus. There, it modulates the expression of certain genes, according to a code that was recently deciphered (Boch et al. 2009; Moscou and Bogdanove 2009). Because *pth*B is crucial for pathogenicity, it is a promising target in the generation of resistant plants.

Conclusions

Cassava bacterial blight is an important disease. Because it is widespread in Colombia, the control methods previously described must urgently be applied. The production and distribution of high-quality stakes that are free of the pathogen is an essential step in controlling the disease.

Current studies on the genetics of both the pathogen and cassava should lead to practical applications in the field. Where methods of biological control (use of antagonists) or chemical control (applications of cupric compounds) do not result in expected reductions of disease incidence, then modifications to farming practices and, especially, the introduction of resistant varieties continue to be effective alternatives for controlling CBB.

The results of characterizing the structure of *Xam* populations can be applied in the selection and introduction of resistant materials. The breeder can now evaluate genotypes, using a reduced number of strains, that is, those that reflect the pathogen diversity faced by the crop in those regions where it is introduced.

Although the defense mechanisms used by the cassava plant against the pathogen are well known, the genes for resistance need to be identified. The cassava genetic map has been established and serves as a basis for searching for markers linked to resistance to CBB. The availability of techniques, together with genetic transformation, would enable rapid acquisition of new genetic materials with resistance to CBB. Recently, the sequence of the cassava genome was released at www.phytozome.net/cassava.php. It covers 416 of the 770 Mbp of its DNA, which is estimated to represent 95% of codifying DNA. Likewise, 47,164 loci that code for proteins have been predicted.

With this large resource, strategies can be developed for identifying the repertoire of genes implicated in this plant's immunity, and for more easily associating those markers with the appropriate phenotypic characteristics to accelerate the development of improved varieties. The big challenge will be to develop functional genomics tools to validate the function of these genes and determine those that are important for resistance to CBB. The development of oligoarrays, mass sequencing of transcripts (RNAseq), and mapping by association with genes, markers, and candidates will help better represent cassava's molecular responses to CBB and identify genes and markers for genetic improvement.

With the complete sequencing of the genomes of both cassava and *Xam*, we have passed from an almost "orphan" state of research in this pathosystem to being possibly part of a pathosystem model that allows us to understand the complex interactions and evolutionary relationships that have been molded over centuries of molecular dialogue between plants and bacteria.

Acknowledgement

The authors dedicate this chapter to the memory of Bernard Boher, a pioneer on the study of this important disease, who opened a lot of other studies on cassava bacterial blight (CBB).

References

Alfano JR; Collmer A. 2004. Type III secretion system effector proteins: double agents in bacterial disease and plant defense. Annu Rev Phytopathol 42:385–414.

Arrieta ML; Rodríguez LM; Koebnik R; Restrepo S; Bernal A. 2011. Genomic survey of pathogenicity determinants in the cassava bacterial pathogen *Xanthomonas axonopodis* pv. *manihotis*. MSc thesis (Biology). Universidad de los Andes, Bogotá, Colombia

Boch J; Scholze H; Schornack S; Landgraf A; Hahn S; Kay S; Lahaye T; Nickstadt A; Bonas U. 2009. Breaking the code of DNA binding specificity of TAL-type III effectors. Science 326:1509–1512.

Boher B; Verdier V. 1994. Cassava bacterial blight in Africa: the state of knowledge and implications for designing control strategies. Afr Crop Sci J 2(4):505–509.

Boher B; Kpémoua K; Nicole M; Luisetti J; Geiger JP. 1995. Ultrastructure of interactions between cassava and *Xanthomonas campestris* pv. *manihotis*: cytochemistry of cellulose and pectin degradation in a susceptible cultivar. Am Phytopathol Soc 85(7):777–788.

Bonas U; Stall RE; Staskawicz B. 1989. Genetic and structural characterization of the avirulence gene *avr*Bs3 from *Xanthomonas campestris* pv. *vesicatoria*. Mol Gen Genet 218:127–136.

Fessehaie A; Wydra K; Rudolph K. 1999. Development of a new semiselective medium for isolating *Xanthomonas campestris* pv. *manihotis* from plant material and soil. Phytopathology 87:591–597.

Hahn SK; Terry ER; Leuschner K; Akobundu IO; Okali C; Lal R. 1979. Cassava improvement in Africa. Field Crops Res 2:193–226.

Jorge V; Fregene MA; Duque MC; Bonierbale MW; Tohme J; Verdier V. 2000. Genetic mapping of resistance to bacterial blight disease in cassava (*Manihot esculenta* Crantz). Theor Appl Genet 101(5–6):865–872.

Jorge V; Fregene MA; Vélez C; Duque MC; Tohme J; Verdier V. 2001. QTL analysis of field resistance to *Xanthomonas axonopodis* pv. *manihotis* in cassava. Theor Appl Genet 102:564–571.

Kim J-G; Park BK; Yoo C-H; Jeon E; Oh J; Hwang I. 2003. Characterization of the *Xanthomonas axonopodis* pv. *glycines Hrp* pathogenicity island. J Bacteriol 185:3155–3166.

Kpémoua K; Boher B; Nicole M; Calatayud P; Geiger JP. 1996. Cytochemistry of defense responses in cassava infected by *Xanthomonas campestris* pv. *manihotis*. Can J Microbiol 42:1131–1143.

López C; Zuluaga A; Cooke R; Delseny M; Tohme J; Verdier V. 2003. Isolation of resistance gene candidates and characterization of a RGC cluster in cassava. Mol Genet Genomics 269:658–671.

López C; Jorge V; Piégu B; Mba C; Cortes D; Restrepo S; Soto M; Laudié M; Berger C; Cooke R; Delseny M; Tohme J; Verdier V. 2004. A unigene catalogue of 5700 expressed genes in cassava (*Manihot esculenta*). Plant Mol Biol 54:541–554.

López C. 2004. Exploitation structurelle et fonctionnelle d'EST impliqués dans l'interaction hôte-pathogène. Cas du pathosystème manioc-*Xanthomonas axonopodis* pv. *manihotis*. Dissertation. University of Perpignan, France. 205 p

López C; Soto M; Restrepo S; Piégu B; Cooke R; Delseny M; Tohme J; Verdier V. 2005. Gene expression profile in response to *Xanthomonas axonopodis* pv. *manihotis* infection in cassava using a cDNA microarray. Plant Mol Biol 57:393–410.

López C; Quesada-Ocampo L; Bohórquez A; Duque MC; Vargas J; Tohme J; Verdier V. 2007. Mapping EST-derived SSRs and ESTs involved in resistance to bacterial blight in *Manihot esculenta*. Genome 50:1078–1088.

Lozano JC. 1986. Cassava bacterial blight: a manageable disease. Plant Dis 70(12):1089–1093.

Lozano JC; Sequeira L. 1974. Bacterial blight of cassava in Colombia: etiology. Phytopathology 64(1):74–82.

Metzker ML. 2005. Emerging technologies in DNA sequencing. Genome Res 15:1767–1776.

Meyers BC; Dickerman AW; Michelmore RW; Sivaramakrishnan S; Sobral BW; Young ND. 1999. Plant disease resistance genes encode members of an ancient and diverse protein family within the nucleotide-binding superfamily. Plant J 20:317–332.

Moscou MJ; Bogdanove AJ. 2009. A simple cipher governs DNA recognition by TAL effectors. Science 326:1501.

Ojeda S; Verdier V. 2000. Detecting *Xanthomonas axonopodis* pv. *manihotis* in cassava true seeds by nested polymerase chain reaction assay. Can J Plant Pathol 22(3):241–247.

Restrepo S; Verdier V. 1997. Geographical differentiation of the population of *Xanthomonas axonopodis* pv. *manihotis* in Colombia. Appl Environ Microbiol 63:4427–4434.

Restrepo S; Duque MC; Tohme J; Verdier V. 1999. AFLP fingerprinting: an efficient technique for detecting genetic variation of *Xanthomonas axonopodis* pv. *manihotis*. Microbiology 145(1):107–114.

Restrepo S; Duque MC; Verdier V. 2000a. Characterization of pathotypes among isolates of *Xanthomonas axonopodis* pv. *manihotis* in Colombia. Plant Pathol 49(6):680–687.

Restrepo S; Vélez CM; Verdier V. 2000b. Measuring the genetic diversity of *Xanthomonas axonopodis* pv. *manihotis* within different fields in Colombia. Phytopathology 90(7):683–690.

Restrepo S; Vélez C; Duque MC; Verdier V. 2004. Genetic structure and population dynamics of *Xanthomonas axonopodis* pv. *manihotis* populations in Colombia during 1995–1999. Appl Envir Microbiol 70:255–261.

Rodríguez LM; Grajales A; Arrieta ML; Salazar C; Restrepo S; Bernal A. 2011. Genomes-based phylogeny of the genus *Xanthomonas*. MSc thesis (Biology). Universidad de los Andes, Bogotá, Colombia.

Robbs CF; Ribeiro R de L; Kimura O; Akiba J. 1972. Variações em *Xanthomonas manihotis*. Rev Soc Brasil Fitopatol 5:67–75.

Vauterin LHB; Kersters K; Swings J. 1995. Reclassification of *Xanthomonas*. Int J System Bacteriol 45:472–489.

Verdier V; Mosquera G. 1999. Specific detection of *Xanthomonas axonopodis* pv. *manihotis* with a DNA hybridization probe. J Phytopathol 147(7–8):417–423.

Verdier V; Schmit J; Lemaitre M. 1990. Étude en microscopie électronique à balayage de l'installation de deux souches de *Xanthomonas campestris* pv. *manihotis* sur feuilles de vitroplants de cassava. Agronomie 2:93–102.

Verdier V; Mosquera G; Assigbétsé K. 1998a. Detection of the cassava bacterial blight pathogen, *Xanthomonas axonopodis* pv. *manihotis*, by polymerase chain reaction. Plant Dis 82:79–8.

Verdier V; Restrepo S; Mosquera G; Duque MC; Gerstl A; Laberry S RA. 1998b. Genetic and pathogenic variation of *Xanthomonas axonopodis* pv. *manihotis* in Venezuela. Plant Pathol 47:601–608.

Verdier V; Restrepo S; Mosquera G; Jorge V; López C. 2004. Recent progress in the characterization of molecular determinants in the *Xanthomonas axonopodis* pv. *manihotis*—cassava interaction. Plant Mol Biol 56(4):573–54.

Wydra K; Zinsou V; Jorge V; Verdier V. 2004. Identification of pathotypes of *Xanthomonas axonopodis* pv. *manihotis* in Africa and detection of quantitative trait loci and markers for resistance to bacterial blight of cassava. Phytopathology 94:1084–1093.

CHAPTER 10

Insects and Mites that Attack Cassava, and their Control*

Anthony C. Bellotti[1], *Bernardo Arias V.*[2], *Octavio Vargas H.*[3], *Jesús A. Reyes Q.*[4], *and José María Guerrero*[5]

Introduction

Cassava (*Manihot esculenta* Crantz) is a major energy source for millions of people who live in the tropics and subtropics. In the last 26 years, considerable efforts have been made to study the crop and its associated pest complex. Research entities include several international organizations such as the Centro Internacional de Agricultura Tropical (CIAT)[6] in Colombia, the International Institute of Tropical Agriculture (IITA) in Nigeria, and the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), in Costa Rica; and many national programs in Latin America (e.g., Colombia, Brazil, and Cuba), Africa (e.g., Cameroon, Nigeria, and Uganda), and Asia (e.g., India, Indonesia, China, and Thailand) (Bellotti et al. 1999; Bellotti 2000b).

Cassava, as plant and crop, originates in the Neotropics. However, the exact place of origin is debatable, but was probably within a wide region of the Amazon Basin, encompassing various habitats (Renvoize 1973; Allem 1994). Bellotti et al. (1994) suggest that this may be one reason why such a diversity of arthropods is recorded as attacking the crop in the Americas (Table 10-1). The host plant does, indeed, display broad genetic variation, which correlates with the numerous types of organisms that feed on the plant or are in symbiosis with it. Of the 17 general groups of pests described in Table 10-1, 35 species are found in America, 11 in Africa, and 6 in Asia. In all, about 200 arthropod species feed on cassava (Bellotti and Schoonhoven 1978a, 1978b). Many are specific to cassava, having adapted, in diverse ways, to this species' natural biochemical defenses, which include laticifers and cyanogenic components (Bellotti and Riis 1994; Bellotti 2000a).

Many of these species are minor pests and cause few or no losses in yield. Others are classified as major pests because, apparently, they have co-evolved with the crop, which has then become their principal or only host. These pests can cause severe damage to the crop, as manifested in yield losses. Such major pests include mites, whiteflies, thrips, mealybugs, lace bugs, stemborers, hornworm, and subterranean burrower bug. Other pests such as insect scales, leafhoppers, white grubs, cutworms, leafcutting ants, fruit flies, shoot flies, and termites can cause sporadic or local damage to the crop. These are considered as minor or generalist pests, and may attack the crop opportunistically, especially during drought when the only source of available food is cassava (Bellotti 2000b).

Insects harm cassava by reducing the photosynthetically active area of the plant (leaves), thus diminishing yields; attacking stems, which debilitates the plant's support and inhibits transport of nutrients; and attacking planting materials ("seed") and thus reducing shoot production in stake germination. They can also attack roots and cause secondary rots. Some pests are vectors and spread diseases.

Observations indicate that pests attacking the plant over a prolonged period—such as mites, whiteflies,

---

* This document contains information published in the Proceedings of the XXVII Congress of the Sociedad Colombiana de Entomología (SOCOLEN), 2000.

1. Emeritus Scientist/Consultant, Entomologist/Agrobiodiversity, IPM, Cassava Program, CIAT, Cali, Colombia. E-mail: a.bellotti@cgiar.org
2. Research Associate, Plant Production, IPM, Cassava Program, CIAT. E-mail: bernaarias1@gmail.com
3. Entomologist, FEDEARROZ, Bogotá, DC, Colombia.
4. Entomologist, Asociación Colombiana de Ciencias Biológicas, Palmira, Colombia. E-mail: jesus_antonior@hotmail.com
5. Research Assistant, Taxonomy of Phytophagous Mites, IPM Unit, CIAT. E-mail: jmguerrerob@yahoo.com
6. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Table 10-1. Global distribution of arthropod pests important to the cassava crop.

Pest	Principal species	Americas	Africa	Asia
Mites	*Mononychellus tanajoa*	X	X	
	Tetranychus urticae	X		X
	Oligonychus peruvianus	X		
Mealybugs	*Phenacoccus manihoti*	X	X	
	P. herreni	X		
Root mealybugs	*Pseudococcus mandioca*	X		
	Stictococcus vayssierei		X	
Whiteflies	*Aleurotrachelus socialis*	X		
	Aleurothrixus aepim	X		
	Bemisia tabaci	X	X	X
	B. tuberculata	X		
Hornworms	*Erinnyis ello*	X		
	E. alope	X		
Lace bugs	*Vatiga illudens*	X		
	V. manihotae	X		
	Amblystira machalana	X		
Burrower bug	*Cyrtomenus bergi*	X		
Thrips	*Frankliniella williamsi*	X	X	
	Scirtothrips manihoti	X		
	Corynothrips stenopterus	X		
Scale insect	*Aonidomytilus albus*	X	X	X
Fruit flies	*Anastrepha pickeli*	X		
	A. manihoti	X		
Shoot flies	*Neosilba perezi*	X		
	Silba pendula	X		
Gall fly	*Jatrophobia (Eudiplosis) brasiliensis*	X		
White grubs	*Leucopholis rorida*	X	X	X
	Phyllophaga spp.	X		
	Others	X		
Termites	*Coptotermes* spp.	X	X	X
	Heterotermes tenuis	X		
Stemborers	*Chilomima* spp.	X		
	Coelosternus spp.	X		
	Lagocheirus spp.	X	X	X
Leafcutting ants	*Atta* spp.	X		
	Acromyrmex spp.	X		
Grasshoppers	*Zonocerus elegans*		X	
	Z. variegatus		X	
Total		**35**	**11**	**6**

SOURCE: Bellotti 2000b; Arias and Bellotti 2001.

thrips, mealybugs, stemborers, ins ect scales, and lace bugs—will reduce yield more extensively than those that cause defoliation and damage to plant parts over short periods. Some pests, such as the hornworm, leafcutting ants, fruit flies, and shoot flies, allow the cassava plant to recover from short-term damage, particularly if this is not repeated.

Because cassava is a crop that is mostly grown in marginal areas, it usually faces prolonged dry seasons and deficient soils (abiotic factors) and many pests and diseases (biotic factors). Farmers in such areas are often in a difficult socioeconomic situation. When a cassava planting is planned, selecting varieties that are resistant or tolerant of most these biotic factors is therefore important. This way, farmers do not need to resort to the application of pesticides in the crop's first months. Nor do they need to accept losses of root yield because of pests and diseases. Varietal resistance, or host-plant resistance (HPR), thus becomes a significant pest control measure. Other control measures such as appropriate farming practices, pesticide applications, and biological control are also used, and are discussed in more detail below.

Cassava Arthropod Pest Complex

Cassava is a no vegetation production cycle develops over 1 to 2 years—a long cycle for a commercial crop. It propagates vegetatively and has considerable drought tolerance. It is usually planted with other species, either as an intercrop or in staggered rotation, the system most commonly used by farmers. Such agronomic characteristics contribute, without doubt, to the diversity of the arthropod pests feeding on this crop.

The arthropod pest complex extends over a broad region of the crop's production area, highlighting the need for care in placing quarantine measures to prevent pathogens being introduced into pest-free areas (Frison and Feliu 1991). The accidental introductions of the cassava green mite (*Mononychellus tanajoa* Bondar or CGM) and mealybug (*Phenacoccus manihoti* Mat. Ferr.) from the Americas into Africa have caused considerable losses throughout the African cassava belt and have required a massive effort in biological control (Herren and Neuenschwander 1991; Neuenschwander 1994a). In Asia, none of the principal cassava pests has yet been established and the arthropod pests so far observed have not caused serious losses in yield (Maddison 1979).

Recent explorations in the Neotropical cassava-growing areas indicate that the arthropod pest complex is not geographically uniform. For example, the mealybug *Phenacoccus herreni*, which causes considerable damage in Northeast Brazil, was probably introduced from northern South America (Venezuela or Colombia), where this insect's populations are controlled by natural enemies not found in Brazil (Bellotti et al. 1994; Smith and Bellotti 1996). *Phenacoccus manihoti*, a serious pest in Africa, is found only in Paraguay and certain areas of the State of Mato Grosso in Brazil and of the Department of Santa Cruz in Bolivia (Lohr and Varela 1990; Bellotti 2000a, 2000b). Studies on the CGM have demonstrated a high degree of polymorphism and a large complex of *Mononychellus* species in northern South America, unlike what is found in Brazil (Bellotti et al. 1994). This diversity is associated with the great wealth of phytoseiids that control *Mononychellus* spp. in cassava crops (Bellotti et al. 1987, 1999; Bellotti 2000a).

Insects that Attack Planting Materials

The planting of stakes free of insect pests and other damage is important for obtaining good shoot development (i.e., germination) and the satisfactory establishment of young plants.

Insect scales

Various species of insect scales have been identified as attacking cassava stems in many cassava-producing regions of the world. The quality of planting materials can be noticeably reduced if stakes are infested with scales.

- White scale, *Aonidomytilus albus* (Cockerell), can reduce shoot development by 50% to 60%, according to the severity of infestation. Immersing infested stakes in insecticide solutions reduces infestations but heavily infested stakes will germinate poorly even after treatment. Accordingly, stakes infested with scales are not recommended for use as planting materials. *Aonidomytilus albus* has been found in most cassava-producing regions of the world.

- Individuals of black scale or *Saissetia miranda* (Cockerell & Parrott), gray scale or *Hemiberlesia diffinis* (Newstead), and *Ceroplastes* sp., as well as those of *A. albus*, are not noticeable when populations are low or are found in young crops. Instead, they are highly visible in older crops, where isolated

plants or sections of the crop become heavily infested and from which epizootics can start in a following cropping cycle if stakes are not selected and treated. Burning of harvest residues is advisable for preventing these pests from resurging.

Fruit fly

Two species of fruit fly have been identified as attacking cassava in the Americas: *Anastrepha manihoti* da Costa Lima and *A. pickeli* da Costa Lima. The larvae of this fly tunnels up or down the plant's stems, forming brown galleries in the pith, thereby promoting stem rot.

In mature plants, affected stems have light to dark brown pith, with an aqueous appearance due to the association existing between this pest and a bacterium, *Erwinia carotovora*. Germination of stakes obtained from such plants may be reduced by as much as 16%, taking several weeks. This pest is described below in more detail under the section "Stem-perforating insects", page 235.

Stemborers

Stemborers, mostly belonging to the orders Lepidoptera and Coleoptera, have been found in stakes used for planting. Infestation usually occurs when plants are growing and also during storage of planting materials. Stored stakes should be carefully inspected before use. Normally, these insects are detected by the presence of galleries and perforations in the stem, accompanied by such signs as milky exudates, fine or coarse sawdust, residues of protective tissues, stem parts, and cankers.

Insects that Attack Stakes and Seedlings

White grub

Together with the Spanish names *mojojoy* and *mojorro*, this name describes beetle larvae (Coleoptera) that attack cassava. They are white, measuring about 5 cm. Their dark coffee-colored heads carry large jaws. Three pairs of legs are found in the thoracic area, and the abdomen is prominent and dark.

They are easy to find, as they live in the top 15 to 30 cm of the soil or on its surface in decomposing organic matter (e.g., trunks and leaves), adopting a crescent or "C" position. However, when temperatures are high and humidity drops, they tend to burrow deep into the soil, seeking cooler and damper places. This makes their control more difficult. They feed on plant roots, that is, they are rhizophagous, and tend to damage newly planted stakes, either before or after shooting (or germination) (FIDAR 1998).

A worldwide pest. White grubs are a cassava pest throughout the world and constitute a serious problem in Indonesia, where the most important species appears to be *Leucopholis rorida*. Another significant pest comprises the *Phyllophaga* spp. in Colombia. The literature also mentions the following: *Lepidiota stigma, Euchlora viridis, E. nigra, E. pulchripes, Anomala obsoleta, Heteronychus plebejus, Opatrum micans, Carpophilus marginallus, Dactylosternum* sp., *Inesida leprosa, Petrognatha gigas*, and *Sternotomis virescens* (Leefmans 1915; Dulong 1971; CIAT 1976).

The white grubs most frequently found in Colombia belong to the family Melolonthidae, which has four subfamilies: Cetoniinae, Melolonthinae, Dynastinae, and Rutelinae. Victoria and Pardo (1999) found that the principal genera of rhizophagous white grubs that attack cassava in the Department of Cauca are *Phyllophaga* sp. (Melolonthinae), *Cyclocephala* sp. (Dynastinae), and *Anomala* sp. (Rutelinae). However, the study of subterranean pests in Colombia verified that white grubs form a complex by virtue of abundance of species, lack of crop specificity, and their temporary and local action.

Victoria and Pardo (1999) used black light traps in several sites in the Municipalities of Caldono, Buenos Aires, and Santander de Quilichao (Department of Cauca) and collected 21,739 examples belonging to 44 species of the subfamilies Dynastinae, Rutelinae, and Melolonthidae. Most had been already recorded for their economic importance to the region and other parts of the country. Captured specimens belonged to the genera *Aspidolea*, *Cyclocephala*, *Stenocrates*, *Ancognatha*, *Dyscinetus*, *Coelosis*, *Strategus*, *Podischnus*, *Golofa*, *Ligyrus*, *Phileurus*, *Plectris*, *Phyllophaga*, *Astaena*, *Chariodemia*, *Macrodactylus*, *Isonychus*, *Barybus*, *Pelidnota*, *Anomala,* and *Leucotureus*.

The damage that these grubs cause consists of destroying the cortex of planted stakes, so that their tissues rot and die. When 1 to 3-month-old plants are attacked, leaves wilt and the plants suddenly die because the larvae feed on the cortex at the base of the stem. They usually feed under the soil, forming tunnels within the stake, preventing nutrients from moving towards the plant's aerial parts. Furthermore, they consume newly forming roots.

Biology. The biology of *Leucopholis rorida* in Indonesia is described as follows, with respect to the cassava crop. Adults are active at the beginning of the rains, but the most severe damage occurs 4 to 6 months later. Nine days after mating, females oviposit deeply in the soil, at 50 to 60 cm. They lay up to 37 pearly white individual eggs that hatch within 3 weeks. The larval stage lasts for almost 10 months, with the 4 to 6-month-old larvae being the most destructive. The larvae live at depths of 20 to 30 cm, where they feed on roots of cassava and other hosts, including maize, rice, grasses, and sweet potato. Pupae are found more deeply, at about 50 cm. The prepupal stage lasts for 14 days and the pupal, about 22 days.

The grubs undergo complete metamorphosis: egg, larva (grub), prepupa, and pupa. The larval or grub stage undergoes three instars, with their capacity to eat increasing as they develop, doing the most damage during the third instar.

The larval stage lasts from 3 or 4 months to 9 months, according to species. Genera of shorter larval stages that attack cassava include *Anomala* and *Cyclocephala*. These have short biological cycles, having two generations a year that appear in the two rainy periods, that is, March–April and October–November. This type of grub is known as *bivoltine*. Other genera have longer biological cycles, appearing once a year, that is, they are *univoltine*. This second group includes the *Phyllophaga* spp., the economically most important genus of cassava pests in Colombia.

Attacks occur most frequently when cassava grows in a soil previously occupied by grasses or weeds. At soil preparation, high populations of larvae are usually seen.

Biological control. Several parasitoids, predators, and entomopathogens have been identified as attacking white grubs. The most studied of these are the entomopathogens, including the fungi *Metarhizium anisopliae* and *Beauveria bassiana*, and the bacterium *Bacillus popilliae*, which causes milky disease of white grubs. Experiments carried out at CIAT (1974) indicated that the fungi can effectively control the grubs.

Londoño (1999) indicated that some natural enemies of white grubs are found in eastern Antioquia. Not only are they useful for their natural incidence but also because they cause significant mortality when inoculated into the soil. These enemies include the three organisms mentioned above (*M. anisopliae, B. bassiana*, and *Bac. popilliae*) and *Beauveria brongniartii*, which, under controlled conditions, cause 50% mortality.

Londoño (1999) had good results when he used insectariums to evaluate 36 isolates of organisms for their control of white grubs. Among the control agents were nematodes *Steinernema carpocapsae*, which caused 90% mortality, and *Heterorhabditis* sp., which achieved 70%. According to Londoño and De Los Ríos (1997), these organisms could cause mortality as high as 100%.

Victoria and Pardo (1999) searched for natural enemies in several sites in the Department of Cauca and found the following entomopathogens associated with white grubs: *M. anisopliae* in seven sites, *B. bassiana* in one site, *Bac. popilliae* in two sites, and several nematodes in seven sites.

Parasitoids and predatory insects are not well studied, but the following have been found: dipterans of the families Tachinidae (10 sites) and Asilidae (one site), and an elaterid coleopteran (*Elateridae* pos. *Conoderus*) in four sites. Hymenopterans were found in two of 21 sites.

Chemical control. White grubs are effectively controlled by lorsban (30 to 40 kg of paste concentrate or p.c. per hectare) or carbofuran (3 to 4 g of p.c. per plant), applied under the stakes in the soil. Treatment by immersing stakes in insecticide solutions is not as effective as applications to moist soil. Another treatment also used when plants are small is liquid carbofuran 4F applied to the soil at the plants' base.

Cutworms

Several species of cutworms attack cassava, damaging the plants in three ways according to their location in the soil:

- *Ground cutworms*, for example, *Agrotis ipsilon*, damage seedlings near the soil surface (either on or under it), leaving the cut piece lying on the soil. These larvae are dark gray with a greasy aspect or brown with streaks of light colors.

- *Climbing cutworms*, for example, *Spodoptera eridania* and *S. sunia*, climb up the stems of seedlings and consume buds and leaves before finally making annular cuts in the stems, which cause plant wilt and death. The well-developed

larva is dark gray or almost black, with yellow or orange lateral bands.

- *Subterranean cutworms* remain in the soil and feed on the roots and underground stem parts, causing losses in planting materials. Losses of young plants can reach 50%, making it necessary to replant.

The biology is similar for the three categories of cutworms that attack cassava. Eggs are oviposited en masse on the lower side of leaves close to the soil. They hatch in 6 to 8 days, and are fully developed within 20 to 30 days. The pupal stage (8 to 11 days) occurs in the soil or under plant residues. Oviposition starts about a week after adults emerge. One generation lasts almost 2 months and, under favorable environmental conditions, several generations may occur in 1 year.

Cutworm attacks are sporadic and usually occur in foci or patches in the crop. They occur more frequently when cassava follows maize or sorghum or when it is planted in lots adjacent to these crops. Longer stakes (30 cm) enable the plants to recover when under attack.

These insects can be effectively controlled with poisoned feed applied to the soil surface (10 kg of sawdust, 8–10 L of water, 500 g of sugar or 1 L of molasses, and 100 g of trichlorform per quarter or half hectare). They can also be controlled with applications of lorsban around the stakes.

Crickets

As soon as they emerge, crickets, *Gryllus assimilis* or common cricket and *Gryllotalpa* sp. or mole-cricket, cut young shoots. They also damage the plant's base, which then becomes more susceptible to lodging by wind. Crickets are controlled by using the same products as recommended for cutworms.

Termites

Termites—a tropical lowland pest—may attack cassava. They are reported as pests in various cassava-producing regions of the world, particularly Africa. In Madagascar, *Coptotermes voeltzkowi* and *C. paradoxus* of the family Rhinotermitidae feed on planting materials, roots that have bulked, and growing plants. The principal damage they cause appears to be stake loss, which seriously affects crop establishment, especially during prolonged dry periods. Bulked roots damaged by termites later rot.

In Colombia, *Heterotermes tenuis* and *Coptotermes niger* feed on planting materials (stakes), roots, or growing plants. Attacked parts then dry or die, particularly if climatic conditions are unfavorable, certain pathogens are present, or stakes are of poor quality. Stakes must be protected at crop establishment if shoot development is to be good and the plants are to "germinate" effectively. Protection may consist of combinations of treatments, such as an application of the fungicides captan + carbendazim (2 g of a.i./L water) with a later application of the insecticide lorsban in powder (3 to 4 g per site or stake) to the soil.

Leaf-Eating Insects

Cassava hornworm

Erinnyis ello (L.), family Sphingidae, is a major cassava pest in the Neotropics (Bellotti and Riis 1994; Bellotti et al. 1992, 1994, 1999). It has a broad geographical habitat, ranging from southeastern Brazil, Argentina, and Paraguay to the Caribbean Region and southeastern USA. The migratory capacity of *E. ello*, its broad climatic adaptation, and wide host range comprise the probable reasons for its extensive distribution and sporadic attacks (Janzen 1987).

Other *Erinnyis* species also feed on cassava, including the subspecies *E. ello encantado* and a closely related species, *E. alope*, which have been recorded in the Neotropics. The insect has not yet been reported in either Africa or Asia.

Biology and behavior. All hornworm larvae feed on young and mature cassava leaves and on tender stems and shoots. Severe attacks cause complete defoliation of the plant, loss in root volume, and poor root quality. Even though yield loss can be severe through complete defoliation after one or several attacks, the cassava plant itself does not die. The carbohydrates stored in the roots enable the plant to recover, especially during favorable conditions such as the tropical rainy season. Repeated attacks are very common when pesticides are not applied in time, as they do not destroy fifth-instar larvae or prepupae. Instead, the pesticides eliminate the pest's natural enemies (Braun et al. 1993). Large cassava plantings are prone to frequent and repetitive attacks from this pest.

Defoliation during the initial months of crop growth can cause significant yield losses. In simulation studies,

losses have been estimated to be between 10% and 64%, according to the intensity of attack, number of attacks, and the ecosystem where the crop is developed (Arias and Bellotti 1985b; CIAT 1989). Severe attacks can kill young plants if the pest consumes all the buds. Such losses occur if the crop is 1 to 2 months old and suffers outbreaks of the pest, with more than four larvae per plant. These studies indicate that defoliation of plants younger than 5 months will reduce yield more than defoliation of plants aged 6 to 10 months.

Although each larva can consume 1107 cm^2 of leaf area, the cassava crop can tolerate relatively high populations. Under favorable environmental conditions, a crop can lose up to 80% of its leaves without reductions in root yield. Of the 1107 cm^2 of leaf area consumed during the larval period, about 75% is consumed during the fifth instar. At 15, 20, 25, and 30 °C, the average duration of the larval stage is, respectively, 105, 52, 29, and 23 days. This indicates that the hornworm's peak activity occurs at low altitudes (<1200 m) or during summer in the subtropics (Bellotti and Arias 1988).

Larvae vary in color: most commonly they are yellow, green, black (combined with small, lateral, white or red spots), dark gray, or cinnamon brown; occasionally, they are pink. Recently hatched larvae measure between 4 and 5 mm, and are mature between 12 and 15 days. In the fifth instar, they are 10 to 12 cm long. They drop to the soil where they pupate in a chitinous capsule that is brown with black streaks. Pupae are found in plant litter.

The adult emerges after 15 to 20 days, usually in the transitional periods between winter and summer or summer and winter. These outbreaks are irregular and years may pass without their occurring. Adults of *E. ello* are nocturnal. Females are a uniform ash color and males present a longitudinal black band in the forewings.

Eggs are olive green or yellow and large, having a 1.5-mm diameter. They are laid individually, preferably on the upper surface of cassava leaves. In pest outbreaks, eggs can also be found on lower leaf surfaces, petioles, and stems. In oviposition cages placed in the field (at 25 °C and 80% rh), females lived as long as 19 days, with an average of 8.6 days, while the male survived to a maximum of 15 days, with an average of 7 days. By day 6 or 7 after emergence, 50% of the adult population (i.e., T_{50}) had died. After a preoviposition period of 2 to 4 days, a female would oviposit a daily maximum of 500 eggs. Under confinement, a female may oviposit throughout her life, producing as many as 1800 eggs. Individual couples of moths may lay an average of 850 eggs while groups of couples may lay an average of 448 (CIAT 1978). These high oviposition rates, combined with the adults' migratory behavior, contribute to the rapid strengthening of hornworm populations and their sporadic appearance (Bellotti et al. 1992; Janzen 1987).

In the pupal state, females and males differ in the position of their genital openings. In the male, the genital opening (gonopore) is located in the ninth, enlarged, abdominal segment, leaving the eighth segment free. In the female, the genital opening is smooth and is found in the eighth segment, which is seen as a "V". The sex ratio is about 1:1, female to male.

This insect's great flight ability and migratory capacity, combined with its broad climatic adaptation and extensive host range (Janzen 1986, 1987) often makes effective control difficult. Pesticides may be adequate if the hornworm populations are detected and treated during the first three instars. However, farmers react to an attack of this pest by excessively applying insecticides outside appropriate times, thus triggering more severe attacks (Laberry 1997). A population of fourth and fifth instars is more difficult to control, but tolerating its presence is uneconomical because of the considerable defoliation they cause.

Applied pesticides also affect the populations of natural enemies, facilitating more frequent attacks from the pest (Urías-López et al. 1987). *Erinnyis ello* does have an associated complex of natural enemies, but its effectiveness is not significant, probably because of the adult's migratory behavior. A mass migration of adults causes a rapid imbalance between the pest and its natural enemies because they lay large numbers of eggs—at more than 600 per plant—in only 6 or 7 days in cassava fields. Accordingly, natural enemy populations are too low to prevent an outbreak of hornworm larvae and, thus, the crop's severe defoliation.

Because their reproduction rate is limited, parasites and predators cannot recover sufficiently fast to prevent the hornworm's dramatic outbreaks (Bellotti et al. 1992). Hence, two or three successive attacks may occur if outbreaks are not detected in time.

Adequate farming practices such as weed control and good soil preparation can reduce this pest's adult and pupal populations.

Biological control with parasitoids and predators. The key to effectively using biological control agents is synchronize the release of a large number of predators or parasites during the pest's early stages, preferably as eggs or as first to third instars. More than 40 species of parasites, predators, and pathogens of cassava hornworm eggs, larvae, and pupae have been identified (Bellotti et al. 1999):

- Eight microhymenopteran species belonging to the families Trichogrammatidae, Scelionidae, and Encyrtidae parasitize eggs of *E. ello*, for example, *Trichogramma minutum,* other *Trichogramma* spp.*, Telenomus sphingis, Tel. dilophonotae, Ooencyrtus* sp., and *O. submetallicus* (CIAT 1989). Some *Trichogramma* and *Telenomus* species have been reported as parasites for 94% to 99% of eggs (Bellotti and Schoonhoven 1978a).

- Dipteran parasitoids of this pest's larvae include the flies of the families Tachinidae (*Thysanomia* sp.), Sarcophagidae (*Sarcophaga* sp. and *Oxysarcodexia innota*), and Dryinidae (*Drino macarensis*). Hymenopteran parasitoids include wasps of the families Ichneumonidae (*Cryptophion* sp.) and Braconidae (especially *Cotesia* species [= *Apanteles*] such as *C. americana* and *C. congregatus*) Bellotti et al. 1992, 1994; Bellotti and Riis 1994).

- The most common egg predators are *Chrysoperla* spp. and *Chrysopa* sp. Other important larva predators are wasps (Hymenoptera: Vespidae) of the *Polistes* genus such as *P. erythrocephalus*; stink bugs *Podisus nigrispinus, P. obscurus*, and *Alceorhynchus grandis* (Hemiptera: Pentatomidae); and several spider species of the families Tomicidae and Salticidae (Bellotti et al. 1992).

The effectiveness of parasites and predators is curtailed by their limited functional response, which lasts about 15 days during a hornworm outbreak. Thus, for control to be successful, hornworm populations must be monitored in the field to detect immigrant adults or early instar larvae. This task requires traps with black light lamps (type BL or BLB, Ref. T20T12BLT) to attract flying adults or to help identify eggs or larvae (CIAT 1983b, 1989).

These light traps do not constitute a control method but function as a tool for discovering fluctuations in the abundance of adult *E. ello* populations. The data obtained permit better planning for applying different techniques to manage the pest. Preliminary trials led to the capture of 3094 adults in one night, mostly between 00:00 and 02:00. This information is highly useful for areas where no electrical power is available because traps run on batteries or gasoline can then be operated at those hours, thereby saving on resources. The difficulty is to synchronize a mass release of parasites and predators when a peak occurs in the pest population. Thus, there is need for an inexpensive and storable biological pesticide.

Biological control with microorganisms. Microbial control with sprays of *Bacillus thuringiensis* in doses ranging from 2 to 3 g p.c. per liter of water provides effective control. Effectiveness increases when larvae are within the first three instars (Arias and Bellotti 1977; Herrera 1999).

In 1973, CIAT found, in *E. ello* colonies, a virus that attacks the pest's larvae. The virus was identified at the University of California–Berkeley, USA, by Gerard M. Thomas as a baculovirus, which identification he reconfirmed in 1974 and 1977. CIAT then developed simple evaluation methods to discover how this virus could be used as a highly effective biological means for controlling the pest. Currently, this processed virus is the flag product for controlling hornworm as it can be applied conventionally and, moreover, stored for several years without its pathogenicity altering significantly.

At a commercial level, the viral compound was first developed and applied to large extensions of the cassava crop in Brazil, when larval populations were in first instar. The result was complete control. Later, in Venezuela, the virus was used instead of insecticides for large plantings (7000 ha) in areas where the hornworm was endemic. Dosage was 70 mL/ha applied to first- and second-instar larvae. Again, the result was complete control. The direct costs of storage, application, processing, and collection of larvae amounted to US$4/ha (CIAT 1995; Laberry 1997).

Fungal entomopathogens also exist, but any collection of affected insects in cassava crops was low. Of five sites evaluated, they were found in only one. Under laboratory conditions, a *B. bassiana* strain caused a 31.6% to 87.5% mortality rate in *E. ello*, with the third instar being the most susceptible. Fungal action is not transmitted from one generation to the

next. When a *B. bassiana* strain was mixed with a *M. anisopliae* strain and applied to third instars, a 90% mortality rate was achieved without antagonism being presented. The dead larvae exhibited the typical symptomatology for each strain (Múnera S and De los Ríos 1999).

A fungus that attacks the pest's pupae was also identified. An ascomycete of the *Cordyceps* genus was very aggressive in the field, controlling the third outbreak of hornworm occurring in 1978 in the Department of Quindío, the only area where the fungus has been found. *Cordyceps* sp. can be easily reproduced on potato dextrose agar (PDA) and, when applied to pupae in the laboratory, achieves almost complete control.

Mechanical control. The manual collection of larvae and pupae is highly effective for reducing hornworm populations in small plantings. This practice is best applied to fields that the insect has only just begun to attack. When weeding tasks are carried out, digging the pupae up to the soil surface is sufficient for control, as they die from solar radiation or are destroyed with the hoe or weeding pole.

Cassava tiger moth caterpillar

This pest (*Phoenicoprocta sanguinea* Walker) belongs to the family Amatidae (also called Ctenuchidae) and is constantly found, although sporadically, within the cassava crop. Known as *bicho tigre* or "tiger bug" in Spanish, it defoliates the plant, although not at an economically significant level. However, it is considered as a potential pest of the crop, and has been reported in Colombia, Ecuador, Mexico, Brazil, and Suriname.

Biology and behavior. The adults of this species are moths of diurnal habit. They are small and showy. Their wing span measures 30 mm and the body is about 12 mm long. Females have black forewings, with the smaller hindwings having transparent areas. The abdomen is colored with metallic blue spots in the center of each abdominal segment. The bodies of males have blue, red, and yellow metallic spots on a black background. Both their forewings and hindwings are transparent (as typical of this family). The male is showier than the female, as it also has lateral red tufts on the abdomen, separated by central blue spots, and the thorax has yellow lateral tufts. The head is blue with black eyes.

The female lays eggs on the underside of leaves, preferably in the upper third of the plants. The eggs are semispherical, of a hyaline cream color, and measure about 1 mm in diameter. Eggs are laid individually, although sometimes in groups of 2, 4, or more eggs (up to 17). Incubation takes 4 to 5 days. The average number of eggs a female lays over 14 days is 192.

The larvae of *P. sanguinea* pass through five instars that together last 10 to 14 days. During this time, they also change colors, with each instar contrasting with the others. Larvae are covered with hairs that give them a furry appearance. The quantity and coloring of this "fur" varies according to instar. The first instars are a yellowish, almost translucent, fawn, becoming coffee-colored and gray until they acquire the red color of the fifth instar.

The first instar feeds in a circular fashion on the lower tissues of leaf blades, leaving an intact film of upper tissues. The film dries and later falls, leaving a circular perforation, which are often seen in mature crops and may join if many larvae eat the same leaf. Later instars uniformly consume the entire leaf, leaving only nervures. This action converts this insect into a potential crop pest. Evaluations of leaf consumption by *P. sanguinea* indicate that it can consume, on average, 78.5 cm^2 of leaf blade over its life cycle. This is 14 times less than that consumed by *E. ello* (Arias and Bellotti 1983). Larvae may measure between 2.6 mm (first instar) and 21 mm long (fifth instar) (Arias and Bellotti 1983).

After completing the fifth instar, the insect passes to the soil where it enters a prepupal state for 1 or 2 days before pupating in the soil litter, forming a cocoon with the setae or hairs of its body. The pupal state lasts 12 to 16 days. Pupae are coffee-colored and measure between 1.5 and 2.0 cm long, and between 0.5 and 0.7 cm wide. The insect's life cycle from egg to adult averages 41.2 days at 26 °C and 70% rh (Arias and Bellotti 1983).

Biological control. *Phoenicoprocta sanguinea* is a pest that, so far, does not require pesticides for its control because it has not yet presented outbreaks of economic importance. Control should, where possible, be through biological control agents that would maintain it at moderate to low levels in the field.

- Eggs of *P. sanguinea* are parasitized by *Trichogramma* sp. From each egg, five to eight small wasps emerge, at a gender ratio ranging from 0.5:1 to 5:1, female to male. In Ecuador, a small black wasp, not yet identified, was also observed to parasitize *P. sanguinea* eggs (B Arias and JM Guerrero 1999, pers. comm.).

- Larvae are parasitized by an *Apanteles* (= *Cotesia*) wasp, adults of which emerge when the pest larvae are in a prepupal state. Hence, *Apanteles* pupae can be seen developing within the cocoon formed by the pest larva. The cocoon thus becomes the wasp's puparium. From each puparium (cocoon) at least 6 to as many as 36 small *Apanteles* wasps emerge, at a sex ratio ranging from 1:1 to 23:1, female to male.

- An unidentified wasp, possibly of the Ichneumonidae family, was once observed in a typical parasitic pose over a pupa of the pest (Arias and Bellotti 1983).

Leafcutting Ants

In America, several ant species (*Atta* spp. and *Acromyrmex* spp.) have been reported as feeding on the cassava plant. An attack on the crop by a large population of worker ants can defoliate plants. The ants make semicircular cuts in leaves and, in severe attacks, buds. They take the cut parts to the anthill, where they then carry them below the soil surface. They then masticate the leaf parts to form a paste on which the fungus *Rhozites gongylophora* grows. The queen and ant larvae feed on this substrate.

Crop damage is usually evident as patches where plants appear defoliated, as when they are attacked by hornworm. However, ant damage differs from hornworm damage by the presence of semicircular cuts and of tracks that lead to anthills, which may be distant from the site of damage. Effects on yield are not known.

The most effective control is by insecticides. Anthills are easily recognized by the heaps of earth around entrances, and colonies can be destroyed by fumigating with smoke of either carbon disulfide or sulfur.

- Lorsban, applied periodically to nest entrances with a blower, is effective for reducing ant populations.

- An economic and ecological control is to attack the fungus that feeds the queen. To achieve this, the pH of the anthill is changed by periodically applying lime to the entrances and within the anthill with a blower (G Sotelo 2000, pers. comm.).

- Lime and Lorsban, mixed at a ratio of 2:1, can also be applied. This will attack both fungus and ants.

An important crop management practice is to determine the time of the queens' nuptial flights and capture them as they begin nest construction. This can be identified by small open orifices in the soil, which have the earth around them removed by the queens on initiating the new colonies. In some parts of the Department of Cauca, young schoolchildren are taught to recognize these small nests and are paid according to the number of queens they collect. In some indigenous areas, these queens are collected as food.

Leaf-Sucking Mites

Mites are a universal pest of cassava plants, causing serious losses in crops in America and Africa (Herren and Neuenschwander 1991; Bellotti et al. 1999). More than 40 species have been reported as feeding on cassava foliage (Byrne et al. 1983), the most frequent of which are *Mononychellus tanajoa* (syn. *M. progresivus*), *M. caribbeanae*, *Tetranychus cinnabarinus*, and *T. urticae* (also recorded as *T. bimaculatus* and *T. telarius*) (Bellotti 2000a, 2000b).

The cassava crop is the principal host of the *Mononychellus* complex. In contrast, the *Tetranychus* complex has a broad range of hosts. Other mite species (e.g., *Oligonychus peruvianus, O. biharensis, Eutetranychus banksi*, and *M. mcgregori*) have little economic importance because they feed on cassava foliage only sporadically (Byrne et al. 1983; Bellotti 2000a). In almost all cassava-producing regions of the world, mites frequently attack the crop during dry seasons, causing severe damage.

The mite *Tetranychus urticae* is universally widespread and is considered the most important pest in some areas of Asia. The distribution of *O. peruvianus* is limited to America. When environmental conditions are optimal, mites are found in large numbers on the underside of cassava leaves.

Mononychellus tanajoa Bondar or the cassava green mite (CGM)

Although this species is native to America, it has considerably reduced crop yield in several parts of East Africa after its introduction to that region and its dissemination to other areas of the African continent.

Mononychellus tanajoa is usually active around the plants' growing points, buds, young leaves, and stems. The central and lower parts of the plant are less affected by this species. In severe attacks, shoots lose their green color, and leaves show yellow points

uniformly distributed throughout the surface, so that the leaves acquire a mottled and bronzed appearance, as if suffering from a mosaic. Leaves are also small and deformed (Byrne et al. 1983).

Stems become scarred, rough, and brown. Sometimes they suffer dieback, that is, a progressive necrosis from the plant's upper parts to its lower parts. Terminal points become lancet-shaped through the loss of leaves and possess a cork-like appearance. Re-shooting can occur but if rains are scarce, the new leaf shoots may also be attacked (Yaninek and Animashaun 1987). If the rains return, tolerant varieties may recover their foliage. An important characteristic of the uniformly green *Mononychellus* mite is that it does not produce webs to disperse from one plant to another.

Tetranychus urticae Koch or the red spider mite

The damage caused by this mite first appears in leaves of the central and lower parts of the plant. Initially, a yellowing appears in the area of convergence of the central nervures of leaf folioles and where the mite populations concentrate. The yellow points then extend throughout the central nervures and become scattered throughout the whole leaf, which then takes on a reddish or rusty brown color. The basal leaves are the first to be affected. Heavily infested leaves dry up and fall. Under normal conditions, the upper parts of plants are green while the central and lower parts are affected or defoliated. In severe drought, this mite can invade entire plants, killing them in susceptible varieties.

This species produces webs to move from one part of the plant to another or between neighboring plants. Like *M. tanajoa*, the mites are green, but differ by being a little larger and presenting on each side of the body a dark spot that is observable only under the microscope.

Tetranychus cinnabarinus Boisduval or the carmine spider mite

This reddish-colored mite produces symptoms similar to those of *T. urticae*.

Oligonychus peruvianus McGregor (flat cassava mite)

In the plant, the pest manifests as small white spots on the underside of leaves. The spots are webs that the females construct, commonly on central, secondary, tertiary, and leaf marginal nervures. Oviposition occurs under the webs, where the immature stages of the mite feed and develop. As adults, the mites abandon the webs to form new colonies. In each web, 5 to 10 mites are found. On the upper surface of leaves, small, brown, irregular, and necrotic areas form, corresponding to the feeding activities of each colony on the leaves' undersides. Colonies usually form in the plant's central and lower parts. When environmental conditions are favorable and if the cassava variety is susceptible, the entire plant can be invaded.

Yield losses caused by mites

Economically, the CGM is the most important mite species, with losses of cassava crops being reported in the Americas and Africa (Herren and Neuenschwander 1991; Bellotti et al. 1999), especially in dry seasons in tropical lowlands (Yaninek and Animashaun 1987; Braun et al. 1989). Nyiira (1972) reported that, in Africa, reductions of yield caused by *M. tanajoa* were as much as 40%; and Bellotti (2000b) estimated that yield losses in Venezuela were 30% to 40%.

In field trials with young crops, reductions were 21%, 25%, and 53% during 3, 4, and 6 months of attack, respectively (Bellotti et al. [1983c]). Under field conditions, a high mite population reduced yields by 15% in a resistant material, 73% or more in a susceptible material, and 67% in planting materials (Byrne et al. 1982, 1983; Bellotti 2000a, 2000b).

The *M. tanajoa* mite was originally found in Northeast Brazil, in 1938. It appeared for the first time in Africa (Uganda) in 1971 and, by 1985, it was dispersed throughout the continent's entire cassava-growing belt, involving 27 countries (Yaninek 1988). Losses ranged from 13% to 80% (Yaninek and Herren 1988; Herren and Neuenschwander 1991; Skovgard et al. 1993; Bellotti 2000a).

Controlling pest mites

Research on the control of *M. tanajoa* has taken two principal directions: host-plant resistance (HPR) and biological control. These two complementary strategies help reduce CGM populations and thus its level of economic damage. Continuous use of acaricides is not an economical option for low-income farmers. Nor are these products recommended because they cause adverse effects on the pest's natural enemies (Bellotti 2000a).

Host-plant resistance. Significant work has been conducted in cassava improvement by two international research centers (CIAT and IITA) and several national research programs, including the National Cassava and Fruits Research Center (CNPMF, coordinated by the Brazilian Agricultural Research Corporation or EMBRAPA, its Portuguese acronym). All had tried to develop hybrids with resistance to CGM (Byrne et al. 1983; Bellotti et al. 1987; Hershey 1987). About 5000 cassava varieties held in the germplasm bank at CIAT were evaluated for their resistance to CGM and the other mites mentioned above. Results indicated that about 6% (300 varieties) possessed low levels of resistance or tolerance of the *Tetranychus* genus, and moderate levels of resistance to the genera *Mononychellus* and *Oligonychus* (CIAT 1999). This basic work enabled the development of varieties with moderate levels of resistance. These varieties were then released to farmers (Arias and Guerrero 2000).

Research carried out by CIAT on cassava resistance to CGM was traditionally conducted at two sites:

- CIAT–Palmira, located in the intermediate Andean area, at 1000 m above sea level, where mite populations are moderate (Arias and Guerrero 2000).

- Pivijay (Magdalena), in the Colombian Atlantic Coastal Region, located in the tropical lowlands. This area is characterized by a dry season of 4 to 6 months and high mite populations (Arias and Guerrero 2000).

The cultivars selected had low to moderate levels of resistance, scoring damage values between 0 and 3.5, according to a scale of 0 to 6 (Arias and Guerrero 2000), where 0 was no damage and 6 was severe damage.

Of the 300 varieties selected as promising for durable resistance (2 to 7 cropping cycles), 72 maintained a score for damage of less than 3.0 (CIAT 1999). Most of these varieties were collected in Brazil, Colombia, Venezuela, Peru, and Ecuador. Some were hybrid (Arias and Guerrero 2000).

Mechanisms for resistance to the mite were interpreted as comprising either antixenosis (where the plant repels insects by morphological means, e.g., pubescence) or antibiosis (where the plant adversely affects insect physiology, e.g., through chemical means) (Byrne et al. 1982). Mites feeding on susceptible varieties develop fast; are highly fecund; readily accept the plant; and have a long life span as adults, and low larval and nymphal mortality rates. Those that feed on resistant materials, however, do not behave this way (Byrne et al. 1983). Instead, they have high mortality rates, long developmental periods, and less oviposition over shorter periods. Recent laboratory studies show *M. tanajoa* as strongly preferring to oviposit on susceptible varieties. When resistant varieties M Ecu 72, M Per 611, and M Ecu 64 were compared with the susceptible CMC 40 (M Col 1468) in a free-choice test, preference for the susceptible variety was 95%, 91%, and 88%, respectively (Arias and Guerrero 2000).

Biological control. Studies were carried in numerous cassava fields, with the experimental data indicating that, despite being present in Neotropical lowlands, CGM attacks rarely cause significant losses, except in some areas of Brazil. Consequently, a work-in-progress, which extended from 1983 to 1990 and covered 2400 sites in 14 countries of the Americas, was conducted to evaluate the complex of the CGM's natural enemies (Byrne et al. 1983; Bellotti et al. 1987).

A reference collection of CGM predators, developed by CIAT and Brazil, is now held at CIAT. It includes the acarophagous mites, known as *phytoseiids*, found on cassava (Table 10-2). It also lists the various geographical areas chosen for collection because of their ecological similarity with sites in Africa and Brazil with mite problems. Of the 87 collected and stored predatory species, 25 were new or had not been recorded before and 66 species (76%) were collected from cassava crops. A taxonomic key of phytoseiid species associated with cassava was then prepared as part of a collaborative project with several Brazilian colleagues. The CIAT–Brazil collection has a database that can be easily used for describing or re-describing species, listing mite types and paratypes.

Of the 66 species of phytoseiids collected from cassava plants, 13 were the most common, including *Typhlodromalus manihoti*, which was the most frequently collected species, being found in more than 50% of sampled fields. This species was followed by *Neoseiulus idaeus*, *T. aripo*, *Galendromus annectens, Euseius concordis*, and *E. ho*. Phytoseiids *T. aripo* and *N. idaeus* are promising biological control agents for *M. tanajoa* in Africa (Yaninek et al. 1991, 1993).

The explorations revealed other insects as predators of the CGM, particularly the staphilinid *Oligota minuta* and the coccinellid *Stethorus* sp. The phytoseiids and other predators were carefully studied in the laboratory and field (Table 10-2), with the phytoseiid mites being verified as more efficient than the predatory insects (Byrne et al. 1983).

Table 10-2. Biological and ecological aspects of phytoseiids that prey on cassava mite pests.[a]

Phytoseiid predator	Colonies (no., 1986–1999)	Relative humidity	Consumption of *Mt* eggs (24 h)	Growth period (days)			Fecundity			Females			
										Longevity		(%)	
				Mt	*Tu*	*Mc*	*Mt*	*Tu*	*Mc*	*Tu*	*Mc*	*Mt*	*Tu*
Typhlodromalus manihoti	31	+	68.0	4.9	4.1	5.5	14.2	—	3.5			74	88
T. aripo	9	+				6.8		13.0	13.0	14.0	20.9		
T. tenuiscutus	7	+	45.4	5.8	5.8	5.7	32.0	2.5	16.1	6.6	16.1	75	81
T. rapax	1			5.0	5.4	5.8	6.0	12.0	19.4			78	62
Neoseiulus idaeus	20	+++	26.8	4.6	4.6	5.1	13.8	32.3	12.5	21.6	27.8	73	84
N. californicus	5	++	26.5	4.7	4.4	7.7	34.8	43.7	23.4			70	79
N. anonymus	4			4.7	5.1	5.2	14.5	34.4	27.7	39.1	12.0	73	58
Galendromus helveolus	5	+		7.4	7.0		18.7	8.0	23.0	14.2	19.0	64	66
G. annectens	6	++	17.8	5.7	6.1		22.4	19.0	31.0	23.0	27.7	74	85
Euseius concordis	1		5.7	5.0			12.7					75	70

a. Relative humidity: + = 75%; ++ = 60%; +++ = 40% to 50%; *Mt = Mononychellus tanajoa; Tu = Tetranychus urticae; Mc = Mononychellus caribbeanae.*

The results of these studies showed that CGM density was higher in Northeast Brazil than in Colombia and that the diversity of phytoseiid species was considerably higher in Colombia than in Brazil. Of the fields evaluated in Colombia, 92% were either not infested with the mite pest or were infested at very low densities (i.e., at less than 25 mites per leaf). In contrast, for crops in Brazil, only 12% of fields were not infested and 25% had intermediate or high densities of CGM (Bellotti et al. 1994).

Results of field experiments in Colombia (Braun et al. 1989) demonstrated the importance of the effect of various phytoseiid species associated with CGM. In Colombia, fresh and dried root production dropped by 33% when natural enemies were eliminated. In comparison, acaricide applications did not increase production, thus indicating that the biological control was good.

Since 1984, numerous phytoseiid species were sent to Africa from Colombia and Brazil. Of the mass-released species, none from Colombia became established, but three species from Brazil (*T. manihoti, T. aripo*, and *N. idaeus*) managed to become established (Yaninek et al. 1991, 1993; Bellotti et al. 1999). Of the three, *T. aripo* seems the most promising, as it dispersed rapidly and, today, is found in more than 14 countries. Field evaluations indicate that *T. aripo* reduces the CGM population by 35% to 60%, resulting in increases of fresh matter production by 30% to 37%.

Neozygites sp. *cf. floridana* (Zygomycetes: Entomophthorales), a pathogenic fungus, causes irregular or periodic mortality in mite populations in Colombia and Northeast Brazil (Delalibera Jr et al. 1992). This pathogen was found in many cassava fields in several Neotropical regions. Some strains were specific to the *Mononychellus* genus (de Morães et al. 1990), and was also found on CGM in Africa, although no epizootics of the fungus were observed (Yaninek et al. 1996). The fungal strain from Brazil may therefore be more virulent than that from Africa. Molecular techniques are currently being used to taxonomically identify the strains and *in vitro* methodologies are being developed to produce the pathogen. This fungus, which appears highly promising for the biological control of CGM, is also being evaluated in Africa.

Leaf-Sucking Insects

Cassava whiteflies

Whiteflies (Hemiptera: Aleyrodidae) feed directly on the cassava plant and also serve as vectors of viruses that attack the crop. They therefore cause significant damage to this crop in the agroecosystems of America, Africa, and, to a lesser extent, Asia. The Neotropical whitefly complex is enormous, with 11 species recorded as associated with cassava (Bellotti et al. 1994, 1999; Castillo 1996; França et al. 1996):

Aleurotrachelus socialis Bondar
Trialeurodes variabilis Quaintance
Bemisia tuberculata Bondar
Aleurothrixus aepim Goeldi
B. tabaci Gennadius
B. argentifolii
Trialeurodes abutiloneus Haldeman
Aleurodicus disperses Russell
Paraleyrodes sp.
Aleuronudus sp.
Tetraleurodes sp.

Aleurotrachelus socialis is the predominant species in northern South America, where it causes considerable damage to crops. It is also found in Brazil, although in smaller numbers (Farias 1994). Small populations of *B. tuberculata* and *Trialeurodes variabilis* have been reported in Brazil, Colombia, Venezuela, and other countries (Farias 1990; Bellotti et al. 1999). The spiralling whitefly (*Aleurodicus dispersus*) causes damage to cassava in western Africa (Neuenschwander 1994b; D'Almeida et al. 1998). In Colombia, small populations of this species have been found in cassava crops of the Atlantic Coast and Valle del Cauca. This whitefly also appears in some provinces of Ecuador (B Arias and JM Guerrero, pers. comm.). *Bemisia afer* has been found in Kenya (Munthali 1992) and Côte d'Ivoire (Bellotti 2000a, 2000b).

Biology and behavior. Whitefly *B. tabaci* is distributed throughout the tropics, feeding on cassava plants in Africa and various regions of Asia, including India (Lal and Pillai 1981) and Malaysia. In 1990, *B. tabaci* biotypes in America were found feeding on cassava. These whiteflies are known to transmit viruses that cause the following diseases in cassava:

- African cassava mosaic disease (ACMD), caused by several geminiviruses transmitted through *B. tabaci* (Thresh et al. 1994; Bellotti 2000a).

- Frogskin disease, which affects cassava in the Neotropics maybe transmitted by *B. tuberculata* (Angel et al. 1990; Bellotti 2000a).

The absence of ACMD in the Americas is believed to be related to its vector's (*B. tabaci*) inability to colonize cassava. At the beginning of the 1990s, a new *B. tabaci* biotype (B), which some consider as a separate species (*B. argentifolii*), was found in the Neotropics feeding on cassava. African cassava mosaic disease is now believed to be a serious threat to cassava production in the Neotropics, as most traditional cultivars of this region are highly susceptible to the disease. Furthermore, the biotype complex of *B. tabaci* comprises vectors of several viruses that affect cultivated species that are often grown in association with cassava or in adjacent fields. The possibility that viral diseases will circulate between these species or that new viruses will appear represents a potential threat to cassava production (Bellotti 2000a, 2000b).

Females of *A. socialis* oviposit individual banana-shaped eggs on the underside of apical leaves. Incubation takes about 10 days and the insect undergoes three nymphal instars and a pupal phase (fourth instar) before reaching the adult stage. During the third instar, the body changes from a cream color to black and is surrounded by a waxy white layer. The black pupae make this species easy to distinguish from other whitefly species that feed on cassava. Development from egg to adult in an incubator is 32 days at 28 ± 1 °C and 70% rh (Arias 1995). Studies on oviposition in *A. socialis* indicate that a female lays as many as 224 eggs (Bellotti 2000b).

A female *Trialeurodes variabilis* oviposits, on average, 161 eggs that have a 62% chance of survival from egg to adult. The female lays the bullet-shaped eggs vertically, as do the *B. tuberculata* and *B. tabaci* females. The average longevity of females was 19.2 days and that of males 8.8 days. Pupae of the *Bemisia* species are oblongate and are normally pale green. Consequently, to differentiate the morphological characteristics of each species, microscopy should be carried out and differences taken into account.

High populations of *T. variabilis* are usually associated with the rainy season when plants are more vigorous. However, population levels may depend more on the plant's physiological conditions than on the climate.

Damage and losses. Whiteflies directly damage leaves through their feeding activities. Both adults and immature states of *A. socialis* are active and destructive. They feed on the phloem, the females even feeding while copulating and ovipositing. This behavior produces chlorosis and cone-like rolling of bud leaves. In susceptible varieties, leaves of the central third of plants, where nymphs are found, are reduced in size and present yellowing from the margins towards the center, together with corrugated areas that are greener than others, thus giving the leaves a mosaic appearance. These leaves usually become yellow, necrose, and eventually fall off.

Depending on the intensity of the attack, they may also become covered by the sooty black growth of a fungal complex known as *fumagina* sooty mold (Arias 1995). In susceptible varieties, especially if attacks start early in the crop's development and last until the late stages of vegetative growth, the plants become rachitic and their thin stems suffer from lodging. Re-shooting therefore occurs, but these shoots are also palatable to the adult pest. The pest thus succeeds in affecting the production of planting materials, crop yield, and quality of harvested roots (Arias 1995).

Populations. Research carried out in the Neotropics has concentrated on *A. socialis* and *Aleurothrixus aepim*. Populations of both species increase during dry seasons, but may be presented throughout the cropping cycle (Farias et al. 1991; Gold et al. 1991). In the Department of Tolima, during summer, *A. socialis* populations increase, wheareas those of *T. variabilis* diminish. In the rainy seasons, the reverse occurs, with the *T. variabilis* populations being high and those of *A. socialis* low (Bellotti 2000a, 2000b).

In the latter half of the 1990s and the first semester of 2000, *A. socialis* populations increased considerably, becoming endemic in the Departments of Cauca and Valle del Cauca and seriously affecting the farming economy of those areas. Populations of this whitefly remained constant both in dry and rainy seasons. Apparently, rainy days alternating with days of strong sun and high temperatures favor and stimulate the incidence of this pest, which even impede the presence of other pests (B Arias and AC Bellotti 1998, pers. comm.). Prolonged attacks of this pest on a crop may affect the capacity of stakes to shoot (G Jaramillo 1999, pers. comm.).

Production losses caused by *A. socialis* and *Aleurothrixus aepim* are common. The duration of an attack by whitefly correlates with losses in cassava root production. Attacks by *A. socialis* over 1, 6, and 11 months resulted in 5%, 42%, and 79%, respectively, of losses in root yield in field trials conducted by CNIA–Nataima of CORPOICA, in the Department of Tolima, Colombia (Vargas H and Bellotti 1981; Bellotti et al. [1983c], 1999).

Whiteflies management. Various methods are used to control the pest, including pesticides, cultural control, varietal resistance (i.e., HPR) and biological control. The last two have been increasingly accepted to complement other pest control practices. A more traditional approach is crop management. These three approaches help reduce environmental pollution and other disadvantages that excessive use of chemical pesticides presents.

In the Neotropics, research initially focused on controlling whitefly in cassava crops through HPR activities and crop practices. More recently, considerable work has been conducted on identifying natural enemies and evaluating their actions in the context of integrated pest management (IPM) (Bellotti 2000a).

Farming practices, including traditional systems of intercalating the cassava crop with other crops, also help reduce pest populations (Leihner 1983), as follows:

- Egg populations of *A. socialis* and *T. variabilis* in a cassava/cowpea association were lower than those in crops under monoculture (Gold et al. 1990). The effects were residual, persisting for 6 months after harvest. Production losses in a cassava/maize association, a cassava monoculture, and a mixed cropping system were about 60%. In contrast, production losses in a cassava/beans system were only 12% (Gold et al. 1989b, 1989c). However, the cassava/maize association did not reduce egg populations (Gold 1993). Thus, the success of this technique depends on the crop species being intercalated, which limits effectiveness and acceptability to farmers. With the right crops, however, it can reduce pest populations in small-farmer crops (Bellotti 2000a).

- For agronomic control, the management of planting dates plays an important role in reducing pest incidence. If planted in a suitable rainy season, the crop can be free of the pest, or needs to support only small populations, in the first 2 to 3 months of vegetative growth, which are significant for crop development. Timely weed control and fertilizer applications (where necessary) will also prevent competition with other plants, giving the crop plants an initial vigor that will enable them to support attacks from this insect (Arias 1995).

- Researchers use yellow traps to physically control whiteflies in different crops. The pest is attracted by surfaces that reflect yellow in the range of 500 to 700 nm (Berlinger, cited by Arias 1995).

Control by varietal resistance (HPR). Varietal resistance offers a stable option that is low-cost and long-lasting in the control of whitefly populations. Resistance to whitefly is rare in crops, although good sources of resistance have been identified and highly productive resistant hybrids are being developed. The HPR studies initiated at CIAT more than 15 years ago have systematically evaluated more than 6000 cassava varieties from the germplasm bank for resistance to whitefly (CIAT 1999), especially to *A. socialis*. In Brazil, research was carried out with *Aleurothrixus aepim* (Farias 1990a, cited by Arias and Guerrero 2000).

Various sources of resistance to *A. socialis* have been identified. The cassava clone M Ecu 72 has consistently shown high levels of resistance. Other varieties presenting moderate to high resistance include M Ecu 64, M Per 335, M Per 415, M Per 317, M Per 216, M Per 221, M Per 265, M Per 266, and M Per 365. These results suggest that resistance to *A. socialis* is found in germplasm native to Ecuador and Peru, but more research is needed. Materials M Ecu 72 and M Bra 12 (agriculturally desirable clones that tolerate whitefly in the field) were used in an improvement program to increase the production and resistance of clones that showed no significant differences in production when grown in either plots treated with insecticides or untreated plots (CIAT 1992; Bellotti et al. 1999).

Greenhouse and field studies showed that *A. socialis*, after feeding on resistant varieties, oviposited less, developed more slowly, were small, and suffered a higher mortality rate than those that fed on susceptible clones. First-instar nymphs of *A. socialis*, after feeding on M Ecu 72, presented a 72.5% mortality rate (CIAT 1994; Arias 1995) (Figure 10-1). Selected progenies (CG 489-34, CG 489-4, CG 489-31, and

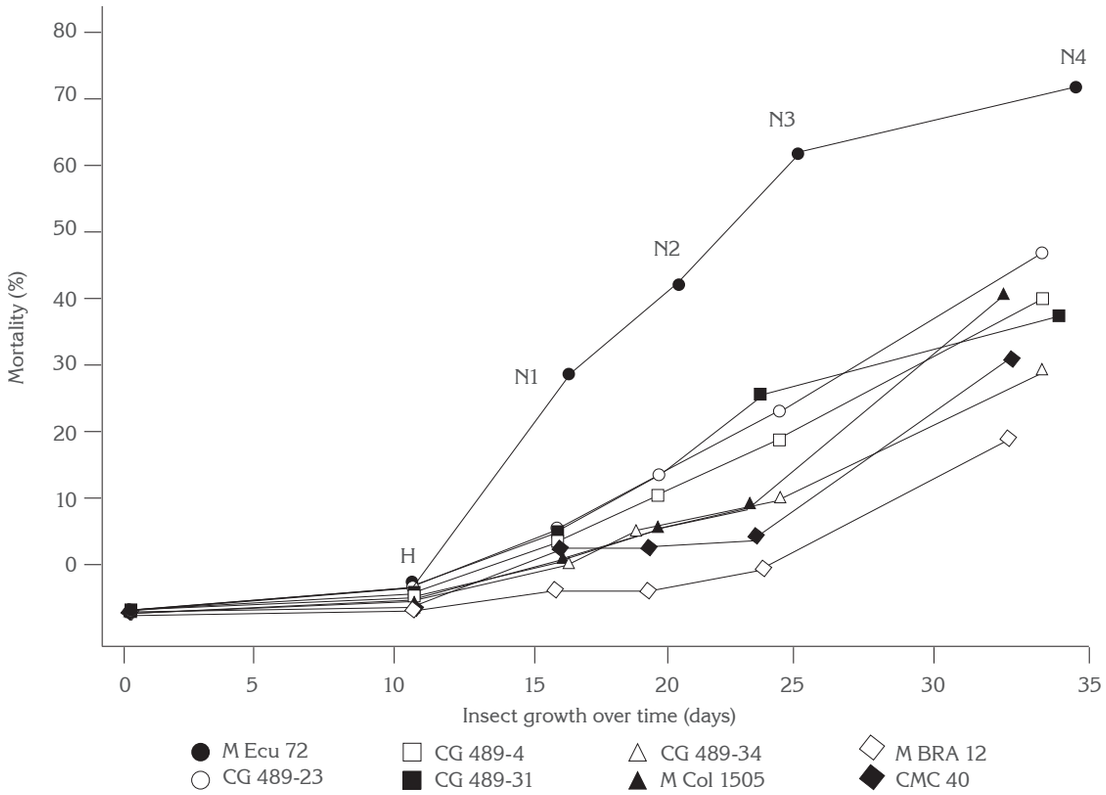


Figure 10-1. Mortality of whitefly *Aleurotrachelus socialis* with respect to its stage of development on cassava clones that are either resistant or susceptible to the pest. H = hatching, N1 = nymph 1, N2 = nymph 2, N3 = nymph 3, N4 = nymph 4.

CG 489-23) of a cross between M Ecu 72 and M Bra 12 had moderate levels of resistance to whitefly. Three of these hybrids are currently being evaluated for release to Colombian farmers in the Department of Tolima, Colombia (Arias and Guerrero 2000).

In Colombia, field evaluations of resistance to natural populations of *A. socialis* have been conducted at two sites:

- In Nataima, Tolima, in cooperation with the Colombian Corporation of Agricultural Research (CORPOICA). Populations of *A. socialis* found in Nataima have been at moderate to high levels in the last 15 years. Hence, long-term research is possible there (Arias and Guerrero 2000).

- In CIAT–Palmira, Valle del Cauca. Initially, the *A. socialis* population was low. However, since 1994, it has increased and is currently higher than it is in Tolima. This sudden increase is not yet understood but the dynamics show an outbreak of this pest in a crop that had previously supported its attacks (Arias and Guerrero 2000).

CIAT is currently conducting research to identify markers linked to genes that confer resistance to *A. socialis* attacks to understand the genetics of resistance in cassava to whitefly in preparation for field evaluations.

Building a 10-cM framework map for QTL analysis and identification of candidate genes for whitefly resistance (WF^R) in cassava

Cassava genetic and genome resources. Cassava is an allopolyploid with 36 chromosomes (Magoon et al. 1969). Due to poor seed set, the heterozygous nature of the crop, the high genetic load, and the high susceptibility to inbreeding depression on the loss of heterozygosity, shoot cuttings, thereby preserving its heterozygous nature, propagate most cassava. This heterozygosity provides challenges to cassava breeders but has enabled the identification of over 600 molecular markers (Blair et al. 2007). Simple sequence repeat (SSR) markers were used to study the genetic diversity and structure in a large collection of local varieties from Africa and Latin America. CIAT constructed the first linkage map of cassava (Fregene et al. 1997). Since then molecular markers have been

linked to the single genes conferring resistance to CMD, green mites, and cassava bacterial blight (CBB), enhanced ß-carotene content, and early root yield (Ferreira et al. 2008; Marín Colorado et al. 2009; Ogunjobi et al. 2006). The above resources are available at cassava database housed at CIAT.

The draft cassava genome (CIAT line AM560-2) was released by the U.S. Department of Energy-Joint Genome Institute (DOE-JGI) under the Community Sequencing Program (www.jgi.doe.gov/CSP). Currently, the Gates Foundation has invested $1.3 M to refine the genome annotation and develop a robust SNP resource to enable molecular mapping in cassava (CGP 2009). Over 47,000 protein-coding loci are currently annotated on the cassava genome and 24,388 of these loci are supported by ESTs (CGP 2009). Two additional full-lenght cDNA libraries were constructed more recently and are being analyzed (CIAT/RIKEN). These libraries contain cDNAs from over 23 treatments including *A. socialis* infestation of MEcu72 (WF^R) leaves.

Genetic linkage maps are a prerequisite to studying the inheritance of both qualitative and quantitative traits (Morgante and Salamini 2003). To identify the mechanisms of WF^R in cassava, we are determining the heritability and the number of loci that contribute to the antibiotic and antixenotic resistance expressed in MEcu72. To this end, it is necessary to construct a 10-cM framework linkage map for MEcu72 using statistically well-supported EST, AFLP, SSR, and SNP markers. Cassava is a highly heterozygous species with strong inbreeding depression (Blair et al. 2007). Homozygous lines cannot be obtained and F_2 populations often suffer from genetic bias induced by the death of some genotypes. For this reason, F_1 plants are used in cassava mapping. We are using 184 F_1 progeny from a cross between MEcu72 (♀ WF^R) x MCol2246 (♂ WF^S). This population size increase LOD score estimation and hence facilitate the identification of WF^R QTL(s) explaining more than 5% of the phenotypic variance. A second F_1 segregating population with 200 individuals from the cross between MEcu72 (♀ WF^R) and CMC40 (♂ WF^S) will be used to validate the markers flanking the QTLs explaining the largest phenotypic variance.

Unravel the genetic mechanism of WF^R using association genetics. Our 10-cM framework map will be used for the identification of WF^R QTLs using composite interval mapping, which is based on mixture models and maximum-likelihood techniques. These analyses will allow us to identify the major and minor QTLs conferring WF^R. For molecular markers to be useful for integrating WF^R into WF^S varieties used by smallholder farmers, the markers must be validated in a second mapping population (MEcu72 x CMC40). At the end of this project period, we will be poised to initiate MAS breeding to incorporate WF^R into cassava lines preferred by smallholder farmers using the SNP/SSR markers linked to the WF^R QTLs, which contain quantitative resistance (*QR*) gene(s) that confer WF^R.

Identification of candidate genes for resistance to whitefly using microarrays. Microarrays technology and subtractive libraries were used to identify differentially expressed genes in cassava during *A. socialis* attack (Bohórquez 2011). These methodologies allowed us to identify 405 sequences induced by *A. socialis* in all stages of their life cycle. These sequences are involved in biological process like defense, cell wall modification, oxidative burst, signal transduction, transport, primary metabolism, and photosynthesis. Some of these sequences are part of the signaling pathways regulated by jasmonic acid (JA) and ethylene (ET), which are involved in defense response to pathogens and herbivores. When *A. socialis* feeding on leaves of genotype MEcu 72, introduce their stylet, and insect-derived elicitor (salivary components and/or chitin) are recognized by a plant receptor. In the case of chitin, it is proven that the family of transcription factors *AP2/ERF* are induced by chitin, which is a component of the insect exoskeleton. This transcription factor is induced by the signaling cascade that begins with plasma membrane depolarization and Ca^{2+} flow, then are activated MAPK signaling cascades and subsequent induction of phytohormones pathways such as JA/ET. *AP2/ERF* transcription factors are potential mediators of the synergistically induction process between JA and ET and induce defense genes such as basic vacuolar proteins *PRB1, CHIB (PR-3),* as well as lectins and proteinase inhibitors. These proteins can have several effects against insects, such as poisoning, may target components of the insect gut that contain carbohydrates, can inhibit the action of proteases preventing whiteflies to digest their food well, dying of malnutrition. The defense response is complex and involves all the processes of cellular metabolism, some of which themselves can be effector mechanisms that are controlling the attacker. Among these are the generation of ROS, which produces enzymes that can affect insect diet or inducing plant hormone signaling pathways mentioned above. Cell wall modification, which may make it difficult to insect feeding and may also mediate the defense response regulated by JA/ET,

and finally the protein degradation machinery in which are various proteases with different roles involved in defense against pathogens. At the same time, the plant represses its primary metabolism and photosynthesis, reallocating C and N resources to the defense.

The application of functional genomics approach in the study of cassava defense responses, opens a wide range of future applications at different levels, both *in silico* and experimentally. Gene expression analysis, construction of physical and genetic maps, genomic sequence analysis, gene silencing, and production of genetically modified organisms are some of the projects will be developed in the future.

Biological control. In explorations carried out recently in the Neotropics—especially in Colombia, Venezuela, Ecuador, and Brazil—numerous species of natural enemies have been identified as associated with the whitefly complex that attacks cassava. Not much is known of the complexes of natural enemies associated with the different whitefly species. Thus, we cannot readily determine each complex's effectiveness and its potential in biological control programs. We know sets of parasitoids exists, but little is known about these insects' levels of parasitism, rates of parasitism per whitefly species, the specific hosts that are chosen, and their effects on the regulation of whitefly populations.

Since 1994, CIAT researchers have conducted explorations to identify natural enemies in northern South America. The most representative group is that of the microhymenopteran parasitoids (Castillo 1996; Evans and Castillo 1998). An abundance of these species exist in Colombia. More than 10 species, some not even recorded, were collected, but the genera that most frequently associated with *A. socialis, B. tuberculata*, and *T. variabilis* were *Encarsia* (especially *E. hispida* and including *E. pergandiella* and *E. bellottii*), *Eretmocerus* (species not yet identified), and *Amitus* (including *A. macgowni*) (Castillo 1996; Evans and Castillo 1998).

The highest levels of parasitism observed in *A. socialis, B. tuberculata*, and *T. variabilis* were 15.3%, 13.9%, and 12.1%, respectively, and varied according to geographical region (Castillo 1996). Parasitism was higher in the Andean Region than in the coastal and flat regions of eastern Colombia.

Studies conducted in Colombia during 1997 to 1999 showed that *Encarsia* was the most frequently collected genus in the Andean Region and that *Eretmocerus* predominated in the low altitudes of the Caribbean Coast (CIAT 1999). Parasitoid species associated with each whitefly species may be influenced by geographical region. In Valle del Cauca (1000 m above sea level), 99.6% of parasitism of *A. socialis* was from *Encarsia* and 0.4% from *Eretmocerus*. The most numerous species in the parasitoid complex was found in association with *B. tuberculata*.

Greenhouse studies on *E. hispida* as a parasite of *A. socialis* show that the third instar of whitefly is the preferred. Parasitism rates on different instars were 15.6%, 44.7%, 75.3%, and 43.1% on the first, second, third, and fourth instars, respectively. The average rate of parasitism was 45%, with the highest levels being between 72 and 96 h after exposure (CIAT 1999; Ortega 2000). *Encarsia hispida* is the parasitoid most frequently seen when *A. socialis* populations are high. However, its effectiveness in regulating whitefly populations in the field is not known.

The way in which cassava varieties resistant to *A. socialis* influence parasitoid behavior has also been evaluated. The survival of *E. hispida* was not negatively affected by resistant cassava genotypes. However, fewer parasitoids emerged from pupae of *A. socialis* whose larvae had previously been fed with resistant variety M Ecu 72 than from pupae of larvae fed on susceptible variety CMC 40 (CIAT 1999).

During December 2000 and the first 3 months of 2001, a large number of the parasitoid *Amitus macgowni* was observed at the CIAT–Palmira experiment station in high populations of *A. socialis.* Between 20 and 80 examples were captured per leaf and more than 2500 per hour (B Arias 1998, pers. comm.).

Three fungal entomopathogens that attack whitefly on a world level have been tried in the laboratory: *Beauveria bassiana, Verticillium lecanii*, and *Metarhizium anisopliae*. Although these fungi have not been found in Colombia as natural parasites, *B. bassiana* was observed to cause mortalities of 28%, 55%, and 39% in first, second, and third instars of *A. socialis*, respectively. The second instar was the most susceptible under laboratory conditions. *Beauveria bassiana* and *M. anisopliae* also caused mortality rates of 18.1% and 18.8%, respectively, when introduced in the morning, and 12.4% and 5.7% when introduced in the afternoon (Sánchez and Bellotti 1997).

Lace bugs

Lace bugs (Hemiptera: Tingidae) attack cassava in several South and Central American countries. These bugs are a pest in the Neotropics, but have not been reported in Africa or Asia. Froeschner (1993) identified several species, of which the most important for cassava are *Vatiga illudens*, *V. manihotae*, and *Amblystira machalana*. *Vatiga manihotae* is found mainly in Colombia and Venezuela, but is also found in Cuba, Trinidad, Peru, Ecuador, Paraguay, Argentina, and Brazil. *Vatiga illudens* predominates in Brazil, but is also found in the Caribbean Region. Black lace bug, *A. machalana*, attacks cassava in Colombia, Venezuela, and Ecuador (Bellotti et al. 1999; Bellotti 2000b).

Vatiga illudens and V. manihotae. These two species attack cassava mainly during dry seasons, with attacks worsening in prolonged droughts. Adult *Vatiga* are gray and measure about 3 mm long and 1 mm wide. The average life cycle of *V. illudens* lasts 75.5 days. The female can lay, on average, 61.2 eggs, which she inserts into leaf tissue, preferably next to central nervures where they converge near the petiole. They thus become imperceptible. The nymph is white and a little smaller than the adult. Both adults and nymphs are found in large numbers on the underside of leaves.

Populations tend to concentrate on the basal and central leaves but, during severe attacks, may reach apical leaves. Damage caused in leaves is similar to that made by mites: small white spots of star-like appearance, giving a whitish appearance to the leaf as they join. They later acquire a reddish-brown tone (Bellotti 2000b). This damage differs from that made by mites by the presence of black points on the underside of leaves, which are excrements from the bugs. Foliage can be sufficiently damaged to extensively reduce photosynthesis and result in the defoliation of basal leaves (Bellotti 2000b).

Amblystira machalana. This pest induces a similar symptomatology to that induced by the *Vatiga* spp. Adults and nymphs of *A. machalana* appear black. The female lays, on average, 93 eggs on the underside of leaves. At first, they are white, but quickly become red or orange. The life cycle of *A. machalana* averages 42.5 days (Arias and Bellotti 2001). In the field germplasm bank held at CIAT, severe outbreaks of *A. machalana* have occurred during wet periods. This species is also found in subhumid zones of Ecuador (B Arias and JM Guerrero 1999, pers. comm.), unlike *V. illudens* and *V. manihoti*, which are more common in dry seasons.

In field trials at CIAT, natural populations of *A. machalana* led to yield losses of 39%, unlike for the plots of plants treated with pesticides (CIAT 1990). The literature contains little information on yield losses caused by *V. illudens* and *V. manihotae*. Populations of *V. illudens* in Brazil are endemic, and do appear to reduce yields, especially in the central Cerrados and, more recently, southern Brazil. Nor is much literature available on the current and potential damage of this pest, requiring more research (Bellotti 2000a, 2000b).

Controlling lace bugs. Control seems difficult, as they have very few natural enemies (Bellotti et al. 1999). Continuous use of insecticides is expensive and may destroy the natural enemies of other pests. Preliminary studies and evaluations made in the cassava germplasm bank held at CIAT indicate that varietal resistance may exist, but that more research is needed to develop the technology (CIAT 1990; Bellotti 2000a).

At CIAT–Palmira, a hemipteran of the family Reduviidae (*Zelus nugax*) was observed preying on the nymphs and adults of the *Vatiga* species mentioned above. It succeeded in consuming, throughout its biological cycle, an average of 475 lace bugs. Several spider species also feed on these insects but, so far, their potential as predators has not been measured.

Planthoppers

Thrips

Several thrips species have been identified as attacking cassava: *Frankliniella williamsi* Hood, *Scirtothrips manihoti*, *Corynothrips stenopterus*, and *Caliothrips masculinus*. All belong to the family Thripidae. Thrips are a pest in Central and South America, and have also been reported in Africa.

Frankliniella williamsi and Scirtothrips manihoti. These two species are the most important for the damage they cause to terminal buds in cassava plants, that is, they break the plants' apical dominance. The adult of both species is uniformly yellow, with microscopic differences.

When these thrips attack the plant, leaves do not develop normally; the folioles become deformed and present chlorotic yellow spots or small and irregular

tears (in the sense of "rip"). The damage done by the thrips' scraping-sucking mouth apparatus to leaves-in-expansion causes them to deform to the point that complete leaf lobes are missing. New leaves are small with deep clefts that run from foliole margins to central nervures.

Brown lesions appear on stems and petioles, corresponding to scars, that is, to cork-like tissue that develop as wounds heal after the insects' scraping. Internodes are also shortened, and terminal growing points may die, inducing the growth of lateral buds, which then undergo attack from the pest. The result is a dwarf plant with a witches'-broom appearance. Thrips mostly attack in the dry seasons, with the affected plants recovering in the rainy season.

Corynothrips stenopterus and Caliothrips masculinus. These two thrips species are considered to be of lesser importance because they prefer the central and lower leaves of the plant. They do not break its apical dominance, thus enabling the plant to develop well. If attack is severe, leaf blades become full of small cork-like wounds that disfigure the plants' general aspect.

Corynothrips stenopterus is yellow with black spots in the last two abdominal segments. This coloring easily distinguishes the insect in the field. *Caliothrips masculinus* has a black body that generally measures 1.0 to 1.5 mm long and less than 1.0 mm wide. It is found on the expanded leaves of young plants, especially in greenhouses or screenhouses. It is rarely observed on field crops.

At CIAT, yield reductions from thrips attacks were studied. Results indicated that thrips can cause yield losses ranging from 15% to 20%, a finding that agrees with the literature. However, in highly susceptible varieties (e.g., 'Chiroza Gallinaza') growing in hot environments such as northern Cauca and Valle del Cauca, thrips attacks can prevent plant development, which, if compounded by weed invasion, will kill the plants (B Arias 1989, pers. comm.).

Some thrips species are fully developed within 15 to 30 days. They pass through four instars, two of which take place in the soil where they do not feed. In one year, they produce five to eight generations (Metcalf and Flint 1972, cited by Tejada 1975).

Control through varietal resistance. The best control method is to plant resistant varieties, which are readily available. Currently, more than 30% of the cassava varieties and hybrids carried by the germplasm bank held at CIAT are highly resistant to thrips attack, with a large percentage presenting symptom, that is, damage, of little consequence (CIAT 1974; Schoonhoven 1974; Arias and Guerrero 2000). Cassava resistance to thrips is based on the villosity of its leaf buds. If leaf pubescence is increased before they are expanded, then resistance to the thrips *F. williamsi* is increased. Such resistance is mechanical (Schoonhoven 1974; Arias and Guerrero 2000).

Cassava mealybugs

More than 15 mealybug species feed on cassava plants in Africa and South America. Species in the Americas include *Phenacoccus herreni*, *P. manihoti*, *P. madeirensis*, *Ferrisia virgata*, and *Pseudococcus mandioca* (Bellotti et al. 1983b; Williams and Granara de Willink 1992). *Phenacoccus herreni* and *P. manihoti* are of tropical origin and are economically important.

Phenacoccus manihoti was introduced into Africa in the early 1970s. The pest spread rapidly, causing considerable losses in crop yields. This motivated the development of a successful biological control program (Herren and Neuenschwander 1991). In the Americas, *P. manihoti* is found in Paraguay, certain areas of Bolivia, and the state of Mato Grosso in Brazil, where it is not economically significant (Lohr and Varela 1990). *Phenacoccus herreni* is dispersed throughout northern South America and Northeast Brazil, where high populations of the insect can cause considerable losses (Bellotti 2000a, 2000b).

Biology and behavior. Both species cause similar damage: feeding nymphs and adults causes leaf yellowing and curling, and a rosette formation in growing points. High populations cause tissue necrosis, defoliation, stem deformation, and bud death. Infested plants also suffer reduced rates of photosynthesis and transpiration, and loss of mesophyll efficiency. Moderate deficits of water pressure occur, and levels of internal CO_2 and leaf temperatures drop (CIAT 1992; Bellotti 2000a, 2000b).

Phenacoccus manihoti is parthenogenic. In contrast, males are needed for *P. herreni* to reproduce. On the underside of leaves and around apical buds, *P. herreni* females deposit ovisacs that contain several hundreds of eggs. The eggs hatch in 6 to 8 days and the insects undergo four nymphal instars, with the fourth instar being the adult. Males, however, have an extra instar. The third and fourth instars occur in a cocoon from which they emerge as winged adults.

Adult males live alone for 2 to 4 days. The female's average life cycle is 49.5 days, whereas that of the male is 29.5 days. The optimal temperature for female development is between 25 and 30 °C (Herrera et al. 1989; Bellotti 2000a, 2000b).

Phenacoccus herreni presents high population peaks during dry seasons. The beginning of the rains reduces these populations, allowing the crop to recover (Herrera et al. 1989). Recent research indicates that, when water supplies are limited, cassava leaves increase the concentrations of certain metabolites, which probably favor mealybug growth and reduce the effectiveness of parasitoids (CIAT 1999; Polanía et al. 1999; Calatayud et al. 2000). These results would help explain the rapid growth of mealybug populations during dry seasons (Bellotti 2000a, 2000b).

Control by varietal resistance. Identifying cassava resistance to the mealybug was hard, involving the evaluation of more than 3000 cultivars held in the germplasm bank at CIAT. Only low levels of resistance or tolerance were identified (Porter 1988). Studies on resistance made by IITA in Africa and by IRD have obtained similar results. Low to weak levels of resistance to *P. manihoti* have also been reported (Le Ru and Calatayud 1994; Neuenschwander 1994a). Such low levels of resistance may therefore require increased use of natural enemies in biological control programs (Bellotti 2000a).

Biological control. Mealybug management is a well-documented example of classical biological control, especially in Africa. *Phenacoccus manihoti* is now successfully controlled by the parasitoid *Apoanagyrus lopezi* after its introduction from the Neotropics. *Phenacoccus herreni* is distributed across northern South America, but only in Northeast Brazil does it cause severe yield losses. The mealybug may be exotic to that region, probably originating from northern South America (Williams and Granara de Willink 1992; Bellotti 2000a).

Numerous species of parasites, predators, and entomopathogens of *P. herreni* have been identified in the Neotropics. Many are generalist predators that feed on numerous species of mealybugs. However, several parasitoids prefer *P. herreni*, including those from northern South America:

Acerophagus coccois
Apoanagyrus diversicornis
Ap. elegeri
Anagyrus putonophilus
An. insolitus
Aenasius vexans

Three encyrtid parasitoids (*Ap. diversicornis, Ac. coccois*, and *Ae. vexans*) were found to be effective for controlling *P. herreni* (Van Driesche et al. 1988, 1990). *Aenasius vexans* and *Ap. diversicornis* noticeably prefer *P. herreni*, although laboratory studies indicate that they also parasitize other species of mealybugs (Bellotti et al. 1983b, 1994; Bertschy et al. 1997). The parasitoid *Ac. coccois* showed equal preference for either *P. herreni* or *P. madeirensis*. The three parasitoids are attracted by infestations of *P. herreni* (Bertschy et al. 1997). Comparative studies of the three parasitoids' life cycles show that each could complete two cycles for every cycle of *P. herreni*, a favorable ratio for biological control.

Apoanagyrus diversicornis prefers third-instar nymphs, while *Ac. coccois*, which is much smaller, parasitizes male cocoons, adult females, and second-instar nymphs with equal frequency. Oviposition of *Ap. diversicornis* caused a 13% mortality rate in third-instar nymphs (Van Driesche et al. 1990). *Aenasius vexans* prefers, with equal frequency, the second and third instars and adult females (CIAT 1990).

Field studies with natural populations of *Ap. diversicornis* and *Ac. coccois* revealed a percentage of parasitism when trap plants were established as hosts of *P. herreni* around the cassava crop (Van Driesche et al. 1988). The combined action of the two parasitoids caused a 55% mortality rate of *P. herreni* (Van Driesche et al. 1990).

Joint efforts by CIAT and EMBRAPA ensured that *Ap. diversicornis, Ac. coccois*, and *Ae. vexans* were exported from CIAT for release in Northeast Brazil, mainly in the states of Bahia and Pernambuco, between 1994 and 1996. Before this introduction, EMBRAPA scientists had conducted field studies to measure pest damage and collect natural enemies. At the end of 1996, more than 35,000 individuals of the three parasitoid species had been released. In Bahia, after release, *Ap. diversicornis* had dispersed up to 130 km in 6 months, 234 km in 14 months, and 304 km in 21 months.

In the same state, *Ac. coccois* also established and was recovered in large numbers at distances of less than 180 km from the release site 9 months later. *Aenasius vexans*, however, was continually recaptured in its site of release in Pernambuco, dispersing only

40 km in 5 months (Bento et al. 1999). Subsequently the authors observed that mealybug populations were noticeably reduced in that region and that the cassava crop was returning to areas that had been abandoned because of *P. herreni* infestations.

Stem-Perforating Insects

Shoot flies

Damage by shoot flies (*Silba pendula* and *Carpolonchaea chalybea*) is found in almost all cassava-producing regions of America. This pest has not been reported in either Africa or Asia.

Damage. Damage caused by larval shoot fly is manifested as a white exudate that flows from the growing point, which then usually dies. The exudates then change color from pale coffee to black as the latex oxidizes and dries up as the terminal point dies. Inside an attacked growing point, several larvae are found, which perforate the first 5 to 7 cm of the plant's terminal point tissue. Hence, the name "shoot fly".

Attacks by this pest delay plant growth and break its apical dominance. This stimulates the development of lateral buds, which may also suffer attack from this fly. Sometimes, only one part of the apical bud dies and the shoot continues growing. The youngest plants are the most susceptible, and repeated attacks may lead to plant dwarfism. In severe outbreaks of the pest, up to 86% of crop plants can be affected.

In studies simulating damage, between 50% and 100% of shoots were cut with a scalpel in each of two sets of plants, one aged 2–5 months, and the other 5–9 months. The late-branching variety M Ecu 150 was more susceptible than the 'Llanera' in the first 2 to 5 months of crop growth, with yields dropping by 30%. Removal of shoots from plants aged 6–9 months did not affect yield in any variety. Other trials in which damage was simulated (Arias and Bellotti 1982) indicated that root yield in variety M Col 22 was not reduced by shoot fly attack. However, an attack on a 3-month-old crop reduced optimal quality of planting stakes by 51% to 71%.

Biology and behavior. The adult fly is black with a metallic blue sheen. The female oviposits among leaves that have not, as yet, initiated expansion and in growing points, perforating a small cavity in the plant tissue with her ovipositor. Up to 22 eggs have been observed in one shoot, although the average is 3 to 8 eggs per shoot. The eggs are shaped like microscopic rice grains and hatch 4 days after oviposition. The young larvae then tunnel into the bud, impeding the meristematic leaves from opening. A milky discharge then appears and the growing point dies. Several whitish larvae can be observed inside the affected terminal point, where they live for about 23 days until they drop to the soil. They then pupate and, about 26 days later, the adult flies emerge. The flies are most active on sunny days, especially affecting cassava crops associated with banana or shade trees.

This pest attacks throughout the year, although, in many non-seasonal areas, they frequently appear at the beginning of the rainy season. At the CIAT–Palmira station, the dry climate favors the development of shoot-fly populations.

Trials that have confirmed a 100% loss of apical buds have not yet provided data on yield losses. Nor have the population dynamics of this pest been studied in detail. For these reasons, shoot fly is considered as a minor pest.

Control. Because this pest does not attack the whole crop and root production is not significantly reduced, the few apical buds found to be infested can be eliminated by hand, thus avoiding unnecessary applications of chemical products. However, when shoot-fly attack occurs early, affects all buds, or populations are high, application of an organophosphorus systemic insecticide is recommended. A mixture of insecticide and sugar solution sprayed onto plants forms an effective bait for controlling adults. Also recommended are traps containing decomposed fruits, casein, or yeast. These attract the insects, which can then be killed with insecticide.

Fruit fly

In Colombia and in America generally, two fruit fly species have been identified as attacking cassava: *Anastrepha manihoti* da Costa Lima and *A. pickeli* da Costa Lima (Diptera: Tephritidae). This observation is the first report of the pest attacking cassava fruit but does not cause significant economic losses. In Colombia, Venezuela, and Central America, fruit flies also cause severe damage to cassava stems.

Biology and behavior. The adult fly is yellowish coffee in color and about 10 mm long. It has transparent wings adorned with yellowish coffee-colored bands, which gives it a showy appearance. The female's abdomen presents a noticeable extension,

corresponding to the ovipositor, whereas the abdomen in the male is rounder.

After oviposition, hatching takes place in the fruit. The larvae perforate and then destroy the developing seed. The infested fruit loses its green color, becomes soft, withers, and finally blackens (CIAT 1976). Damage to fruit is important to plant-breeding programs because seeds developed from crosses or hybridizations are then lost.

If it does not find cassava fruits, the female fruit fly seeks tender tissue on which to deposit her eggs. Such tissue is found in stems of young plants or in the terminal points of adult plants. The eggs are inserted into the tissue and can be recognized by the presence of a respiratory siphon, which looks like a small whitish eyelash that stands up from the stem tissue. Plant tissue around the eggs decomposes and becomes blackish. The whitish larvae that emerge from these eggs soon begin boring into the stems, moving either up or down and forming brown galleries in the stem's pith, which then begins to rot. Sometimes, the bud dies. When the larvae reach the prepupal state, they make orifices in the stems, which are then abandoned as the insects fall to pupate in the soil (Vidal and Marín 1974). Latex then oozes out of these orifices and drips down the length of the stems. The total life cycle of the fruit fly *A. pickeli* averages 39.5 days.

Damage. The damage caused by *Anastrepha* flies is associated with the rot caused by the bacterium *Erwinia carotovora* pv. *carotovora* (Mattos 1977). The bacterium penetrates the plant at oviposition or when the larvae leave to pupate. Other secondary pathogens are also found together with this bacterium.

The association between fruit fly and bacterium is not yet fully understood. Apparently, the bacterium is found on the stem where it lives as an epiphyte. However, it is most unlikely that the fly itself transports the bacterium. On the contrary, the bacterium penetrates the stems through the openings that the larvae have dug in stem tissues under conditions of high humidity. Under favorable conditions of precipitation and humidity, the stems rot (CIAT 1976). Stem rot does not favor larvae. When researchers examined rotten stems, they found that 40% of the larvae had died. Consequently, population increases of the insect may be attributed mostly to infestation of fruits of either cassava or other alternative hosts, and not so much to infestation of stems (Bellotti and Schoonhoven 1978c).

In affected stems, the rotting medulla region is either coffee-colored or brown, changing from pale to dark. Stakes obtained from these stems may lose as much as 16% of their capacity for shooting and may take several weeks to sprout.

Control. At crop establishment, stakes must be selected and only those that have healthy white piths should be planted. The most serious damage coincides with the rainy season, a time during which plants may recover rapidly and thus perhaps not need control measures.

The braconid *Opius* sp. parasitizes the larvae found in fruits by as much as 16%. However, it has not been found parasitizing larvae in stems.

Compared with other tried solutions, McPhail traps, which contain hydrolyzed maize at 2%, capture the most adult fruit flies from developing plants.

When adult populations are very high during the crop's first 3 to 4 months, chemical control may provide an alternative. Fenthion or dimethoate controls this pest well at doses between 2 and 3 mL of p.c. per liter of water. To avoid heavily contaminating the environment, chemical control should be carried out in that small area of the crop from which stakes will be obtained for the next cropping cycle.

Stemborers

The economically most important arthropod stemborers belong to the orders Coleoptera and Lepidoptera. They form a complex that feeds on cassava stems and branches, causing considerable damage to the crop, whether sporadically or locally, or mostly in adult plants. Although global in distribution, stemborers are much more important in the Neotropics, especially in the Latin American countries of Brazil, Colombia, and Venezuela. They tend to be highly specific to cassava, with only a few, reportedly, feeding on alternative hosts. None can be considered as a universal pest. They include the following species:

- The longhorned beetle (*Lagocheirus* spp.) is distributed throughout the entire world, but does not cause severe damage in the field.

- In Brazil, several species of *Coelosternus* (Coleoptera: Curculionidae) have been reported as reducing cassava yields and the quality of planting materials. Damage is usually sporadic

and does not significantly affect yield (Bellotti and Schoonhoven 1978a, 1978b).

- Several lepidopterans and coleopterans attack cassava in Africa, with *Coelosternus manihoti* being considered a pest on that continent.

- Seven species of *Coelosternus* attack cassava in America.

The pests *Coelosternus* spp., *Lagocheirus araneiformis*, and *Chilomima clarkei* are presented below in more detail.

Coelosternus spp. This insect's larvae vary in size and form, according to species. Some measure as long as 30 mm. They are usually white, yellow, or cinnamon, and can be found tunneling into the plants' aerial parts. In susceptible varieties, the cassava plant's stems and branches may break or are reduced to sawdust. During dry seasons, the branches lose their leaves and may die. If infestation is severe, young plants may die. In infested branches, or on the soil below, waste matter and sawdust residues excreted or expelled by the larvae can be found.

The *Coelosternus* female may oviposit anywhere in the cassava plant, although it prefers the tender parts. For example, *C. alternans* oviposits near broken or cut extremes of branches or under the cortex in cavities perforated by the insect with its proboscis. Three days after mating, the *C. granicollis* female will penetrate the stem and oviposit white eggs.

When totally developed, *C. alternans* larvae measure 16 mm long and a maximum of 4 mm wide. Those of *C. tardipes* measure 9 × 2.5 mm. The white or reddish-brown bodies of most of these larvae curve. Their jaws are black. For *C. rugicollis*, only one larva is found per stem, whereas other species may have several larvae per stem. The larval phase lasts from 30 to 69 days. In all species, well-developed larvae pupate within cells they construct in the stem's pith. A pupa can hang within its own cell because one extreme is attached by substances excreted by the larva to the perforation made in the stem. The pupal phase lasts about 1 month.

The adult is a weevil, that is, it has a long proboscis. After emerging from the pupa, it remains in the cell for several days before abandoning the stem. Adults may be 6 (*C. granicollis*) to 12 mm long (*C. alternans* and *C. rugicollis*), and range from pale to dark brown, being almost totally covered with yellowish scales. Adults are active throughout the year, although less so at some sites during cool months.

Lagocheirus araneiformis. This insect (Coleoptera: Cerambycidae) has been found in a diversity of places such as the USA, Caribbean Region, Central and South America, the West Indies, and Indonesia. In Colombia, it is found in most cassava-growing regions and is believed to be the most abundant cerambycid in the country's cacao-growing areas (Villegas 1984). In addition to cacao (*Theobroma cacao*), other host plants include an ornamental plant known as tree spinach (*Cnidoscolus aconitifolius*).

Biology and behavior**.** The adult of this insect has antennae that are longer than its body. Its head, wide and grooved, stands out from between antennal tubercles, which are distant from each other. The *L. araneiformis* body is covered by short, light brown pubescence, with spots due to a darker or whitish pubescence. The elytra present rounded shoulders that darken at the base. Each elytron has two short spiny ribs. Two spots can also be seen on the elytra: one that is more or less triangular with its middle point at the base on the margin; and the other is lateral, darker, and located on each side close to where the elytron joins the body at the third pair of legs.

The female insect has an average body length of 1.64 cm and is 0.69 cm wide. The average male is similar, at 1.60 cm long by 0.72 cm wide. Mouth parts are used for masticating, and the antennae are filiform and light brown in color, and possess 11 segments. These also enable differentiation of sexes in both adults and pupae.

The adult female oviposits in stems and branches at about 2.5 mm below the cortex. She first uses her jaws to open a small perforation with a diameter of about 0.72 mm in the cortex of buds and internodes. She then deposits her egg in either a horizontal or oblique position. The postures adopted are individual and, occasionally, two eggs are placed at an average depth of 1.02 mm. The preoviposition period is usually 9.7 days and that of oviposition is 28.8 days (ranging from 13 to 62). During the latter period, the female lays an average of 150 eggs (ranging from 87 to 202). She prefers to oviposit at night, although 10.2% of eggs are laid during the day (Villegas 1984).

A newly laid egg of *L. araneiformis* is whitish cream, turning yellow by the second day. Close to hatching, one extreme shows a dark coffee-colored spot, which corresponds to the larva's jaws. The egg is elliptical, of hard consistency, and measures 0.76 mm at its equatorial and 2.04 mm at its polar diameters. Incubation takes an average of 3.13 days (ranging from 2 to 6 days).

The larva is apodal, cream in color, and, because of its shape, is often known as *gusano tornillo* in Spanish. The name comes from its compressed and prognathic head, which is adhered to a very wide prothorax that gives the insect a cylindrical appearance. This feature is carried to adulthood, giving rise to its name as *flat-faced longicorn beetle*. The head is dark brown, chitinized, and carries strong jaws. Dorsally, the thorax presents two, chitinized, light brown plates. The abdomen has 10 well-defined segments, with the last one being rounded and smaller. The larva measures 0.3 mm in the first instar, growing to 37 mm by the sixth instar.

Pupae are exarate. When recently formed, pupae are light brown, becoming darker as they develop. When an adult is close to emerging, its sex can be differentiated by its antennae. The male also exhibits, between the fourth and fifth joints, a wisp of hair that is not found in the female, who, in contrast, has two pairs of spinules in the last abdominal segment.

In the field, the life cycle of *L. araneiformis* lasts 86 to 194 days, with an average of 128.2 days. Adult females live an average of 89.7 days and males 91.6 days. In the laboratory, these periods were shorter, at 45.8 and 71.8 days, respectively (Villegas 1984).

Damage. The larvae of *L. araneiformis* move within the stem by using their jaws and contracting their bodies. Recently hatched larvae are located in the cortex on which they feed during the first instar. Second instars partially consume the cortex but also open galleries to tissues lying nearest to the ligneous area, where they begin the third instar. They continue to bore through the stake or stem to its central parts, where the last instars and pupae develop, thus completing their life cycle.

In the field, the pest attacks both recently planted stakes and already developed plants. They also attack planting materials that have been stored for long periods. When recently planted stakes are attacked, the seedlings die or they suffer poor sprouting. In contrast, when already developed plants are attacked, damage is local, usually at the base of the stem, which may provoke lodging if the attack is severe. In plants that have fallen, up to 30 larvae per plant have been found. Larvae also attack roots, forming galleries through which microorganisms can penetrate to cause secondary rots that reduce yields. Plants attacked by *L. araneiformis* are easily recognized in the field by the presence of light brown or reddish brown sawdust, of rough texture, that larvae expel as they bore through stems.

Control. Chemical control of this and all stemborers is difficult. The following farming practices are therefore recommended:

- Harvest residues, which help disseminate the insect, should be collected and burned.
- Biological control of this insect has not yet been found. Hence, one method for regulating adult populations is to place traps made of packages of fresh stakes in the field, thus attracting them and enabling their capture.
- Careful selection of planting stakes.

Chilomima clarkei. This stemborer (Lepidoptera: Pyralidae) is a butterfly whose larvae bore or perforate cassava stems. Recently, this insect has greatly increased its populations in Colombia and Venezuela to become, currently, the most important cassava pest (López et al. 1996). The pest causes root production losses of more than 60% because the stems break, debilitated by the attacks. In Colombia, in the late 1990s, *C. clarkei* became the most important pest in several departments of the Atlantic Coast, destroying planting materials to the point of causing a crisis. The pest disseminated very rapidly through the exchange of stakes from region to region among farmers (B Arias 1985, pers. comm.). In the Colombian Caribbean Region, 85% of planted cassava is attacked by *C. clarkei* (López et al. 1996).

This pest has also been found in Tolima, Huila, Caldas, the two Santanders, the Eastern Plains of Colombia, and the Western Plains of Venezuela. It has also been reported in other countries such as Argentina and Brazil (A Bellotti 1985, pers. comm.). To date, the pest has not been reported in environments at altitudes of more than 400 to 500 m above sea level. It is very important, therefore, that planting materials from these sites are not transported to areas where the pest does not exist, without the necessary precautions being taken or without phytosanitary certification.

Females are nocturnal in habit, and live for 5 to 6 days (males for 4 to 5 days). Oviposition takes place at night on cassava stems, usually near a node or bud, with females laying an average of 229 eggs. The eggs are very small and flat, and difficult to see in the field, as they measure less than 1 mm in diameter. They are laid either individually or in small groups of 2 to 5. They are at first cream in color and, as they mature, take on a pink tinge. The eggs hatch about 6 days later (at 28 °C).

Damage. After hatching, the first-instar larvae feed on the stem cortex or epidermis. These larvae are very mobile, seeking appropriate sites at which to feed, almost always near axillary buds. They form a capsule for protection, living and feeding within it until they reach fourth instar. At each instar, the capsule's tissues stretch. A fine and abundant sawdust can then be observed, unlike for *L. araneiformis*. During fifth instar, the larvae penetrate the stems where they complete the next 6 to 12 instars, pupate, and then emerge as adults (Lohr 1983). The larval states take 32 to 64 days to complete and the pupal state 12 to 17 days.

Populations of *C. clarkei* may be present throughout the year and increase during rainy seasons. Four to six cycles of the pest may occur during a cropping year, potentially increasing damage and making control much more difficult. When the number of perforations made in the stem is already considerable (e.g., more than 20 per stem), the stem could break, reducing the quality and quantity of planting materials. In the field, plants with more than 35% of stem parts under attack suffer significant reductions (45% to 62%) in root yields (Lohr 1983).

Control by host-plant resistance. Once the larvae enter the stems, control is very difficult. The capsules woven by the larvae for protection against natural enemies also protects against pesticides. However, the great mobility of first-instar larvae makes them highly vulnerable, which means they can be controlled by entomopathogens such as *Bacillus thuringiensis*. Given the pest's generational increase, several applications will be needed, increasing production costs. Field research conducted by Gold et al. (1990) indicated that intercropping with maize reduces stemborer populations until the maize is harvested.

In Pivijay, Department of Magdalena, nearly 2000 cultivars held in the germplasm bank at CIAT were evaluated during 2 years for varietal resistance to this pest. Significant differences were found among the varieties, where some presented 20 to 30 holes, with a maximum of 70, in six plants; and others an average of one hole per plant, also in six plants. CIAT will continue to assess varieties to tackle the pest through cassava plant resistance.

Biological control. Several biological control agents have also been identified as attacking both eggs and larvae of *Chilomima* sp. Eggs are parasitized by *Trichogramma* microhymenopterans; and larvae by *Bracon* wasps, *Brachymeria conica*, and *Apanteles* sp. (Lohr 1983).

Known control methods were evaluated in the 1980s when research on the pest started. Applications of *Bacillus thuringiensis,* the fungus *Spicaria* sp., and macerated larvae that had died from a probable viral disease were each sprayed over pest larvae, resulting in a mortality rate of 99%, 88%, and 100%, respectively (Herrera 1999). The great mobility of first instars made them much more vulnerable to several products, to the point where they could be controlled with *B. thuringiensis*.

CIAT initiated research to introduce resistance genes to insects, using *B. thuringiensis* through the vector *Agrobacterium* to transform embryonic tissues of cassava, thereby developing cultivars resistant to *C. clarkei*. Initial results are so far promising (CIAT 1999).

Other controls. As mentioned previously, control with insecticides is not practical because adult stemborers are difficult to kill and their larvae feed inside stems. Farming practices that reduce this pest's populations include the removal and burning of infested plant parts and the planting of healthy undamaged stakes (Bellotti et al. 1983a). Other useful practices are to treat the stakes, burn harvest residues, store stakes for short periods, and avoid exchanging stakes between sites. Technical personnel and farmers must also be trained to manage the pest and disseminate the message of how important such management is.

Technicians working in the Colombian Atlantic Coast have evaluated the local use of insecticides to manage *Chilomima* attacks. Among the several pesticides they evaluated, they found that malathion, applied manually with "polyspray" in doses ranging from 0.5 to 1.0 p.c. per liter of water and directly into holes containing sawdust, resulted in 100% larval mortality over time and even prevented the pest's dissemination in the locality (E Ortega 2001, pers. comm.). The practice is interesting because the

applications were not generalized but made specifically at the points, thus favoring both beneficial fauna and the environment. Furthermore, applications were easy to do, although workers must be duly protected.

Cassava burrower bug

Cyrtomenus bergi Froeschner is an arthropod pest that feeds directly from cassava roots. The species is polyphagous and so had not coevolved with the crop. García and Bellotti (1980) first reported this pest attacking cassava in Colombia in 1980.

Distribution and behavior. Recently, the pest was reported as causing commercial damage in Panama, Costa Rica, and Venezuela (Riis 1997). The insect is present in many other Neotropical regions, where it has been found feeding on many crops, including onion, groundnut, maize, potato, *Arachis pintoi* (forage groundnut), sorghum, sugarcane, coffee, coriander, asparagus, beans, peas, some grasses, and several weeds (Riis 1997; Bellotti et al. 1999; Bellotti 2000a, 2000b).

The pest prefers certain host plants to others. Free-choice feeding tests conducted in the laboratory indicated that cassava is not the optimal host. The bug prefers groundnut or maize to cassava (78% vs 22%), growing much faster in maize. The adult life span in maize was 95 days, 69 in onion, 66 in sweet cassava (CMC 40), and 64 days in bitter cassava (M Col 1684) (Riis 1990). Optimal fecundity, survival rate, and intrinsic rate of increase in the population were recorded in groundnut and *Arachis pintoi* but not in maize. Sweet cassava, sorghum, and onion were the least favored hosts. It could not complete its life cycle in bitter cassava varieties (Riis 1997; Bellotti 2000a, 2000b).

Damage. Nymphs and adults of *C. bergi* feed on cassava roots, penetrating the peel and parenchyma with their thin and strong stylets. This feeding action enables several soil pathogens (e.g., fungal species of *Aspergillus, Diplodia, Fusarium, Phytophthora*, and *Pythium*, and the alga *Genicularia* sp.) to enter the root parenchyma (Arias and Bellotti 1985a; Bellotti and Riis 1994) and cause coffee-colored to black lesions that give the insect the Spanish name of *chinche de la viruela* or, literally, "smallpox bug". Lesions begin appearing in roots 24 h after feeding (Arias and Bellotti 1985a). They may lead to reduced starch contents and hence to serious losses in the roots' commercial value. Damage is not detected until the roots are harvested and peeled. Consequently, farmers lose the investment they made in cultivation tasks, time, and use of land.

Populations of *C. bergi* are present in the soil throughout the cropping cycle and damage to roots can be seen within the crop's first month. At the end of the cycle, the bugs may have damaged, through their feeding action, between 70% and 80% of all roots, reducing starch content by more than 50%. Serious economic damage is not necessarily caused by large *C. bergi* populations (Arias and Bellotti 1985a). Riis (1990) showed that, even with very small populations (close to zero), 22% of roots can be affected. The economic threshold, where a cassava buyer would reject a load of roots, is damaged parenchyma in 20% to 30% of roots, that is, when they present "cosmetic" damage due to the dark bite points, which are not acceptable to fresh-cassava markets (Bellotti 2000a, 2000b).

Life cycle. *Cyrtomenus bergi* presents five nymphal instars. The nymphs and adults may live for more than 1 year, feeding on cassava roots (García and Bellotti 1980). In the laboratory, at 23 °C and 65% ± 5% rh, when *C. bergi* was fed slices of cassava root with low levels of cyanide (HCN), its life cycle was 286 to 523 days. On average, eggs took 13.5 days to hatch, the five nymphal states 111.3 days to develop, and the adult life span was 293.4 days.

This bug is strongly attracted to moist soils. It will accordingly migrate when soil moisture content is less than 22% and will remain in soil that has more than 31%. The rainy season therefore enormously favors the survival of adults and nymphs and, thus, their behavior and dispersion. In contrast, low soil moisture content during dry periods will restrict the adults from hiding and migrating, and will increase nymph mortality (Riis 1997; Bellotti 2000a, 2000b).

Effects of cyanogenic glycosides. Field trials and laboratory studies suggest that *C. bergi* feeding preferences may be related to the levels of cyanogenic glycosides in cassava roots, as follows:

- Adults and nymphs that feed on a variety with high HCN content (i.e., more than 100 mg of cyanide [CN^-] per kilogram of roots) experience longer nymphal development, reduced egg production, and increased mortality.

- Oviposition on CMC 40 (43 mg CN^-/kg roots) was 51 eggs per female, compared with only 1.3 eggs on M Col 1684 (627 mg CN^-/kg roots).

- Adult life span on CMC 40 was 235 days, that is, more than double than that on M Col 1684 (112 days) (Bellotti and Riis 1994).

- Riis (1997) demonstrated that oviposition on clones with a cyanogenic potential (CNP) of less than 45 ppm fw was significantly higher than on clones with a CNP of more than 150 ppm. However, the rate changed considerably for clones where the CNP ranged between 45 and 150 ppm.

- Other studies have indicated that early instars are more susceptible than late instars to the roots' CNP. Indeed, the length of the bug's stylet during the first two nymphal instars probably restricts the insect's feeding action mainly to the root peel (Riis 1990; Riis et al. 1995), whereas the third to fifth instars can feed directly from the parenchyma. In cv. CMC 40, cyanogen levels in root parenchyma are low, but high in the peel at 707 mg CN/kg roots. Laboratory experiments in which the bug was fed CMC 40 resulted in a 51% mortality of first- and second-instar nymphs. This rate is high, even when compared with the 82% mortality of similar nymphs fed M Col 1684. Consequently, the high level of cyanogens in the CMC 40 cortex may be responsible for the insect's high mortality (Bellotti and Riis 1994; Bellotti 2000a).

- Studies of preferential feeding conducted in cassava fields in Colombia indicated that the level of damage was considerably higher for CMC 40 (low cyanogen contents) than for M Col 1684. Clone M Mex 59, whose cyanogen content is intermediate at 106 mg CN^-/kg roots, suffered moderate damage (Arias and Bellotti 1985a).

These data indicate that the CNP can impede *C. bergi* survival and that any damage caused should not be a problem when clones with a high CNP value are cultivated (e.g., in Northeast Brazil and Africa) (Bellotti and Riis 1994; Bellotti 2000a).

Control. Controlling *C. bergi* is difficult because of its polyphagous habits and adaptation to soil environments. Measures must be adopted in the crop's initial stages, either at planting or in the first 2 months, when initial damage may occur. The application of a pesticide may reduce pest populations and, thus, the damage. However, frequent applications would be necessary; these would be expensive, environmentally dangerous, and with no guarantee that the economic threshold of loss would be reduced (Castaño et al. 1985).

In cassava crops intercalated with *Crotalaria* sp., damage to roots was reduced to less than 4%, as opposed to monoculture where damage was 61%. However, yields of intercalated cassava were reduced by 22%. Unfortunately, *Crotalaria* sp. has little commercial value and farmers therefore refuse to adopt this technology.

Experimental data and field studies show that varieties with high CNP values are resistant to *C. bergi* attack and the damage it does. However, in many cassava-producing regions, sweet varieties (or those with low CNP) are preferred for fresh consumption. Recent studies indicate that potential for resistance or tolerance of *C. bergi* exists in 15 varieties with low CNP (Riis 1997). To take advantage of this varietal resistance, research needs to be carried out on the pest's behavior and the plant's mechanisms of resistance, both biochemical and genetic.

The potential for biological control of *C. bergi* is being researched. Recent studies with entomopathogenic nematodes and fungal pathogens indicate that they could be used for control. This research has, so far, been conducted only in the laboratory and greenhouse. Field studies must be carried out before the most acceptable technology can be recommended. Promising technologies include:

- The nematode *Steinernema carpocapsae*, which has successfully parasitized *C. bergi* in the laboratory. Infection was established within 5 to 8 days after exposure to the insect. The adult was the most sensitive to infection (58.6% parasitized after 10 days). The least susceptible were the first and second instars, with 17% and 31% parasitized, respectively (Caicedo and Bellotti 1994).

- A native nematode, *Heterorhabditis bacteriophora,* found as a field parasite in Colombia, had an average rate of parasitism at 84% on all instars of the pest (Barberena and Bellotti 1998).

- Isolates of the fungal entomopathogen *Metarhizium anisopliae* parasitizing *C. bergi* were collected in the field. Laboratory studies verified that the mortality rate is 61% for fifth instars, which is much higher than the overall average mortality rate at 33% (CIAT 1994).

Insects that Attack Stems Externally

Scale insects

In most cassava-producing regions, the following species of scale insects have been identified: *Aonidomytilus albus* Cockerell, *Saissetia miranda* Cockerell et Parrott, *Hemiberlesia diffinis* (Newstead), and *Ceroplastes* sp. Scale insects stay on stem surfaces, mostly close to buds, on which they feed. As their reproduction rate increases, the more they invade the stems.

These insects belong to the order Hemiptera, suborder Homoptera, superfamily Coccoidea, family Diaspididae. *Aonidomytilus albus* is commonly known as the white mussel scale, cassava scale, or tapioca scale. Economically, it is considered a major stem-sucking pest.

The family Diaspididae, the largest of the Coccoidea, includes protected scales, which themselves include the different scales that attack cassava. The name "scale" comes from the dense waxy secretion that the adult secretes, adding to the exuviae of the insect's first two nymphal states.

Damage. When a stem is invaded by scale insects, the leaves become yellow and fall. If the attack is severe, plant growth is retarded, stems dry up, and the plant dies. Such damage occurs especially when the attack is early, that is, when the plant is 2 to 3 months old. A generalized attack of scale early in the cropping cycle will seriously affect yields. Attacks occur especially during dry seasons. The greatest damage that scale insects cause is, apparently, the loss of planting materials. Heavily infested stakes produce few shoots (i.e., a low rate of germination), with a resultant deficient development of unpleasant-eating roots. The adult *A. albus* is shaped like a mussel and is covered with a waxy white secretion.

Life cycle. Swaine (1950) studied the biology of *A. albus* in detail. The molted exoskeletons (also called *exuviae*) of the first and second nymphal states are incorporated into the scale. Unlike the females, males have well-developed legs and wings. The female produces, on average, 47 eggs that are oviposited between the upper cover of the scale and the lower cottony secretion. During oviposition, the female drops in size. Eggs hatch 4 days later.

The first nymphal states are mobile and can disperse. One to four days later they become fixed and covered with numerous fine threads. After 11 days, they molt and become immobile. After 4 days, the adult female begins ovipositing 1 to 2 days later. A generation lasts 22 to 25 days.

Scale insects are dispersed by wind, by moving around on the soil, or through infested stakes. The environment in which scale insects spread most readily is the area where stakes are stored, when infested stakes come into contact with healthy ones.

Control. Two highly effective farming practices control scale insects: planting stakes that are not infested and burning infested plants to prevent dissemination. Biological control agents include the following:

- *Chilocorus distigma* (Coccinellidae), preys on *A. albus*.
- In Cuba, two hymenopterans have been reported (Aphelinidae) as parasitizing *A. albus*: *Aspidiophagus citrinus* and *Signiphora* sp. A brown, sponge-like fungus (*Septobasidium* sp.) was also found attacking *A. albus*.
- In Colombia, *Saissetia miranda* was found being parasitized by two microhymenopterans—*Anagyrus* sp. and *Scutellista* sp.—at a level of more than 79%.

Gall fly

In the Americas, several species of gall fly have been reported on the cassava crop, the most frequent of which is *Jatrophobia brasiliensis* Rubs. (Diptera: Cecidomyiidae). This small fly is usually found on the underside of leaves, where it lays its eggs. The tiny larvae leave the egg and penetrate the leaf mesophyll, provoking a defense reaction that is manifested as an abnormal growth (hypergrowth) of the leaf cells, giving its name *cassava leaf gall*.

Leaf galls are found on the upper leaf surface. They range in color from yellow to red, depending on the cassava variety, and are narrower at the base and are often curved. They measure up to 1 cm long and 0.5 mm wide. When a gall is opened, a cylindrical tunnel, containing a small yellow larva, is found. At the base of the gall, on the underside, the tunnel is connected to a small hole from which the adult emerges.

The gall fly is believed to have little economic importance and that it usually does not need to be controlled. In some regions of Colombia and Venezuela, galls are found almost as clusters on certain leaves and, in isolated cases, small plants are heavily attacked. To reduce a population of this fly, collecting and destroying affected leaves at weekly intervals is recommended.

Pests of Dried Stored Cassava

Storage of dried cassava started in Colombia in 1981 when a project of natural cassava drying was established in the country's Atlantic Coastal Region. Before then, farmers handled a highly perishable product that, after 2 days, was no longer adequate for human consumption or animal feed. In contrast, dried cassava provides a more stable product (Román 1983). However, storage conditions sometimes permit flour and dried cassava pieces and chips to deteriorate through the action of biological factors, including insect attack (Piedrahíta 1986). Pests of stored dried cassava not only reduce their quality but also consume significant quantities of this product.

Damaging species

Two principal species infest cassava chips: *Rhyzopertha dominica* and *Lasioderma serricorne*. They infest cassava during sun-drying. After 2 months of storage, the total weight of stored pieces may drop by as much as 16% (Motta 1994). Parker and Booth (1979) reported that, in Malaysia, the most abundant insects in a trial on stored dried cassava pieces were *Sitophilus zeamais*, *Cryptolestes klapperichi*, *Rhyzopertha dominica*, *Tribolium castaneum*, *Stegobium paniceum*, *Dinoderus minutus*, and *Latheticus oryzae*. For the most part, damage occurred to dried cassava imported from Asia or Africa.

CIAT scientists (CIAT 1983a) reported 38 insect species, mainly Coleoptera, in cassava flakes or other dried products. Many were polyphagous. In cassava flour, four species were found: *Tribolium castaneum, Lasioderma serricorne, T. confusum*, and *Rhyzopertha dominica*. In cassava pieces, three species were found: *T. castaneum, Araecerus fasciculatus*, and *L. serricorne*.

Tribolium castaneum H.

At CIAT, scientists studied *T. castaneum* H, also known as the red cassava weevil, which often causes serious damage, both as larvae and as adults. This pest enables other species to degrade stored dried cassava even further, causing losses in weight and quality.

Biological cycle. The total duration of the life cycle is 67.6 days at 25 °C and 56.6 days at 30 °C. At 20 °C, the larva does not completely develop. The egg incubates for an average 3.4 and 14 days, respectively, for the same temperatures. The average oviposition period for a group of five females was 60, 95, and 104 days at temperatures of 20, 25, and 30 °C, respectively. The average numbers of fertile eggs at temperatures of 20, 25, and 30 °C were, respectively 70, 217, and 214. The rate of oviposition per female was 0.16, 0.39, and 0.44 eggs per day, at the same respective temperatures (Motta 1994).

Damage. The red weevil feeds on cassava dried pieces, turning them into powder and so causing economic losses. It also infests flour, with losses being more moderate than for dried pieces. However, product contamination is inevitable, degrading product quality.

- In flour, an initial infestation of 50 adult insects per kilogram resulted in losses that ranged between 0.212% at 20 days and 0.875% at 90 days.

- In dried pieces, an initial infestation of 70 adult insects per kilogram resulted in losses that ranged between 0.462% at 30 days and 3.1% at 90 days (Motta 1994).

Evaluations of the type of packaging used to store dried cassava pieces and cassava flour have given interesting results: for example, polyethylene bags better preserve the quality of both pieces and flour than cloth bags or sisal sacks.

Control and management. Practices that control dried-cassava pests are the same as those applied to pests of stored grains. In both cases, the pests are the same and storage is usually under the same conditions.

The most effective measures for sanitary control are to clean and disinfect the storerooms before storage, rapid removal of infested material, and as short a storage as possible, preferably less than 3 months.

Bitter cassava varieties are more resistant than sweet varieties to these weevils, although this observation has yet to be confirmed. Fumigation is also effective for controlling these pests, provided that all the safety standards are met to guarantee success of the control operation.

Integrated System of Pest Control

Cassava is an ideal crop for developing a program of biological pest control because its vegetative phase (from 8 to 14 months) is long. The basic principles of such a program include:

- Ready availability of some resistance to pests, although high levels of resistance are not required.
- Inclusion of the insect–plant–environment interaction, as rainfall appears to be a key factor.
- Availability of agronomic practices (e.g., selection of planting materials and crop rotation) that will reduce pest incidence.
- Rational use of insecticides, only when strictly necessary.
- Avoidance of indiscriminate use of insecticides to prevent their interrupting established biological control programs.

Researchers are firmly convinced that a program of integrated pest management for the cassava crop should be supported by three actions: biological control, varietal resistance, and farming practices. Each will play an important role in the future.

References

The following acronyms are used to save space:

CIAT = Centro Internacional de Agricultura Tropical
SOCOLEN = Sociedad Colombiana de Entomología

Allem AC. 1994. The origin of *Manihot esculenta* Crantz (Euphorbiaceae). Genet Resour Crop Evol 41(3):133–150.

Angel JC; Pineda BL; Nolt B; Velasco AC. 1990. Moscas blancas (Homoptera: Aleyrodidae) asociadas a transmisión de virus en yuca. Fitopatol Colomb 13:65–71.

Arias B. 1995. Estudio sobre el comportamiento de la "mosca blanca" *Aleurotrachelus socialis* Bondar (Homoptera: Aleyrodidae) en diferentes genotipos de yuca, *Manihot esculenta* Crantz. MSc thesis. Universidad Nacional de Colombia–Palmira, Colombia. 181 p.

Arias B; Bellotti AC. 1977. Eficiencia de *Bacillus thuringiensis* sobre el gusano cachón de la yuca (*E. ello*), en un programa de control biológico. Rev Colomb Entomol 3(3/4):93–97.

Arias B; Bellotti AC. 1982. Daño simulado de la mosca del cogollo, *Silba pendula* Bezzi (Diptera: Loncheidae), en yuca (*Manihot esculenta* Crantz). In: Abstracts [of the] Proc IX Congress of SOCOLEN, Cali, Colombia. SOCOLEN, Bogotá, DC, Colombia. 9 p.

Arias B; Bellotti AC. 1983. *Phoenicoprocta sanguinea* (Lepidoptera: Ctenuchidae): Ciclo de vida y enemigos naturales. In: Abstracts [of the] Proc X Congress of SOCOLEN, Cali, Colombia. SOCOLEN, Bogotá, DC, Colombia.

Arias B; Bellotti AC. 1985a. Aspectos ecológicos y de manejo de *Cyrtomenus bergi* Froeschner, chinche de la viruela en el cultivo de la yuca (*Manihot esculenta* Crantz). Rev Colomb Entomol 11(2):42–46.

Arias B; Bellotti AC. 1985b. Ciclo biológico de *Erinnyis ello* (gusano cachón de la yuca) a diferentes temperaturas. In: Abstracts [of the] Proc VI Congress of SOCOLEN, Manizales, Colombia. SOCOLEN, Bogotá, DC, Colombia.

Arias B; Bellotti AC. 2001. Ciclo biológico, comportamiento e importancia económica de *Amblystira machalana* Drake (Hemiptera: Tingidae), la chinche negra de encaje, en el cultivo de la yuca. In: Abstracts [of the] Proc XXVIII Congress of SOCOLEN. SOCOLEN, Bogotá, DC, Colombia.

Arias B; Guerrero JM. 2000. Control de plagas de la yuca (*Manihot esculenta* Crantz) por resistencia varietal. In: Symposium on "Avances en el Manejo de Plagas". Proc XXVII Congress of SOCOLEN, Medellín, Colombia, July 2000. SOCOLEN, Bogotá, DC, Colombia. p 243–259.

Barberena MF; Bellotti AC. 1998. Parasitismo de dos razas del nemátodo *Heterorhabditis bacteriophora* sobre la chinche *Cyrtomenus bergi* (Hemiptera: Cydnidae) en el laboratorio. Rev Colomb Entomol 24(1/2):7–11.

Bellotti AC. 2000a. El manejo integrado de las principales plagas de la yuca (*Manihot esculenta* Crantz). In: Proc. Primer Curso-Taller Internacional sobre Control Biológico, held at the Corporación Colombiana de Investigación Agropecuaria (CORPOICA), Palmira, Valle, Colombia. Produmedios, Bogotá, DC, Colombia. p 210–243.

Bellotti AC. 2000b. Las plagas principales del cultivo de la yuca: Un panorama global. In: Symposium on "Avances en el Manejo de Plagas". Proc XXVII Congress of SOCOLEN, Medellín, Colombia, July 2000. SOCOLEN, Bogotá, DC, Colombia. p 189–217.

Bellotti AC; Arias B. 1988. Manejo integrado de *Erinnyis ello* (L.). CIAT, Cali, Colombia. 24 p.

Bellotti AC; Riis L. 1994. Cassava cyanogenic potential and resistance to pests and diseases. Acta Hortic 375:141–151.

Bellotti AC; Schoonhoven A van. 1978a. Cassava pests and their control. CIAT, Cali, Colombia. 71 p.

Bellotti AC; Schoonhoven A van. 1978b. Mite and insect pests of cassava. Annu Rev Entomol 23(1):39–67.

Bellotti AC; Schoonhoven A van. 1978c. Plagas de la yuca y su control. CIAT, Cali, Colombia. 71 p.

Bellotti AC; Reyes Q JA; Arias V B. 1983a. Manejo de plagas en yuca. In: Reyes JA, ed. Yuca: Control integrado de plagas. CIAT, Cali, Colombia. p 265–281.

Bellotti AC; Reyes JA; Varela AM. 1983b. Observaciones de los piojos harinosos de la yuca en las Américas; Su biología, ecología y enemigos naturales. In: Reyes JA, ed. Yuca: Control integrado de plagas. CIAT, Cali, Colombia. p 313–339.

Bellotti AC; Vargas H, O; Peña JE; Arias V, B. [1983c]. Pérdidas en rendimiento en yuca causadas por insectos y ácaros. In: Domínguez CE, ed. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (PNUD), Cali, Colombia. p 393–408.

Bellotti AC; Mesa N; Serrano M; Guerrero JM; Herrera CJ. 1987. Taxonomic inventory and survey activities for natural enemies of cassava green mites in the Americas. Insect Sci Appl 8(4/5/6):845–849.

Bellotti AC; Arias B; Guzmán OL. 1992. Biological control of the cassava hornworm *Erinnyis ello* (Lepidoptera: Sphingidae). Fla Entomol 75:506–515.

Bellotti AC; Braun AR; Arias B; Castillo JA; Guerrero JM. 1994. Origin and management of Neotropical cassava arthropod pests. Afr Crop Sci J 2(4):407–417.

Bellotti AC; Smith L; Lapointe SL. 1999. Recent advances in cassava pest management. Annu Rev Entomol 44:343–370.

Bento JMS; Bellotti AC; Castillo JA; de Morães, GJ; Lapointe SL; Warumby JF. 1999. Introduction of parasitoids for control of cassava mealybugs in northeastern Brazil. Bull Entomol Res 89(5):403–410.

Bertschy C; Turlings TCL; Bellotti AC; Dorn S. 1997. Chemically-mediated attraction of three parasitoid species to mealybug-infested cassava leaves. Fla Entomol 80(3):383–395.

Blair MW; Fregene MA; Beebe SE; Ceballos H. 2007. Marker-assisted selection in common beans and cassava. In: Guimarães EP; Ruane J; Scherf BD; Sonnino A; Dargie JD, eds. Marker-assisted selection: current status and future perspectives in crops, livestock, forestry and fish. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. p 81–115.

Bohórquez C, A. 2011. Aislamiento de secuencias expresadas diferencialmente durante la respuesta de defensa al ataque de la mosca blanca (*Aleurotrachelus socialis*) en el cultivo de yuca (*Manihot esculenta* Crantz) mediante genómica funcional. Dissertation. Universidad Nacional de Colombia-Palmira, Colombia.

Braun AR; Bellotti AC; Guerrero JM; Wilson LT. 1989. Effect of predator exclusion on cassava infested with tetranychid mites (Acari: Tetranychidae). Environ Entomol 18(4):711–714.

Braun AR; Bellotti AC; Lozano JC. 1993. Implementation of IPM for small-scale cassava farmers. In: Altieri MA, ed. Crop protection strategies for subsistence farmers, Westview, Boulder, CO, USA. p 103–115.

Byrne DH; Guerrero JM; Bellotti AC; Gracen VE. 1982. Yield and plant growth responses of *Mononychellus* mite resistant and susceptible cassava cultivars under protected vs. infested conditions. Crop Sci 22(5–6):486–550.

Byrne DH; Bellotti AC; Guerrero JM. 1983. The cassava mites. Trop Pest Manage 29(4):378–394.

Caicedo AM; Bellotti AC. 1994. Evaluación Del potencial del nemátodo entomógeno *Steinernema carpocapsae* Weiser (Rhabditida: Steinernematidae) para el control de *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae) en condiciones de laboratorio. Rev Colomb Entomol 20(4):241–246.

Castaño O; Bellotti AC; Vargas O. 1985. Efecto del HCN y de cultivos intercalados sobre daño causado por la chinche de la viruela *Cyrtomenus bergi* Froeschner al cultivo de la yuca. Rev Colomb Entomol 11(2):24–26.

Castillo J. 1996. Moscas blancas (Homoptera: Aleyrodidae) y sus enemigos naturales sobre cultivos de yuca (*Manihot esculenta* Crantz) en Colombia. MSc thesis. Universidad del Valle, Cali, Colombia. 173 p.

CGP. 2009. Cassava Genome Project. Available at http://www.phytozome.net/cassava

CIAT. 1974. Informe anual [del] Programa de Yuca 1973. Cali, Colombia. 287 p.

CIAT. 1976. Sistema de producción de yuca. In: Informe anual 1975. Cali, Colombia. p B1–B59.

CIAT. 1978. Sistema de producción de yuca. In: Informe anual 1977. Cali, Colombia. p C03–C29.

CIAT. 1983a. Almacenamiento de raíces frescas de yuca: Guía de estudio para ser usada como complemento de la unidad audiotutorial sobre el mismo. Cali, Colombia. 35 p.

CIAT. 1983b. Yuca: Bol Info (Cali, Colombia) 1:1–7.

CIAT. 1989. Manejo integrado de *Erinnyis ello* (L.) gusano cachón de la yuca: Guía de estudio, 3a. ed. Cali, Colombia. 62 p.

CIAT. 1990. Annual report [of the] Cassava Program, 1989. Cali, Colombia. 385 p.

CIAT. 1992. Annual report [of the] Cassava Program, 1987–1991. Cali, Colombia. 475 p.

CIAT. 1994. Annual report [of the] Cassava Program, 1993. Cali, Colombia. 325 p.

CIAT. 1995. Annual report [of the] Cassava Program, 1994. Cali, Colombia. p 144–163.

CIAT. 1999. Annual report: integrated pest and disease management in major agroecosystems. Cali, Colombia. 136 p.

D'Almeida YA; Lys JA; Neuenschwander P; Ajuonu O. 1998. Impact of two accidently introduced *Encarsia* species (Hymenoptera: Aphelinidae) and other biotic and abiotic factors on the whitefly *Aleurodicus dispersus* (Russell) (Homoptera: Aleyrodidae) in Benin. Biocontrol Sci Technol 8(1):163–173.

De Morales GJ; de Alencar JA; Wenzel-Neto F; Mergulhão SMR. 1990. Explorations for natural enemies of the cassava green mite en Brazil. In: Proc 8th Symposium International Society of Tropical Root Crops, Bangkok, October 1988. Thai Department of Agriculture; CIAT; Centro Internacional de la Papa (CIP), Bangkok, Thailand. p 351–353.

Delalibera Jr, I; Sosa-Gómez DR; de Morães GJ; Alencar JA; Farias-Araujo W. 1992. Infection of the spider mite *Mononychellus tanajoa* (Acari: Tetranychidae) by the fungus *Neozygites* sp. (Entomophthorales) in Northeast Brazil. Fla Entomol 75(1):145–147.

Dulong R. 1971. Le manioc á Madagascar. Agron Trop 26(8):791–829.

Evans GA; Castillo JA. 1998. Parasites of *Aleurotrachelus socialis* (Homoptera: Aleyrodidae) from Colombia, including descriptions of two new species (Hymenoptera: Aphelinidae: Platygasteridae). Fla Entomol 81(2):171–178.

Farias ARN. 1990. Especies de "mosca blanca": Situação atual e perspective de controle. Centro Nacional de Pesquisa em Mandioca e Fruticultura (CNPMF) of the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Cruz das Almas, BA, Brazil. 9 p.

Farias ARN. 1994. Flutuação poblacional de *Aleurothrixus aepim* em mandioca, em São Miguel das Matas, Bahia. Rev Bras Mandioca 13:119–122.

Farias ARN; Sousa JDS; Siweira JRS. 1991. Flutuação populacional de *Bemisia tuberculata* em mora, Gogipe, Bahia. Rev Bras Mandioca 10(1–2):103–107.

Ferreira CF; Alves E; Pestana KN; Junghans DT; Kobayashi AK; Santos VD; Silva RP; Silva PH; Soares E; Fukuda W. 2008. Molecular characterization of cassava with yellow-orange roots for beta-carotene improvement. Crop Breed Appl Biotechnol 8:23–29.

FIDAR (Fundación para la Investigación y el Desarrollo Agrícola). 1998. Reconocimiento e identificación de chisas rizófagas del cultivo de yuca en la zona de ladera del norte del Departamento del Cauca. Folleto divulgativo. FIDAR–PRONATA, Cali, Colombia. 12 p.

França FH; Villas-Boos GL; Branco MC. 1996. Occurrence of *Bemisia argentifolli* Bellow & Perring (Homoptera: Aleyrodidae) in the Federal District. An Soc Entomol Bras 25(2):369–372.

Fregene M; Angel F; Gómez R; Rodríguez F; Chavarriaga P; Roca W; Tohme J; Bonierbale M. 1997. A molecular genetic map of cassava (Manihot esculenta Crantz). Theor Appl Genet 95:431–441.

Frison EA; Feliu E, eds. 1991. Technical guidelines for the safe movement of cassava germplasm. Food and Agriculture Organization of the United Nations (FAO); International Board of Plant Genetic Resources (IBPGR), Rome. 48 p.

Froeschner RC. 1993. The Neotropical lace bugs of the genus *Vatiga* (Heteroptera: Tingidae), pests of cassava: new synonymies and key to species. In: Proc Entomol Soc Wash 95(3):457–462.

García CA; Bellotti AC. 1980. Estudio preliminar de la biología y morfología de *Cyrtomenus bergi* Froeschner: Nueva plaga de la yuca. Rev Colomb Entomol 6(3–4):55–61.

Gold CS. 1993. Effects of cassava intercropping and varietal mixtures on herbivore load, plant growth, and yield: applications for small farmers in Latin America. In: Altieri MA, ed. Crop protection strategies for subsistence farmers. Westview, Boulder, CO, USA. p 117–142.

Gold CS; Altieri MA; Bellotti AC. 1989. Cassava intercropping and pest management: a review illustrated with a case study from Colombia. Trop Pest Manage 35(4):339–344.

Gold CS; Altieri MA; Bellotti AC. 1990. Effects of intercropping and varietal mixtures on the cassava hornworm, *Erinnyis ello* L. (Lepidoptera: Sphingidae), and the stemborer, *Chilomima clarkei* (Amsel) (Lepidoptera: Pyralidae), in Colombia. Trop Pest Manage 36(4):362–367.

Gold CS; Altieri MA; Bellotti AC. 1991. Survivorship of the cassava whiteflies, *Aleurotrachelus socialis* and *Trialeurodes variabilis* (Homoptera: Aleyrodidae) under different cropping systems in Colombia. Crop Prot 10:305–309.

Herren HR; Neuenschwander P. 1991. Biological control of cassava pests in Africa. Annu Rev Entomol 36:257–283.

Herrera CJ. 1999. Manejo integrado de plagas en el cultivo de la yuca. Paper presented at the seminar-workshop "Hacia una producción bioracional de la yuca", held by PMD, IICA, and BIOCARIBE S.A. at Pivijay, Carmen de Bolívar, February 1999. 45 p.

Herrera CJ; Van Driesche RG; Bellotti AC. 1989. Temperature dependent growth rates for the cassava mealybug, *Phenacoccus herreni*, and two of its encyrtid parasitoids, *Epidinocarsis diversicornis* and *Acerophagus coccois* in Colombia. Entomol Exp Appl 50:21–27.

Hershey CH. 1987. Cassava germplasm resources. In: Proc Cassava breeding: a multidisciplinary review, held at Manila, the Philippines, March 1985. CIAT, Cali, Colombia. p 1–24.

Janzen DH. 1986. Biogeography of an exceptional place: what determines the saturniid and sphingiid moth fauna of Santa Rosa National Park, Costa Rica, and what does it mean to conservation biology? Brenesia 25/26:51–87.

Janzen DH. 1987. When and when not to leave. Oikos 49:241–243.

Laberry R. 1997. La aplicación de un programa MIP en producción industrial de yuca. In: Proc Congreso Biodiversidad y Micorrizas. CIAT; Asociación Colombiana de Fitopatología y Ciencias Afines, Cali, Colombia. p 136–137.

Lal SS; Pillai KS. 1981. Cassava pests and their control in southern India. Trop Pest Manage 27(4):480–491.

Le Ru B; Calatayud PA. 1994. Interactions between cassava and arthropod pests. Afr Crop Sci J 2(4):419–421.

Leefmans S. 1915. De cassave-Oerets, vol 13. Mededeelingen van het Laboratorium voor Plantenziekten, Java departement van landbow, Bogor, Indonesia. 120 p.

Leihner DE. 1983. Management and evaluation of intercropping systems with cassava. CIAT, Cali, Colombia. 700 p.

Lohr B. 1983. Biología, ecología, daño económico y control de *Chilomima clarkei* barrenador de la yuca. In: Reyes JA, ed. Yuca: Control integrado de plagas. CIAT, Cali, Colombia. p 159–161.

Lohr B; Varela AM. 1990. Exploration for natural enemies of the cassava mealybug, *Phenacoccus manihoti* (Homoptera: Pseudococcidae), in South America for the biological control of this introduced pest in Africa. Bull Entomol Res 80:417–425.

Londoño M. 1999. Complejo de chisas en Colombia y perspectivas para su manejo. In: Proc XXVI Congress of SOCOLEN, Bogotá, July 1999. SOCOLEN, Bogotá, DC, Colombia.

Londoño M; De los Ríos ML. 1997. Efectos de diferentes agentes de control biológico sobre *Phylophoga obsoleta* y *Anomatha undulata* (Coleoptera: Melolonthidae). In: Antecedentes entomológicos para comprender los insectos: Estudiarlos, GEUN, SOCOLEN, Universidad Nacional–Medellín. Sociedad Colombiana de Entomología, Bogotá, DC, Colombia. p 35–42.

López V, OA; Díaz S, OE; Suárez G, HD; Tolosa P, A. 1996. El barrenador del tallo de la yuca *Chilomima clarkei* (Lepidoptera: Pyralidae) en el CRECED Provincia del Río. Corporación Colombiana de Investigación Agropecuaria (CORPOICA), Bogotá, Colombia 12 p.

Maddison P. 1979. Pests associated with cassava in the Pacific regions: Auckland Pacific Islands pest survey. Entomology Division, Department of Scientific & Industrial Research, Auckland, New Zealand. 16 p.

Magoon ML; Krishnan R; Bai KV. 1969. Morphology of the pachytene chromosomes and meiosis in Manihot esculenta Crantz. Cytologia 34:612–626.

Marín Colorado JA; Ramírez H; Fregene M. 2009. Mapeo genético y análisis de QTL para carotenos en una población S1 de yuca = Genetic mapping and QTL analysis for carotenes in a S1 population of cassava. Acta Agron (Palmira) 58(1):15–21.

Mattos L. 1977. Bacteriosis del tallo de la yuca. MSc thesis. Faculty of Agricultural Sciences, Universidad Nacional Agraria La Molina, Lima, Peru. 83 p.

Morgante M; Salamini F. 2003. From plant genomics to breeding practice. Curr Opin Biotechnol 14:214–219.

Motta E, JC. 1994. Biología y comportamiento alimenticio del gorgojo rojo de la harina *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), en yuca seca almacenada. Thesis. Universidad Nacional–Palmira, Colombia.

Múnera S, DF; De los Ríos TJ. 1999. Patogenicidad sobre *Erinnyis ello* (L) en condiciones de laboratorio de hongos entomopatógenos recolectados en cultivos comerciales de yuca *Manihot esculenta* Crantz. Rev Colomb Entomol 25(3/4):161–167.

Munthali DC. 1992. Effect of cassava variety on the biology of *Bemisia afer* (Priesner & Hosny) (Hemiptera: Aleyrodidae). Insect Sci Appl 13(3):459–465.

Neuenschwander P. 1994a. Control of cassava mealybug in Africa: lessons from a biological control project. Afr Crop Sci J 2:369–383.

Neuenschwander P. 1994b. Spiralling whitefly *Aleurodicus dispersus*, a recent invader and new cassava pest. Afr Crop Sci J 2(4):419–421.

Nyiira ZM. 1972. Report of investigation of cassava mite, *Mononychellus tanajoa* Bondar. Kawanda Research Station, Kampala, Uganda. 14 p. (Typescript.)

Ogunjobi AA; Fagade OE; Dixon AGO. 2006. Molecular variation in population structure of Xanthomonas axonopodis pv manihotis in the south eastern Nigeria. Afr J Biotechnol 5:1868–1872.

Ortega GA. 2000. Determinación de la efectividad de *Encarsia hispida* De Santis (Hymenoptera: Aphelinidae) como parasitoide de "mosca blanca" de la yuca, *Aleurotrachelus socialis* Bondar (Homoptera: Aleurodidae), bajo condiciones de invernadero. Thesis. Universidad Nacional–Palmira, Colombia. 89 p.

Parker BL; Booth RH. 1979. Storage of cassava chips (*Manihot esculenta*): insect infestation and damage. Exp Agric 15(2):145–153.

Piedrahíta C. 1986. Empaque y almacenamiento de harina de yuca. Progress report. Proyecto U.V. IIT-CIID.

Polanía MA; Calatayud PA; Bellotti AC. 1999. Comportamiento alimenticio del piojo harinoso *Phenacoccus herreni* (Sternorhyncha: Pseudicoccidae) e influencia del déficit hídrico en plantas de yuca sobre su desarrollo. Rev Colomb Entomol 26(1/2):1–9.

Porter RI. 1988. Evaluation of germplasm (*Manihot esculenta* Crantz) for resistance to the mealybug (*Phenacoccus herreni* Cox and Williams). Dissertation. Cornell University, Ithaca, NY, USA. 117 p.

Renvoize BS. 1973. The area of origin of *Manihot esculen*ta, as a crop plant: a review of the evidence. Econ Bot 26:352–360.

Riis L. 1990. The subterranean burrowing bug *Cyrtomenus bergi* Froeschner, an increasing pest in tropical Latin America: behavioral studies, population fluctuations, botanical control, with special reference to cassava. MSc thesis. Zoology Section of the Institute of Ecological and Molecular Biology, Royal Veterinary and Agricultural University, Copenhagen, Denmark. 167 p.

Riis L. 1997. Behaviour and population growth of the burrower bug, *Cyrtomenus bergi* Froeschner: effects of host plants and abiotic factors. Dissertation. Royal Veterinary and Agricultural University, Copenhagen, Denmark. 167 p.

Riis L; Bellotti AC; Vargas O. 1995. The response of a polyphagous pest (*Cyrtomenus bergi* Froeschner) to cassava cultivars with variable HCN content in root parenchyma and peel. In: Proc Second International Scientific Meeting of the Cassava Biotechnology Network, Bogor, Indonesia, Aug 1994. CIAT, Cali, Colombia. p 501–509.

Román A. 1983. Secado natural, una solución al mercadeo de la yuca. Yuca Bol Inf 7(1):57–88.

Sánchez D; Bellotti AC. 1997a. Evaluación de la patogenicidad de hongos *Hyphomycetes* sobre mosca blanca de la yuca *A. socialis.* Report of the Convenio Cooperativo CIAT-COLCIENCIAS, Programa COLCIENCIAS-BID para jóvenes investigadores. 20 p.

Schoonhoven A van. 1974. Resistant to thrips damage in cassava. J Econ Entomol 67(6):728–730.

Skovgard H; Tomkiewicz J; Nachman G; Münster-Swendsen M. 1993. The effect of the cassava green mite *Mononychellus tanajoa* on the growth and yield of cassava *Manihot esculenta* in a seasonally dry area in Kenya. Exp Appl Acarol 17(1/2):41–58.

Smith L; Bellotti AC. 1996. Successful biocontrol projects with emphasis on the Neotropics. In: Proc Cornell Communications Conference on Biological Control, held at Cornell University, April 1996. Cornell University Press, Ithaca, NY, USA. 12 p.

Swaine G. 1950. The biology and control of the cassava scale. East Afr Agric J 16:90–93.

Tejada GAP. 1975. Identificación morfológica y algunos aspectos ecológicos de tres especies de trips, en variedades resistentes y susceptibles de yuca (*Manihot esculenta* Crantz). Thesis. Faculty of Agricultural Sciences, Universidad Nacional–Palmira, Colombia. 83 p.

Thresh JM; Fargette D; Otim-Nape GW. 1994. Effects of African cassava mosaic geminivirus on the yields of cassava. Trop Sci 34:26–42.

Urías-López, MA; Bellotti AC; Bravo M, H; Carrillo S, JL. 1987. Impacto de insecticidas sobre tres parasitoides de *Erinnyis ello* (L.), gusano de cuerno de la yuca. Agrociencia 67:137–146.

Van Driesche RG; Castillo JA; Bellotti AC. 1988. Field placement of mealybug-infested potted cassava plants for the study of parasitism of *Phenacoccus herreni*. Entomol Exp Appl 46:117–123.

Van Driesche RG; Bellotti AC; Castillo JA; Herrera CJ. 1990. Estimating total losses from parasitoids for a field population of a continuously breeding insect, cassava mealybug, *Phenacoccus herreni* (Homoptera: Pseudococcidae) in Colombia, SA. Fla Entomol 73(1):133–143.

Vargas O; Bellotti AC. 1981. Pérdidas en rendimiento causadas por moscas blancas en el cultivo de la yuca. Rev Colomb Entomol 7(1/2):13–20.

Victoria JAT; Pardo LC. 1999. Avances en el estudio de las chisas (Coleoptera: Melolonthidae) observadas en la rizosfera de yuca y otros cultivos en tres municipios del Cauca, Colombia.

Vidal JG; Marín H. 1974. Identificación y ciclo biológico de un díptero barrenador de la yuca (*Manihot esculenta* Crantz). Thesis. Faculty of Agricultural Sciences, Universidad Nacional–Palmira, Colombia. 45 p.

Villegas AG. 1984. Biología, morfología, y hábitos de *Lagocheirus araneiformis* Linné (Coleoptera: Cerambycidae) barrenador de la yuca en Palmira, Valle del Cauca. Thesis. Universidad Nacional–Palmira, Colombia. 68 p.

Williams DJ; Granara de Willink MC. 1992. Mealybugs of Central and South America. CAB International, Wallingford, UK. 635 p.

Yaninek JS. 1988. Continental dispersal of the cassava green mite, an exotic pest in Africa, and implications for biological control. Exp Appl Acarol 4:211–224.

Yaninek JS; Animashaun A. 1987. Why cassava green mites are dry season pests. Proc seminar on Agrometeorology crop protection in lowland humid and sub-humid tropics, held by the World Meteorological Organization (WMO) and International Institute of Tropical Agriculture (IITA), Contonou, Benin, July 1986. International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. p 59–66.

Yaninek JS; Herren HR. 1988. Introduction and spread of the cassava greenmite, *Mononychellus tanajoa* (Bondar) (Acari: Tetranychidae), an exotic pest in Africa, and the search for appropriate control methods: a review. Bull Entomol Res 78(1):1–13.

Yaninek JS; Mégev B; de Morães GJ; Bakker F; Braun A. 1991. Establishment of the Neotropical predator *Amblyseius idaeus* (Acari: Phytoseiidae) in Benin, West Africa. Biocontrol Sci Technol 1(4):323–330.

Yaninek JS; Onzo A; Ojo JB. 1993. Continent-wide releases of Neotropical phytoseiids against the exotic cassava green mite in Africa. Exp Appl Acarol 17(1/2):145–160.

Yaninek JS; Saizonou S; Onzo A; Zannou I; Gnanvossou D. 1996. Seasonal and habitat variability in the fungal pathogens, *Neozygites* cf. *floridana* and *Hirsutella thompsonii*, associated with cassava mites in Benin, West Africa. Biocontrol Sci Technol 6(1):23–33.

CHAPTER 11

Insects and Mites Causing Yield Losses in Cassava*

Anthony C. Bellotti[1], Bernardo Arias V.[2], Octavio Vargas H.[3], and Jorge E. Peña[4]

Introduction

Farmers in the tropics frequently cultivate cassava for subsistence. This crop is regarded as hardy, as it is usually free of arthropod pests. Crop yields have exceeded 70 t/ha in experiments at the Centro Internacional de Agricultura Tropical (CIAT)[5], whereas commercial production in regions of Colombia reaches 40 t/ha. World average, however, is 10 to 15 t/ha. These figures indicate that several factors limit production, including pests as a significant constraint.

Cassava pests include a broad range of arthropods (Bellotti and Schoonhoven 1978a). According to the crop's stage of development in which they attack (crop phenology), pests can be divided into four categories:

- Those that attack planting materials, affecting plants in the field and stored stakes (fruit flies, stemborers, scale insects, white grubs, and cutworms).
- Those that attack the plant during vegetative development (leaf eaters, sap suckers, leaf deformers, and borers that attack stems, branches, and buds).
- Those that attack fresh roots, damaging their culinary and industrial qualities (subterranean burrower bug, mealybugs, and white grubs).
- Those that attack stored dried cassava (weevils attacking flour, cassava chips, and cassava starch).

At CIAT, studies on yield losses have been conducted for over 25 years to help identify research priorities in the Cassava Program. This research has helped determine the true potential that key or primary pests have for causing losses, while at the same time, evaluate the susceptibility, resistance, or tolerance of many cultivars to pest attack. This research was developed in different ecosystems, particularly in sites where the targeted pest is endemic, as in the case of mites in the Atlantic Coast, whiteflies in the Department of Tolima, and mealybugs in the Eastern Plains. This research also confirmed that less important pests, such as fruit fly and shoot fly, do not cause significant production losses even though they may cause noticeable plant damage.

This paper discusses those results and analyzes the possible physiological causes of such reductions. Although pest damage is emphasized, some results on losses caused by poor quality planting materials are also presented. Pests that defoliate or cause other damage over a short period (hornworm, fruit fly, and shoot fly) are compared with long-term pests (mites, thrips, whiteflies, and scale insects) and those that directly attack roots.

Distribution of Significant Pests

The widest diversity of cassava (*Manihot esculenta* Crantz) occurs in the Americas (Bellotti and Schoonhoven 1977; Bellotti 1978), the crop's center of origin. The cassava pests most often reported in the

---

* This document contains information published in the Proceedings of the XXVII Congress of the Sociedad Colombiana de Entomología (SOCOLEN), 2000

1. Emeritus Scientist/Consultant, Entomologist/Agrobiodiversity, IPM, Cassava Program, CIAT, Cali, Colombia. E-mail: a.bellotti@cgiar.org
2. Research Associate, Plant Production, IPM, Cassava Program, CIAT. E-mail: bernaarias1@gmail.com
3. Entomologist, FEDEARROZ, Bogotá, DC, Colombia.
4. Entomologist, University of Florida, Homestead, FL, USA. E-mail: jepe@mail.ifas.ufl.edu

5. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Americas are hornworm (*Erinnyis ello* L.); thrips (*Frankliniella williamsi* Hood and *Scirtothrips, manihoti)*; lace bugs (*Vatiga manihotae* Drake, *V. illudens* Drake, and *Amblystira machalana* Drake); whiteflies (*Aleurotrachelus socialis* Bondar, *Bemisia tuberculata*, and *Trialeurodes variabilis*); and fruit fly (*Anastrepha pickeli* Costa Lima). None of the aforementioned pests has been reported in Asia or Africa.

So far, few specific cassava pests have been disseminated to other areas. However, more than 20 years ago, two important pests, the cassava green mite (*Mononychellus tanajoa* Bondar), and the mealybug (*Phenacoccus manihoti* Matile-Ferrero), were accidentally introduced into Africa, where they caused serious losses in yield (Nyiira 1976; Leuschner and Nwanze 1978). The mealybug is subjected to high levels of natural control in the Americas, which is why it is not reported there as causing high yield reductions.

The white mussel scale, *Aonidomytilus albus* Cockerell, is found in almost all cassava-growing regions of the world. It can cause losses in planting materials, thus reducing stake germination and, hence, yields.

Relationships between Pest Damage and Yield Loss

The damage that cassava suffers is usually indirect, as most arthropod pests feed on leaves or stakes, thus reducing leaf area, longevity, and rate of photosynthesis. Field studies indicate that pests that attack the crop for prolonged periods (3 to 6 months), such as mites, mealybugs, thrips, whiteflies, and lace bugs, can cause severe reductions in root yield because they feed on the cellular fluids of leaves, thus reducing photosynthesis (Table 11-1). Many attacks can induce premature defoliation and death of apical meristems (Bellotti 2000).

The potential these pests have for reducing yields is greater than that of cyclic pests such as the cassava hornworm and leafcutting ants, which cause sporadic defoliation. However, such visible pests usually induce farmers to apply insecticides (Bellotti 2000).

The subterranean burrower bug (*C. bergi*; Hemiptera: Cydnidae) is one of the few pests that directly damage cassava roots. The perforations of the stylet into roots during feeding enable pathogenic fungi to penetrate roots, thus reducing their quality (García

Table 11-1. Losses in cassava yields caused by major pests.

Pest	Yield loss	References
Hornworm (*Erinnyis ello*)	In farm fields, natural attacks resulted in losses of 18%. Studies, using simulated damage, resulted in losses ranging from 0% to 64%, depending on the number of attacks, plant age, and soil fertility.	Arias and Bellotti 1984; Bellotti et al. 1992
Mite (*Mononychellus tanajoa*)	Yield losses of 21%, 25%, and 53%, with attacks lasting 3, 4, and 6 months, respectively; 73% for susceptible cultivars versus 15% for resistant cultivars; and 13% to 80% in Africa.	Bellotti et al. [1983b]; Byrne et al. 1982; Herren and Neuenschwander 1991
Whitefly (*Aleurotrachelus socialis*)	1, 6, and 11 months of attack resulted in 5%, 42%, and 79% losses, respectively, in field trials in Tolima, Colombia.	Bellotti et al. [1983b], 1999; Vargas and Bellotti 1981
Mealybugs (*Phenacoccus herreni, P. manihoti*)	In Colombia, 68% to 88%, depending on the cultivar's susceptibility. In Brazil, up to 80% of farms reported. In Africa, losses of 80% were reported.	Bellotti et al. 1999; Vargas and Bellotti 1984; Herren and Neuenschwander 1991
Subterranean burrower bug (*Cyrtomenus bergi*)	Dark brown to black lesions make roots commercially unacceptable. Starch content in roots reduced by more than 50%.	Arias and Bellotti 1985; Bellotti et al. 1999
Lace bugs (*Vatiga manihotae*, *Amblystira machalana*)	Field trials with *A. machalana* and *V. manihoti* resulted in yield losses of 39%.	CIAT 1990
Stemborer (*Chilomima clarkei*)	In Colombia, root yield losses increase from 45% to 62% when stem breakage is more than 35%.	Lohr 1983
Thrips (*Frankliniella williamsi*)	In susceptible cultivars (no pubescence on apical buds or leaves), yield drops from 17% to 25% or more.	Schoonhoven 1974; Bellotti and Schoonhoven 1978a

SOURCE: Bellotti 2000.

and Bellotti 1980). Centipede larvae and termites are occasionally reported to feed on roots and, although they damage roots and cause losses, they are usually minor pests (Bellotti 2000).

Biological and Physiological Bases of Yield Losses

The physiological bases that explain yield losses in cassava as caused by insects and mites have been explored by Cock (1978). He established that cassava may tolerate pest attack more than other crops, because it has no critical periods during production. Once the plant is established, its growth may be completely determined in almost any stage of development without affecting the formation of the organs responsible for yield, that is, bulked roots.

Pests can reduce yields indirectly by (1) consuming and thus reducing leaf area and therefore the photosynthetic rate; (2) attacking and thus weakening stems and preventing nutrient transport; and (3) attacking planting materials, thus reducing their germination rates. Direct attacks to roots may cause a cosmetic effect ("cassava smallpox"), which may affect yields and, nevertheless, makes the product unacceptable to fresh-root markets and for industrial uses. Cutworms, which attack stakes, produce lesions or holes through which soil pathogens may enter. These insects may also completely destroy the stakes' epidermis or buds. Other insects cut through roots or buds of recently germinated stakes.

In general, arthropod pests are more damaging to cassava crops during dry seasons than during the rains (Bellotti et al. 1999). The cassava plant is well adapted to long dry periods and takes advantage of short rainy seasons by reducing evapotranspiration from leaves by partly closing their stomata. Thus, water-use efficiency increases (Cock et al. 1985; El-Sharkawy et al. 1992). In plants suffering water stress, both the rapid defoliation of old leaves and the notable loss of photosynthetic activity enable young leaves to play a key role in acquiring carbon for the plant. Because several pests prefer young apical leaves, dry seasons tend to cause major yield losses in cassava. Once the crop enters in a humid cycle (rain or irrigation), new leaves sprout in apical parts, thus increasing the photosynthetic rate. This represents potential for recovery and compensates for yield losses caused by pest attack in the dry season (Bellotti 2000).

Economically Significant Pests

Mites

Mites constitute a major cassava pest throughout the world. The economically most important species include *Mononychellus tanajoa*, *Tetranychus urticae* Koch, and *Oligonychus peruvianus* McGregor. Bellotti and Schoonhoven (1977, 1978a) detail the damage they cause, principally during dry periods, when environmental conditions favor their development and permit populations to reach high levels. The duration of an attack depends on the length of the dry periods and the amount of available food. Continuous feeding by mites may lead to defoliation, which then reduces the photosynthetic rate. In experiment plots in Uganda, losses in yield caused by *M. tanajoa* were as high as 46% (Nyiira 1976; Cock 1978).

Four species of mites (*M. tanajoa, M. macgregori* [Flechtmann & Baker], *T. urticae*, and *O. peruvianus*) were evaluated for their effect on yields. Depending on plant age and duration of attack, yield was reduced by 21% to 53% at CIAT (Table 11-2). A 3-month attack reduces yield by 21%; 4 months, by 25%; and 6 months, by 53%. Damage led to necrosis and defoliation of the lower leaves, but complete defoliation did not occur.

On the Atlantic Coast (Colombia), Byrne (1980) found that prolonged damage caused by mites (e.g., *Mononychellus* sp.) to susceptible or resistant varieties has a differential effect on leaf size, rate of leaf formation, plant weight, and root yield. Yield losses ranged between 43% and 87%, with an average of 73% for susceptible and 16% for resistant varieties.

Table 11-2. Effect of populations of the mites *Mononychellus* spp., *Oligonychus peruvianus*, and *Tetranychus urticae* on the yield of cassava variety M Col 22. Artificial infestations of *T. urticae* were made.

Planting code	Artificial infestations	Plant age (months)	Duration of infestation (months)	Production (t/ha)		Mites (no./leaf)		Yield loss (%)
				Treated	Untreated	Treated	Untreated	
I	1	6	3	110	425	21.8	17.3	21
II	2	4 and 10	4	77	349	16.4	12.3	25
III	3	2 and 8	6	60	263	27.9	13.1	53

Production of vegetative "cuttings" (stakes) was reduced by 67% for susceptible and 16% for resistant varieties.

Thrips

Thrips are cassava pests mainly in the Americas. Their attacks are more frequent during the dry season but plants recover as the rains start. *Frankliniella williamsi* and *Scirtothrips manihoti* appear to be the most economically important species. The insects attack the plants' terminal buds. Leaves do not develop normally: the folioles become deformed and present deep clefts from the margins to the leaves' central nervures. Irregular chlorotic spots appear. Buds may die, thus destroying the apical dominance and stimulating lateral shooting. These, at their turn, may also be attacked, giving rise to a witches'-broom appearance (Bellotti and Schoonhoven 1977). Thrips attack does not result in defoliation, even though the photosynthetic area is greatly reduced.

Corynothrips stenopterus prefers to attack the plant's lower and central parts and therefore does not affect apical dominance. As a result, its importance is less significant.

At CIAT, thrips attacks reduced yields between 5.6% and 28.4%, depending on the variety's susceptibility (Schoonhoven and Peña 1976, 1978). One consequence of a 3-months' thrips attack was an average 17.2% reduction of yield for eight varieties.

Highly susceptible varieties such as 'Chiroza Gallinaza' can be totally destroyed by thrips in ecosystems such as those found at CIAT (Valle del Cauca) and Santander de Quilichao (northern Cauca), where varieties must be continually sprayed with insecticides so they may develop. In ecosystems such as that found in Quindío, although the variety is attacked by thrips, their effect on yield is not significant (B Arias 1978, pers. comm.).

Scale insects

Several species of scale insects that attack cassava stems and branches have been identified in many regions of the Americas, Asia, and Africa (Bellotti and Schoonhoven 1978a). The most important and widespread species is *Aonidomytilus albus*.

The leaves on branches become yellow and fall. In severe attacks on young plants, when the stem is invaded, plant stunting occurs, the terminal may die, and stems may dry, causing plant death. Scales may be present throughout the year, but their attacks are more severe during summer, which exacerbates conditions by intense dryness. Although the main damage caused by scale attack appears to be the loss of planting materials, studies carried out at CIAT have shown yield reductions when populations are continuously high. For an evaluation, a classification system was developed, as follows:

0 = plants have considerable foliage; scales on stems are absent or scarce
1 = reduced foliage; scales cover less than 50% of stem surfaces
2 = severe defoliation with death of terminal buds; scales completely cover stem surfaces

One hundred plants, corresponding to each level of damage, were harvested and root weight measured. Damage was correlated with reduced yields. According to results, loss of yield was 4% for plants scoring 1, and 19% for those scoring 2, with the latter representing a loss of 3 t/ha.

Other species such as black scale, *Saissetia miranda;* gray scale*, Hemiberlesia diffinis*; and *Ceroplastes* sp. do not have economic importance, as they appear only in sporadic isolated attacks on old plants. *Saissetia miranda* is subject to natural and effective biological control.

Whitefly

In the cassava crop, several whitefly species of variable importance are distributed in the Americas, Africa, and certain parts of Asia.

The family Aleyrodidae has 126 genera that include 1156 species, of which the most important for the cassava crop are *Aleurotrachelus socialis*, *Bemisia tuberculata*, and *Trialeurodes variabilis* in Colombia; *Aleurothrixus aepim* (Goeldi), in Brazil; and *B. tabaci* (Gennadius) in Africa and Asia.

Bemisia tabaci, so far, has not established well on cassava in Colombia. Yet, it is of particular importance, as it is the vector of the virus African cassava mosaic disease found in India and Africa, where it has caused yield losses of up to 80%.

Recent studies conducted by scientists of the National Cassava & Fruits Research Center (CNPMF) with farmers in Bahia, Northeast Brazil, demonstrated that high populations of *A. aepim* can cause losses of more than 40% of root production.

In the last 6 years of the 1990s, in Colombia, large outbreaks of *A. socialis* has alarmed farmers in northern Cauca, southern Valle del Cauca, Tolima, and parts of the Atlantic Coast (Arias 1995). In some regions, the pest occurs throughout the year, obliging farmers to resort to pesticide use for control.

Damage in susceptible varieties manifests as a mottling or rolling-up of leaves, symptoms very similar to those of the African mosaic mentioned above. Leaf yellowing and deformation of growing points may also occur. Furthermore, *fumagina*, a black sooty fungus *(Capnodium* sp.) and a sooty-colored complex of fungi and other pathogens, may develop on the insect's sugary excretions, affecting the photosynthetic rate, In severe infestations, lower leaves are defoliated.

Vargas and Bellotti (1981) mention that, before 1978, no records existed on yield losses caused by the whitefly's feeding action on the cassava crop.

The effect of whitefly attack was evaluated on three cassava varieties (CMC 57, CMC 40—also called M Col 1468—and M Mex 59), which were treated with monocrotophos every 10 days until harvest. Whitefly populations appeared throughout the year. The treated plants showed lower densities of whitefly populations, both adults and pupae, and a higher yield than did untreated plants (Table 11-3). Reductions in yield were 33.6% for M Mex 59, 52.0% for CMC 40, and 76.7% for CMC 57. These percentages indicate considerable damage to the crop.

In another trial, whiteflies were permitted to attack cassava over increasingly prolonged periods until plants were 11 months old. Correlation (r = 0.9) between the duration of attack and yield reduction was significant, with a negative correlation (r = 0.8) occurring between duration of attack and number of stakes produced per plant. The effect of duration of attack became significant after 3 months of plant growth (Table 11-4).

Hornworm

Erinnyis ello, in its larval stages, is a voracious consumer of foliage and is usually considered as a highly significant cassava pest in the Americas. Its ability to cause rapid defoliation of crops alarms cassava farmers.

The larval stages (five instars) last about 15 days, during which time the insect consumes 1107 cm^2 of leaf area. However, 75% of this area is consumed during the last instar, that is, in the last 3 or 4 days.

A Colombian commercial crop was planted with the variety Chiroza, which has a high yield potential. A very severe attack occurred when the plants were 3 months old, with four plots being completely defoliated. At harvest, when the crop was 12 months old, the attacked plants were compared with an equal number of those plants that had escaped attack. The average yield of unattacked plants was 4.58 kg/plant, while the defoliated plants yielded 3.75 kg each. This 18% loss was equivalent to 6 t/ha on that farm.

Taking into account that the intensity of attack may be severe at any age of the crop, the effect on production varies with plant age, number of attacks, soil type, and ecosystem in which the crop is grown. CIAT recently conducted research on crops with 100% defoliation across two sites: one in Santander de Quilichao (Cauca) that had poor soil and the other in CIAT–Palmira that had fertile soil. Results showed that, in the poor soil, yield losses could be as high as 64% with two continuous

Table 11-3. Yield of three cassava varieties reduced by whitefly (*Aleurotrachelus* sp.) attack in Espinal (Tolima, Colombia), 1978. Average of four replications.

Variety[a]	Treated (T)[b]			Untreated (NT)			Yield loss (%)	(T-NT) × % per infestation	
	Yield (kg/plant)	Infestation		Yield (kg/plant)	Infestation				
		In leaves[c]	With pupae[d]		In leaves[c]	With pupae[d]		In leaves[c]	With pupae[d]
CMC 57	3.31	0.57	0.28	0.77	3.92	3.17	76.7	85.5	91.2
(SE)	(0.41)	(0.19)	(0.12)	(0.27)	(0.27)	(0.23)			
CMC 40	5.35	0.82	0.21	2.57	4.75	4.87	52.0	82.7	95.7
(SE)	(0.60)	(0.23)	(0.10)	(0.43)	(0.17)	(0.08)			
M Mex 9	3.63	0.71	0.17	2.41	4.70	4.65	33.6	84.9	96.4
(SE)	(0.74)	(0.21)	(0.07)	(0.67)	(0.16)	(0.10)			

a. SE = standard error.
b. Monocrotophos: 1.5 cc a.i./L water.
c. Population: percentage of leaves infested by adults, nymphs, and pupae, where 0 = no infestation; 1 = <20%; 2 = 21% to 40%; 3 = 41% to 60%; 4 = 61% to 80%; 5 = 81% to 100%.
d. Pupae per leaf, where 0 = no pupae; 1 = <5; 2 = 6 to 10; 3 = 11 to 25; 4 = 26 to 50; 5 = >51.

Table 11-4. Relationship between the duration of whitefly (*Aleurotrachelus socialis*) attack and yield loss in cassava variety CMC 305-122.

Duration of attack (months)	Insecticide applications (no.)†	Yield of fresh roots (t/ha)‡	Reduction in yield (%)	Starch contents‡
0	22	42.1 a		29.6 a
1	20	40.1 ab	4.8	29.5 a
2	18	36.1 abcd	14.3	28.7 a
3	16	37.8 abc	10.2	29.4 a
4	14	30.6 bcde	27.3	30.7 a
5	12	29.8 cde	29.2	28.7 a
6	10	24.5 ef	41.8	27.7 a
7	8	26.7 de	36.6	29.4 a
8	6	16.4 fg	61.0	27.8 a
9	4	14.3 g	66.0	27.9 a
10	2	11.5 g	72.7	28.3 a
11	0	8.6 g	79.6	27.6 a

† Dimethoate was applied at 0.8 g a.i./L of water.
‡ The values within the same column followed by the same letter are not significantly different at 95%.

attacks, and as high as 46% with one attack on the crop. In the fertile soil, these losses were, respectively, as high as 47% and 25.5% (Arias and Bellotti 1984).

Severe attacks may also affect the production of planting materials: 1- and 2-month-old crops attacked in each month may lose as much as 72%, and 1-month-old crops attacked only once may lose as much as 62% (Arias and Bellotti 1984).

Mealybugs

Throughout the tropics, the mealybug constitutes one of the cassava crop's worst pests, causing serious damage to crops in the Americas and Africa. The principal species attacking cassava in the Americas are *Phenacoccus herreni* and *P. manihoti* Matile-Ferrero. In Africa, only *P. manihoti* causes economic losses.

The mealybug attacks both stems and leaves in cassava. *Phenacoccus herreni* and *P. manihoti* prefer buds, deforming and crinkling both leaves and buds, and giving the plant a rosette appearance. In severe attacks, these buds are filled with *fumagina* and finally dry up. When attacked early, plants become dwarfed, severely affecting root production.

Cassava varieties M Col 22 and CMC 40, evaluated at CIAT, respectively lost 88.3% and 67.9% of their yields. Plant height was reduced by as much as 33%, thus affecting stake number and quality. Depending on variety, as much as 74% of planting materials (stakes) may be lost (Vargas and Bellotti 1984).

Fruit fly

Fruit flies *Anastrepha pickeli* and *A. manihoti* were originally reported because they attacked the fruit. Although the flies do not cause economic damage by attacking fruit, in crops that are too young to fruit, they deposit their eggs on the stems' tender terminal buds. The larvae then damage the growing points by tunneling into them. A bacterial pathogen (*Erwinia carotovora* var. *carotovora*) is frequently found associated with the larvae, entering the tunnels and causing tissue rot. Severe attacks can retard and kill terminal buds, thus delaying plant growth and favoring lateral bud development (Bellotti and Peña 1978).

However, cassava plants can recover rapidly from fruit-fly damage, especially when rains are well distributed. For example, plants that were severely attacked at 3 months old were compared with healthy plants over 6 months. Measurements of plant height showed that, at 5 months old, the attacked plants had grown little (CIAT 1977), but no significant differences in yield were found between attacked and unattacked plants. However, stake quality was significantly different (CIAT 1980, unpublished data). Treated plots produced between 40% and 50% more stakes of good quality than the untreated plots.

Shoot fly

Damage caused by shoot fly has been found in most cassava-growing regions of the Americas, but has not been reported in Africa or Asia.

Several *Lonchaeidae* species have been described but *Silba pendula* Bezzi and *Lonchaea chalybea* Wiedemann are the most important (Bellotti and Schoonhoven 1978a, 1978b). The larval stage may last from 20 to 25 days, depending on the temperature (Bellotti and Schoonhoven 1978a; Waddil 1978). Hence, the duration of the attack is relatively short. However, successive attacks may occur, when damage by larval feeding manifests as a white to coffee-colored discharge that flows from the terminal buds, which finally die. Plant growth is therefore delayed and apical dominance is broken, inducing the germination of lateral buds, which may then be attacked. Studies conducted in Costa Rica (Saunders 1978), Florida, USA (Waddil 1978), and at CIAT (1975) have demonstrated that such attacks do not cause yield loss.

Arias and Bellotti (1982) simulated damage in 100% of buds, with continuous damage from 1 to 5 months in clone M Col 22, and at different crop ages. Results were similar to those observed in Costa Rica. No critical period exists for pest attack from the viewpoint of yield. However, attacks during the crop's first and second months diminished planting-material quality by 51% to 71%.

Stemborers

A complex of stem-boring arthropods includes species of Coleoptera and Lepidoptera that feed on the interiors of cassava stems, causing damage (Bellotti 2000).

Lagocheirus araneiformis. The longhorn beetle is found throughout the world. Its attack does not severely damage crops in the field. These stemborers are most important in the Neotropics, especially in Colombia, Venezuela, and Brazil. Seven species of the Coelosternus genus (Coleoptera: Curculionidae) have been reported as reducing cassava yields and the quality of planting materials in Brazil. However, such damage tends to be sporadic and does not imply significant reductions in yield (Bellotti 2000).

Chilomima clarkei. Populations of this stemborer (Lepidoptera: Pyralidae) have recently been increasing dramatically in Colombia and Venezuela, currently constituting an important cassava pest (Vides et al. 1996). Females oviposit more than 200 eggs on stems during the night, usually near an internode or bud. The egg stage lasts about 6 days at 28 °C. After hatching, the first instars feed on the stem's cortex or epidermis. These larvae are highly mobile and usually locate themselves near axillary buds, where they form a protective capsule in which they live until the fifth instar. From there they penetrate the stem to complete their cycle to adult emergence (Lohr 1983). The larval stages last from 32 to 64 days (Bellotti 2000).

Populations of *C. clarkei* may be present the year round, but are higher during the rainy season. As the pest, and therefore the damage, increases, control becomes more difficult. When larvae make a sufficient number of perforations (i.e., >20 per stem) in the stems, these break, reducing the quality and quantity of planting materials. Field studies indicate that fields with more than 35% of broken stems suffer significant reductions (45% to 62%) in root yield (Lohr 1983). In the Colombian Caribbean Region, 85% of planted cassava is attacked by *C. clarkei* (Vides et al. 1996).

The mobility of the first-instar larvae makes them vulnerable. They can be controlled by using *Bacillus thuringiensis*. Given its rapid generational increase, several applications will be needed, thus, increasing production costs. Field research (Gold et al. 1990) indicates that crop rotation with maize reduces stemborer populations until the maize is harvested (Bellotti 2000).

Termites

In Colombia, *Heterotermes tenuis* Hagen has been identified as the most important termite species determined by attacking cassava. In the 1980s, CIAT evaluated the importance of this pest in the Atlantic Coast and found that it can cause losses of 46% to 100% of unprotected planting materials in storage. In the field, production may decline by 40%. These studies also showed that no direct relationship exists between the percentage of plants attacked at the neck of the root (stump) and the percentage of damaged roots. Over 30 treatments, the percentage of attacked plants was high (64% to 95%) at harvest. However, the percentage of damaged roots was low at 0% to 1.7% (Arias et al. 1979). When introduced cultivars were evaluated, the average level of damage in roots increased between 16.5% (ecosystem trial) and 25.5% (pest complex trial).

Termites penetrate roots through wounds or through cracks caused by climatic effects on the soil. The insects form galleries in the root parenchyma, which then fill with sand.

Subterranean burrower bug

This cydnid is another root pest, although it does not directly affect root yields, but attacks the roots' culinary and commercial qualities. The bug feeds on the root, using its stylet (beak) to penetrate the cassava peel to reach the parenchyma. When the affected roots are peeled, a series of small colored spots can be seen on the surface. The spots range from light to dark brown or almost black, giving this type of damage the Spanish name, meaning "cassava smallpox". These perforations correspond to fungal pathogens of the soil, which penetrate through the wounds. Roots in such conditions are rejected by traders and consumers alike, obliging farmers to keep back production and suffer the consequent economic losses. These roots are usually fed to farm animals. Trials at CIAT have shown that starch production may be affected by as much as 50%, can effect-lower starch content depending on the magnitude of the attack.

Other pests

Although many other pests attack cassava, little or no data are available on their effects on yields (Table 11-5). Many insects attack planting materials, causing losses in germination, thus reducing yields if as many as 30% of plants are destroyed. Such pests include white grubs (*Phyllophaga* sp. and *Leucopholis rorida* [Fabricius]); and cutworms (*Prodenia* spp., *Agrotis ipsilon*, *Spodoptera frugiperda* (J.E. Smith), and *Lagocheirus araneiformis*). Pests attacking foliage include ants, lace bugs (*Vatiga manihotae* and *V. illudens*), and leafhoppers.

Discussion

Cassava is a crop with a growing period that may take 8 to 24 months to complete, according to variety and environmental conditions. It can suffer a high level of economic damage. Under certain conditions, even vigorous varieties may lose more than 40% of their foliage but, in certain periods, the plant may tolerate higher levels of defoliation without suffering significant reductions in yield. These two factors are important in the relationship between damage by pests and yield reductions in cassava. The long growing period implies that plants are subject to continuous attack from pests that cause different types of damage. The most severe attacks usually occur in summer, when damage by pests is combined with intense dryness. Although some pests do attack the crop during the rainy season, the plant usually recovers in this period and grows vigorously.

The experiments presented in this chapter show that some arthropod pests reduce yields (e.g., whitefly, Table 11-4). The magnitude of reductions is influenced by environmental conditions, soil fertility, plant age, type of damage, and duration of attack.

Pests that attack the plant's aerial parts over prolonged periods reduce yield more than those that defoliate or cause damage over short periods (Table 11-6). Cock (1978), using field data and computer simulations, suggests that "relatively minor losses in yield result from a small reduction in leaf area". However, when yield is severely reduced, causes relate to reductions in leaf longevity and the photosynthetic rate.

The results of the experiments presented tend to support the following conclusions:

- Attacks by pests such as fruit fly and shoot fly, which destroy the plant's apical parts but have little or no effects on the photosynthetic rate, do not result in losses of yield (Table 11-5).
- The damage done by the hornworm through consumption of foliage reduces leaf area but, as the attack occurs over a brief period, the plant produces new foliage (Figure 11-1).
- In a field study, when the photosynthetic rate was artificially interrupted for 1 to 2 weeks over the plant's entire vegetative cycle, yield was reduced by 18% after the experiment. This loss was predicted (20%) by a simulated model in computer for this type of damage (Cock 1978).
- Thrips reduce leaf area over about 3 months, with yield dropping by 17%.
- Scale insects cause considerable injury to the principal stem and branches because of their continual feeding. At CIAT, yield loss was 19%, supporting Cock's (1978) conclusions that severe damage to stems will reduce yield.
- Reduced photosynthetic rate throughout the vegetative cycle appears to have the most negative effect on yield (Table 11-1).
- Mites and whiteflies attack foliage over long periods, in which the photosynthetic rate declines (Figure 11-2). If the duration of the attack increases, the yield decreases.

Table 11-5. Occasional and sporadic pests or less important pests of the cassava crop.

Common name	Important species	Region	Type of damage and/or symptoms	Yield losses reported	Control strategy	References
Scale insects	*Aonidomytilus albus*, *Saissetia miranda*	Almost all cassava-growing regions in the Americas, Africa, and Asia	Stems and leaves are attacked; Leaf yellowing and defoliation; Plants may wilt and die; Attacked stakes have reduced germination	<20% of fresh root yield; 50% to 60% loss of stakes	Destroy infested branches; Use only healthy stakes with no scales; Treat stakes with malathion	Bellotti and Schoonhoven 1978a; Frison and Feliu 1991
Fruit flies	*Anastrepha pickeli*, *A. manihoti*	The Americas, Costa Rica, Panama, Venezuela, Colombia, Brazil, and Peru	Fruits, seeds, and apical stems tunneled; Fruits destroyed and stake quality reduced but, normally, not much economic damage is caused	0% to 30% when infested stems are used as planting materials	Damaged stakes should not be used	Bellotti and Schoonhoven 1978a, 1978b; Lozano et al. 1981; Peña and Waddill 1982
Shoot flies	*Neosilba perezi*, *Silba pendula*	Throughout most of the Americas	Larvae kill the apical buds, delay plant growth, and induce sprouting	Losses not reported for yield; Reduced stake quality	Not required	Bellotti and Schoonhoven 1978a, 1978b; Lozano et al. 1981; Arias and Bellotti 1982
Gall fly	*Jatrophobia (Eudiplosis) brasiliensis*	All the Americas	Greenish-yellow to red galls formed on upper leaf surface	None reported	Not required	Bellotti and Schoonhoven 1978a, 1978b; Lozano et al. 1981; Samways 1980
White grubs	*Phyllophaga* spp., *Leucopholis rorida*, Others	The Americas, Asia, and Africa	Feeding on stakes and roots; Possible seedling death	Up to 95% of losses in germination	Apply pesticides to soil at planting	Bellotti and Schoonhoven 1978a, 1978b; Peña and Waddill 1982
Termites	*Coptotermes voltkevi*, *C. paradoxis*, *Heterotermes tenuis*	All regions	Feeding on stakes, roots, seedlings, and stems; Wilting and/or plant death	46% to 100% of stakes lost; Up to 25.6% of roots lost in clones introduced to the Atlantic Coast	Treat stakes with pesticides; Keep fields clean	Bellotti and Schoonhoven 1978a, 1978b; CIAT 1984; Arias et al. 1979; Lal and Pillai 1981; Lozano et al. 1981

(Continued)

Table 11-5. (Continued.)

Common name	Important species	Region	Type of damage and/or symptoms	Yield losses reported	Control strategy	References
Stemborers	*Lagocheirus* sp.	All regions	Tunneling in stems, leading to breakage	None reported	Select healthy stakes	Villegas and Bellotti 1985
	Coelosternus spp.	The Americas, especially Brazil	Tunneling in stems and branches, leading to breakages	None reported	Select healthy stakes; Keep fields clean; Destroy infested stems	Bellotti and Schoonhoven 1978a, 1978b; Samways 1980
Leafcutting ants	*Atta* spp., *Acromyrmex* spp.	The Americas	Defoliation	Losses not reported	Fumigate nests; Introduce poisoned baits	Bellotti and Schoonhoven 1978a, 1978b; Samways 1980
Leafhoppers	*Zonocerus elegans, Z. variegatus*	Mainly Africa, occasionally the Americas	Defoliation, stem damage, and branches cut	Losses not reported	Use of entomopathogens is being evaluated	Bellotti and Riis 1994; Bellotti and Schoonhoven 1978a, 1978b; Lomer et al. 1990; Modder 1994
Cutworms	*Agrotis ipsilon, Prodenia eridania, Spodoptera frugiperda*	Mainly the Americas	Feeding at the stem base, buds, and cortex of stakes and roots	Loss in germination of stakes; Seedling death	Introduce poisoned baits at planting	Bellotti and Schoonhoven 1978a, 1978b

SOURCE: Bellotti 2000.

Table 11-6. Yield losses to insects and mites, according to the duration of attack on the cassava crop.

Pest or simulation	Type of attack	Duration	Reduction in yield (%)
Shoot fly	Shoot destruction	21 days	0
Fruit fly	Tunneling in branches	11 days	0 to 5
Simulation of hornworm attack	Complete defoliation (for leaf consumption by the pest)	15 days	0 to 64
Thrips	Leaf deformation	3 months	17
Scale insects	Sap suckers on stems	3 to 4 months	19
Mites	Sap suckers on leaves (reduced photosynthesis)	3 months 4 months 6 months	21 25 53
Whitefly	Sap suckers (reduced photosynthesis)	10 months	76

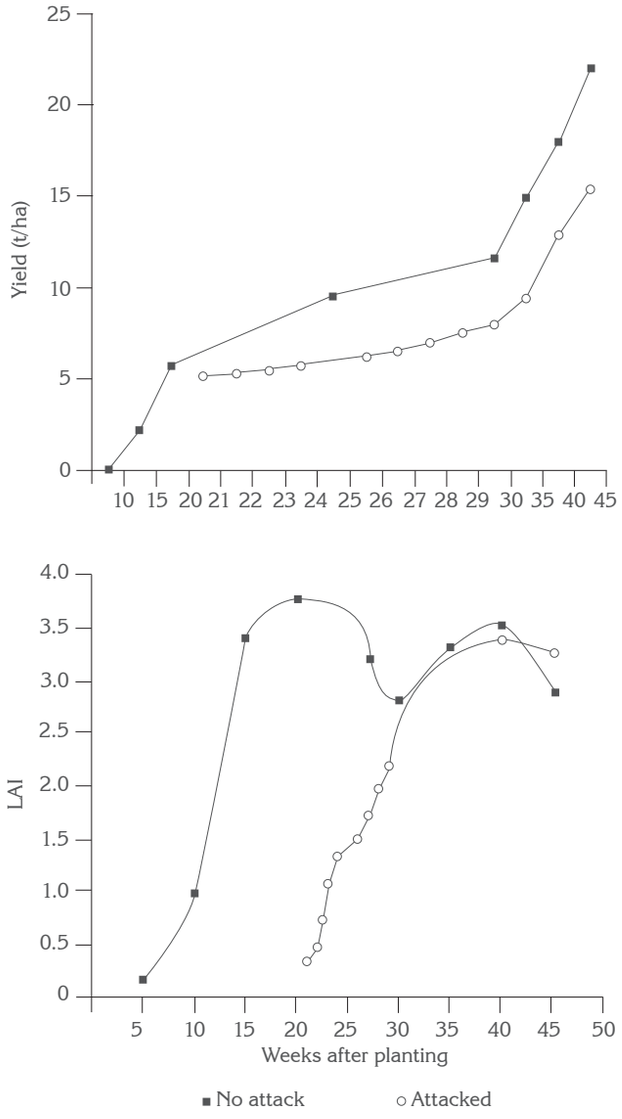


Figure 11-1. Effect of hornworm attack on yield and leaf area index (LAI) of a 20-week-old cassava crop (computer-simulated data) (from Cock 1978).

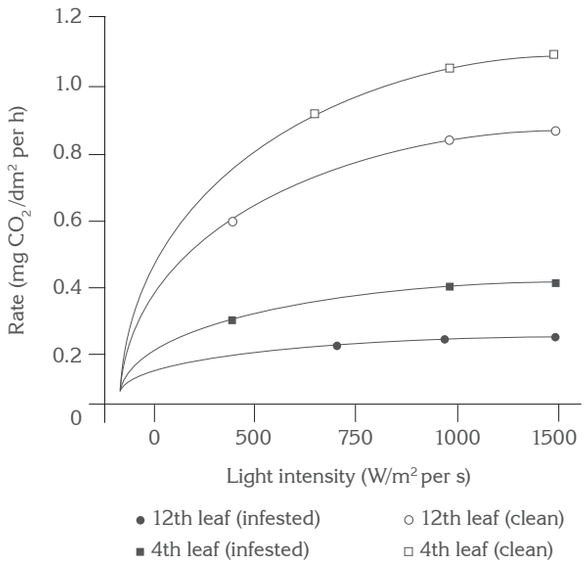


Figure 11-2. Effect of high mite infestation on the photosynthetic rate in cassava variety M Col 72 (measured in 2 leaves) (from Cock 1978).

Cock (unpublished data) suggests that computer simulations indicate that a 10% reduction in photosynthesis over the vegetative cycle of an ideal plant type will result in a 20% smaller root production. The plant seems to recover better from rapid defoliation or the death of its buds than from continuous reduction of the photosynthetic rate over a long period. In this case, pests such as the lace bug and mealybug could cause considerable yield loss (Table 11-1). However, mealybugs are known to cause as much as 88% of losses in susceptible varieties (Vargas and Bellotti 1984).

Conclusions

Sufficient information from the field is available to demonstrate that insect and mite attacks can drastically

reduce cassava yield. Several factors seem to influence the pest-crop relation, among them environmental conditions and soil fertility. Frequently, adequate rains will permit the plant to recover from the damage with minimal reductions in yield.

The type of damage and duration of pest attack will also determine the level of reduction in yield. Pests that attack plants over prolonged periods (mites, whiteflies, thrips, and scale insects) have been proven to reduce yields more than pests that attack plants over short periods (hornworm, shoot fly, and fruit fly).

The most detrimental form of damage is that which continually reduces the photosynthetic rate.

References

The following acronyms are used to save space:

CIAT = Centro Internacional de Agricultura Tropical
SOCOLEN = Sociedad Colombiana de Entomología

Arias B. 1995. Estudio sobre el comportamiento de la "mosca blanca" *Aleurotrachelus socialis* Bondar (Homoptera: Aleyrodidae) en diferentes genotipos de yuca, *Manihot esculenta* Crantz. MSc thesis. Universidad Nacional–Palmira, Colombia. 181 p.

Arias B; Bellotti AC. 1982. Pérdidas en rendimiento (daño simulado) causadas por *Silba pendula* (Bezi) mosca del cogoyo de la yuca. In: Proc IX Congress of SOCOLEN. SOCOLEN, Bogotá, DC, Colombia.

Arias B; Bellotti AC. 1984. Pérdidas en rendimiento (daño simulado) causadas por *Erinnyis ello* (L.) y niveles críticos de población en diferentes etapas de desarrollo de tres clones de yuca. Rev Colomb Entomol 10(3–4):28–35.

Arias B; Bellotti AC. 1985. Aspectos ecológicos y de manejo de *Cyrtomenus bergi* Froeschner, la chinche de la viruela, en el cultivo de la yuca (*Manihot esculenta* Crantz). Rev Colomb Entomol 11(2):42–46.

Arias B; Reyes JA; Bellotti AC. 1979. Tratamiento de estacas de yuca para prevenir ataques de termitas (*Coptotermes* sp.). In: Abstracts [of the] Proc VI Congress of SOCOLEN, Cali, Colombia. SOCOLEN, Bogotá, DC, Colombia. 29 p.

Bellotti AC. 1978. An overview of cassava entomology. In: Brekelbaum T; Bellotti AC; Lozano JC. eds. Cassava protection workshop, held in Cali, Colombia, 1977. CIAT, Cali, Colombia. p 29–39.

Bellotti AC. 2000. Las plagas principales del cultivo de la yuca: Un panorama global. In: Symposium on "Avances en el Manejo de Plagas". Proc XXVII Congress of SOCOLEN, Medellín, Colombia, July 2000. SOCOLEN, Bogotá, DC, Colombia. p 189–217.

Bellotti AC; Peña J. 1978. Studies on the cassava fruit fly, *Anastrepha* spp. In: Brekelbaum T; Bellotti AC; Lozano JC, eds. Proc Cassava protection workshop, held in Cali, Colombia, 1977. CIAT, Cali, Colombia. p 203–208.

Bellotti AC; Riiss L. 1994. Cassava cyanogenic potential and resistance to pests and diseases. Acta Hortic 375:141–151.

Bellotti AC; Schoonhoven A van. 1977. World distribution, identification and control of cassava pests. In: Proc Fourth Symposium of the International Society for Tropical Root Crops, held in Cali, Colombia, 1976. International Development Research Centre (IDRC), Ottawa, Canada. p 188–193.

Bellotti AC; Schoonhoven A van. 1978a. Cassava pests and their control. CIAT, Cali, Colombia. 71 p.

Bellotti AC; Schoonhoven A van. 1978b. Mite and insect pests of cassava. Annu Rev Entomol 23:39–67.

Bellotti AC; Vargas H, O; Peña JE; Arias V, B. [1983b]. Pérdidas de rendimiento en yuca causadas por insectos y ácaros. In: Domínguez CE, ed. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (UNDP), Cali, Colombia. p 393–408.

Bellotti AC; Arias B; Guzmán OL. 1992. Biological control of the cassava hornworm *Erinnyis ello* (Lepidoptera: Sphingidae). Fla Entomol 75:506–515.

Bellotti AC; Smith L; Lapointe SL. 1999. Recent advances in cassava pest management. Annu Rev Entomol 44:343–370.

Byrne DH. 1980. Studies of resistance to mites *Mononychellus tanajoa* (Bondar) and *Mononychellus caribbeanae* (McGregor) in cassava (*Manihot esculenta* Crantz). Dissertation. Graduate School of Cornell University, Ithaca, NY, USA. 174 p.

Byrne DH; Guerrero JM; Bellotti AC; Gracen VE. 1982. Yield and plant growth responses of *Mononychellus* mite resistant and susceptible cassava cultivars under protected vs infested conditions. Crop Sci 22(5/6):486–550.

CIAT. 1975. Annual report 1974. Cali, Colombia. 260 p.

CIAT. 1977. Cassava production systems. In: Annual report 1976. Cali, Colombia. p B1–B76.

CIAT. 1984. External program review: Cassava Program report. Cali, Colombia. p 23.

CIAT. 1990. Annual report [of the] Cassava Program 1989. Cali, Colombia. 385 p.

CIAT. 1999. Annual report: integrated pest and disease management in major agroecosystems. Cali, Colombia. 136 p.

Cock JH. 1978. Physiological basis of yield loss in cassava due to pests. In: Brekelbaum T; Bellotti AC; Lozano JC, eds. Cassava protection workshop, held in Cali, Colombia, 1977. CIAT, Cali, Colombia. p 9–16.

Cock JH; Porto MCM; El-Sharkawy MA. 1985. Water-use efficiency of cassava, III: Influence of air humidity and water stress on gas exchange of field grown cassava. Crop Sci 25:265–272.

El-Sharkawy MA; Hernández ADP; Hershey C. 1992. Yield stability of cassava during prolonged mid-season water stress. Exp Agric 28:165–174.

Frison EA; Feliu E, eds. 1991. Technical guidelines for the safe movement of cassava germplasm. Food and Agriculture Organization of the United Nations (FAO); International Board for Plant Genetic Resources (IBPGR), Rome. 48 p.

García CA; Bellotti AC. 1980. Estudio preliminar de la biología y morfología de *Cyrtomenus bergi* Froeschner, nueva plaga de la yuca. Rev Colomb Entomol 6(3–4):55–61.

Gold CS; Altieri MA; Bellotti AC. 1990. Effects of intercropping and varietal mixtures on the cassava hornworm, *Erinnyis ello* (Lepidoptera: Sphingidae), and the stemborer, *Chilomima clarkei* (Amsel) (Lepidoptera: Pyralidae), in Colombia. Trop Pest Manage 36(4):362–367.

Herren HR; Neuenschwander P. 1991. Biological control of cassava pests in Africa. Annu Rev Entomol 36:257–283.

Lal SS; Pillari KS. 1981. Cassava pest and their control in southern India. Trop Pest Manage 27(4):480–491.

Leuschner K; Nwanse K. 1978. Preliminary observations of the mealybug (Homoptera: Pseudococcidae) in Zaire. In: Brekelbaum T; Bellotti AC; Lozano JC, eds. Cassava protection workshop, held in Cali, Colombia, 1977. CIAT, Cali, Colombia. p 195–198.

Lohr B. 1983. Biología, ecología, daño económico y control de *Chilomima clarkei,* barrenador de la yuca. In: Reyes JA, ed. Yuca: Control integrado de plagas. CIAT, Cali, Colombia. p 159–161.

Lomer CJ; Bateman RP; Godonou I; Kpindou D; Shah PA. 1990. Field infection of *Zonocerus variegatus* following application of oil-based formulation of *Metarhizium flavoviridae* conidia. Biocontrol Sci Technol 3:337–346.

Lozano JC; Bellotti A; Reyes JA; Howeler R; Leihner D. 1981. Field problems in cassava, 2nd ed. CIAT, Cali, Colombia. 205 p.

Modder WWD. 1994. Control of the variegated grasshopper *Zonocerus variegatus* (L.) on cassava. Afr Crop Sci J 2(4):391–406.

Nyiira ZM. 1976. Advances in research on the economic significance of the green cassava mite, *Mononychellus tanajoa* (Bondar) in Uganda. In: Terry ER; McIntyre R, eds. The international exchange of cassava germplasm in Africa, Proc interdisciplinary workshop, held in Ibadan, Nigeria, 1975. International Development Research Centre (IDRC), Ottawa, Canada. p 22–29.

Peña JE; Waddill V. 1982. Pests of cassava in South Florida. Fla Entomol 65(1):143–149.

Samways MJ. 1980. O complexo de artrópodas da mandioca (*Manihot esculenta* Crantz) em Lavras, Minas Gerais, Brasil. An Soc Entomol Brasil 9(1):3–10.

Saunders JL. 1978. Cassava production and vegetative growth related to control duration of shoot flies and fruit flies. In: Brekelbaum T; Bellotti AC; Lozano JC, eds. Cassava protection workshop, held in Cali, Colombia, 1977. CIAT, Cali, Colombia. p 215–219.

Schoonhoven A van. 1974. Resistance to thrips damage in cassava. J Econ Entomol 67:728–730.

Schoonhoven A van; Peña JE. 1976. Estimation of yield losses in cassava following attack from thrips. J Econ Entomol 69(4):514–516.

Schoonhoven A van; Peña JE. 1978. Thrips on cassava; economic importance, sources and mechanisms of resistance. In: Brekelbaum T; Bellotti AC; Lozano JC, eds. Cassava protection workshop, held in Cali, Colombia, 1977. CIAT, Cali, Colombia. p 209–214.

Vargas O; Bellotti AC. 1981. Pérdidas en rendimiento causadas por moscas blancas en el cultivo de la yuca. Rev Colomb Entomol 7(1/2):13–20.

Vargas O; Bellotti AC. 1984. Pérdidas en rendimiento causadas por *Phenacoccus herreni* Cox et Williams en dos clones de yuca. Rev Colomb Entomol 10:41–46.

Vides OL; Sierra OD; Gómez HS; Palomino AT. 1996. El barrenador del tallo de la yuca *Chilomima clarkei* (Lepidoptera: Pyralidae) en el CRECED, Provincia del Río. Boletín. Corporación Colombiana de Investigación Agropecuaria (CORPOICA), Bogotá DC, Colombia. 12 p.

Villegas GA; Bellotti AC. 1985. Biología, morfología y hábitos de *Lagocheirus araneiformis* Linne (Coleoptera: Cerambycidae) barrenador de la yuca, en Palmira, Valle del Cauca. Acta Agron 35(4):56–67.

Waddill VH. 1978. Biology and economic importance of cassava shoot fly, *Neosilba perezi* Romero y Ruppel. In: Brekelbaum T; Bellotti AC; Lozano JC, eds. Cassava protection workshop, held in Cali, Colombia, 1977. CIAT, Cali, Colombia. p 209–214.

CHAPTER 12

Cassava Pest Management*

Anthony C. Bellotti[1], *Bernardo Arias V.*[2], *and Jesús A. Reyes Q.*[3]

Introduction

The management of cassava pests should be based on biological control, host-plant resistance, and use of cultural practices. These components of integrated control have played an important role in programs for managing cassava pests during the last 35 years. Thus, this management model should continue to be implemented to prevent environmental degradation and possible food contamination in the future.

One practical objective of entomologists is to maintain populations of insect pests at levels below economic importance. Stated like this, the objective is clear and easy to understand but, in practice, it becomes lost because its true sense is unknown.

When speaking of maintaining destructive insects at low levels of economic importance, it should be understood that the presence and damage caused by an insect pest does not always mean reduced production. Almost all crops can support a certain level of damage and still recover. Hence, the mere presence of a harmful insect does not necessarily mean that insecticides must be applied.

The cassava plant's ability to recover from pest damage is a significant quality that should always be taken into account before resorting to the application of control inputs, unless yield loss has been estimated.

Currently, accurate information exists on the pests that most reduce yields, the times and key stages of the crop when plants are more susceptible to pest attack, and the precautions or suitable management actions to be taken. Some pests are known not to affect production, even though symptoms appear severe enough to induce the application of what are, in fact, unnecessary control measures.

In controlling this crop's pests, costly inputs, especially pesticides, should be kept at a minimum. One way of achieving this objective is to increase basic knowledge on the biology and ecology of many of these pests and their natural enemies. Advantage must also be taken of the favorable factors involved in the insect–plant–environment interaction, so that developing a system for cassava pest management is both attractive and practical. Some of these factors are:

1. The cassava cropping cycle is 8 to 24 months long. Hence, continuous use of pesticides is costly and uneconomical with regard to profitability.

2. Because it is a long-cycle crop, cassava is ideal for biological control programs, especially in areas where it is continuously cultivated and over large extensions. Many biological control agents of many major pests have already been identified and studied in-depth.

3. The cassava plant often recovers from the damage caused by insects. During seasons with adequate rainfall, high levels of defoliation will cause little or no yield reduction.

4. Many pests do not disseminate widely and their incidence is often seasonal, with dry seasons

---

* This document contains information published in the Proceedings of the XXVII Congress of the Sociedad Colombiana de Entomología (SOCOLEN), 2000.

1. Emeritus Scientist/Consultant, Entomologist/Agrobiodiversity, IPM, Cassava Program, CIAT, Cali, Colombia. E-mail: a.bellotti@cgiar.org
2. Research Associate, Plant Production, IPM, Cassava Program, CIAT. E-mail: bernaarias1@gmail.com
3. Entomologist, Asociación Colombiana de Ciencias Biológicas. Palmira, Colombia. E-mail: jesus_antonior@hotmail.com

favoring their population increase. However, the plant's ability to resist long dry periods usually enables it to recover when the rains start.

5. Cassava has a high threshold for economic damage by pests. Vigorous varieties may lose 40%, or even more, of their foliage without yield being significantly affected. Newly developed varieties may possess mechanisms other than defoliation, resulting in higher tolerance, because of the selection methods used for both vigor and resistance to biotic and abiotic factors.

6. Very few pests can actually kill the plant. Hence, the plant recovers from damage and can produce edible roots.

7. The selection of healthy and vigorous planting materials, together with treatment with low-cost fungicides and insecticides, permits fast and successful germination. The plant's initial vigor is thus ensured during this important early phase and yield is ultimately increased.

8. Cassava has been shown to possess adequate sources of resistance—at low, medium, and high levels—to prevent serious crop losses to certain pests.

9. Cassava is often cultivated on small farms, under mixed cropping conditions. This system not only reduces pest incidence, but also prevents outbreaks in large crop extensions.

10. Insects can reduce yields during specific periods of plant development. For many cassava pests, these periods have already been identified, permitting the intensification of control during these times.

Insect Pests

Insects have existed for more than 300 million years and have survived and evolved, despite all the drastic changes derived from the Earth's evolution.

Insects possess high reproductive capacity. A queen termite may oviposit 30,000 eggs daily. When dichlorodiphenyltrichloroethane (DDT)[4] appeared for agricultural use, its lethal effect on insects was of such a magnitude that many entomologists began collecting insect species to conserve them, as the belief was that the DDT would exterminate them. However, insects have survived much more difficult situations, and responded by developing resistance not only to DDT but also to most insecticides.

To date, 321 insect species resistant to several groups of insecticides have been recorded, meaning that the chemicals are no longer effective for reducing their populations. Hence, humans must seek other, more rational and economic alternatives that do not continue to increase insect resistance to insecticides or contaminate the environment at critical levels for humanity.

Many entomologists and scientists, past and current, have dedicated their lives to study beneficial insects and promote their use in pest control programs. These researchers are convinced that the use of insecticides only would augment biological imbalance, which would have catastrophic consequences for humanity. These studies are found in specialized books and bulletins that detail the methods and recommendations for programs of integrated pest management (IPM). Today, the situation has changed. It falls to entomologists, technical personnel, and people generally to practice these principles and use these experiences. Not only would production problems be solved, but environmental contamination would also be minimized.

The cassava crop may serve as a model for understanding some basic principles of integrated control, particularly biological control by means of beneficial insects.

Although pest outbreaks sometimes occur, the cassava crop does not permanently suffer severe attacks from insects. On the contrary, it maintains an excellent biological equilibrium. Mortality factors also function to maintain pest populations at levels of low economic importance.

This favorable situation should be conserved. The example of the cotton crop in Colombia illustrates this point: during 1977, pest control had arrived at a "situation of catastrophe". *Heliothis* larvae, the cotton crop's principal pest, had attained such a high degree of resistance to insecticides that its control was impossible. Yet, when the cotton crop was established in Colombia, more than 35 years ago, the pests that attacked it were few and their control was relatively esay.

4. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

This situation is similar to that presented by the cassava crop 20 years ago. Thus, if cassava pests are not handled rationally and if insecticides continue to be indiscriminately applied, then, in the not very distant future, the same situation of despair affecting cotton growers will also develop for cassava growers.

Cassava pests have been studied in terms of their relationships with biotic and abiotic factors, crop management techniques, and production of varieties adapted to different ecosystems. Yet, increased awareness of the problem is still needed if the type of management that prevents epizootics happening on a regional or national scale is to be adopted.

One epizootic—an outbreak of the cassava stemborer (*Chilomima clarkei*)—occurred in the Atlantic Coast of Colombia in the 1990s. Quarantine standards had not been observed. That is, stakes were exchanged from one area to another, harvest residues were not destroyed, storage conditions for planting materials (stakes) were poor, stakes of poor quality and infested with the pest were used, and pesticides were inappropriately used. As a result, the pest became a social problem: the scarcity of asexual seed led many farmers—mostly resource-poor families who depended on cassava for sustenance—into precarious situations.

A similar situation has occurred with the cassava whitefly (*Aleurotrachelus socialis*) in northern Cauca, southern Valle del Cauca, Tolima, and some areas of the Atlantic Coast and Eastern Plains. This pest has become endemic. Its populations have increased dramatically, to the point of causing severe damage to the crop over prolonged periods and thus significantly affecting root production. In response, farmers indiscriminately applied insecticides, exacerbating the problem. The pest is now appearing at times and in areas where it had not previously been seen.

Currently, CIAT is searching for varietal resistance and biological control to manage these pests. Future results will respond positively to these problems (Bellotti et al. 1999).

Integrated Pest Management

Integrated management appears to be the most rational way of tackling insect pests. It consists of combining and integrating all available techniques and applying them harmoniously to maintain insect pests at levels where their economic damage to crops is not significant. Integrated management therefore consists of all available techniques, not only of biological control and insecticides. These, however, form two of its basic components.

Other techniques available are the use of plants that resist or tolerate insect attack, mechanical and physical methods that attract or repel, and compliance with quarantine standards. Although the available techniques are many, their successful application is more important. They must be understood and used correctly by technical personnel and farmers.

Biological control

Biological control may be defined as managing pests through the deliberate and systematic use of their natural enemies. Parasites, predators, and pathogens can help maintain population densities of pests at lower levels than would have occurred in their absence. This form of control has several advantages:

- It is relatively permanent
- It is economic
- It helps maintain environmental quality
- Food is less like to be contaminated by pesticides

The idea that an insect population may be reduced by other insects is ancient. For example, the use of predator ants to control certain citrus pests probably originated in China. This system is currently being followed in some areas of Asia. Insect parasitism was recorded for the first time by Vallisnieri (1661–1730) in Italy. He noted, in particular, the association between the parasitic wasp *Apanteles glomeratus* and the cabbage worm *Pieris rapae.*

Parasites for biological control in agricultural crops were first used in Europe, mostly in France, Germany, and Italy, during the 19th century. However, the science of biological control was developed in USA during the 19th and 20th centuries.

The project to control cottony cushion scale (*Icerya purchasi*) attacking citrus crops in California, USA, was the first successful example of biological control. The scale was accidentally introduced into Australia and, in 1888, entomologists brought in two of its natural enemies, one of which was the vedalia beetle (*Rodolia cardinalis*), a coccinellid predator. Scale populations declined rapidly. The technique for mass-rearing parasites and predators and releasing them periodically for pest control was developed in

California in 1919 during a project on the coccinellid *Cryptolaemus montrouzieri*, a predator of the mealybug.

Since then, more than 96 biological control projects have been evaluated and considered substantially successful. Another 66 or so, conducted in many parts of the world, have been evaluated as partially successful (DeBach 1964).

Describing pest management

Pest management can therefore be described as "a set of actions that results from understanding that, instead of eliminating insect pests, we should learn to live with them and to intelligently manage resources, not only economically but also ecologically".

Pest management is more inclusive than integrated control (defined on page 265, this chapter) because, in addition to the factors implicated by integrated control, several fundamental biological and ecological principles are also involved. Pest management recognizes that an insect can become a pest because of human activities such as taking pests to previously uninfested regions through the introduction of exotic plants and animals, producing varieties or races of organisms, simplifying ecosystems, or misusing pesticides. Such actions are usually a result of agricultural or industrial activities.

Controlling cassava pests

During the last 2 decades, collaborative studies of the cassava crop and the control of several of its major pests were carried out by institutions such as the Centro Internacional de Agricultura Tropical (CIAT), the International Institute of Tropical Agriculture (IITA), and the Brazilian Agricultural Research Corporation (EMBRAPA). They successfully used biological control, involving both insects and entomopathogens. Examples of achievements include:

- Mass release of the microhymenopterous parasitoid *Anagyrus lopezi* to control *Phenacoccus manihoti* in Africa.

- Controlling the cassava hornworm in Colombia, Brazil, and Venezuela by applying a baculovirus that attacks *Erinnyis ello*. This virus was found in hornworm colonies at CIAT in 1973. It was applied to commercial crops in Brazil in the 1980s and in Venezuela in the 1990s.

- Using predator mites of the Phytoseiidae family to control the cassava green mite (*Mononychellus* spp.) in Africa and Brazil.

Managing a Specific Pest: the Cassava Hornworm

Research conducted at CIAT on the hornworm *Erinnyis ello* may be used to develop an IPM program for this insect, using the different techniques offered.

The hornworm is attacked by several parasitic and predator insects, bacteria, fungi, and viruses. They can make control of *E. ello* feasible, without having to resort to insecticides that are likely to upset the balance that should exist between the hornworm and its natural enemies (Table 12-1). If insecticides are not applied, then, not only are entomophagous agents conserved, but the reduced number of applications will also help prevent the appearance of other pests, especially mites, that are more difficult to manage.

Natural enemies of *E. ello* eggs

Parasitism of *E. ello* eggs by *Trichogramma* spp. and *Telenomus* sp. helps reduce hornworm populations.

Trichogramma is a parasite of considerable importance, as it is present throughout the year in cassava fields and has a parasitism rate of more than 50%. Furthermore, it is easy to mass-rear in the laboratory. For release, 50 to 100 square inches per hectare should be used over 2 or 3 work days per week, as the parasitoids emerge. This amounts to releasing between 150,000 and 300,000 adults per hectare. During the growing period, 5 to 10 releases (established by previous evaluations) are carried out, costing about US$25/ha.

The moment at which *Trichogramma* adults are released must be determined by periodically evaluating cassava plots to detect the timing of the largest populations of *E. ello* eggs.

No pattern exists to serve as a basis for determining the number of *E. ello* eggs with the timing for release of *Trichogramma* spp. However, the experience of technical personnel and farmers indicates that if the parasite is released when the hornworm first appears, then the parasite can establish in time to control the *E. ello* populations that may suddenly appear.

Table 12-1. Parasites, predators, and pathogens of various stages of the life cycle of the cassava hornworm (*Erinnyis ello*).

Agent attacking	Habit	Order	Family
Eggs			
Trichogramma minutum	Parasite	Hymenoptera	Trichogrammatidae
T. fasciatum	Parasite	Hymenoptera	Trichogrammatidae
T. australicum	Parasite	Hymenoptera	Trichogrammatidae
T. semifumatum	Parasite	Hymenoptera	Trichogrammatidae
Telenomus dilophonotae	Parasite	Hymenoptera	Scelionidae
T. sphingis	Parasite	Hymenoptera	Scelionidae
Chrysopa sp.	Predator	Neuroptera	Chrysopidae
Dolichoderus sp.	Predator	Hymenoptera	Formicidae
Larvae			
Apanteles congregatus	Parasite	Hymenoptera	Branconidae
A. americanus	Parasite	Hymenoptera	Branconidae
Euplectrus sp.	Parasite	Hymenoptera	Eulophidae
Cryptophion sp.	Parasite	Hymenoptera	Ichneumonidae
Microgaster flaviventris	Parasite	Hymenoptera	Ichneumonidae
Sarcodexia innota	Parasite	Diptera	Sarcophagidae
Chetogena (*Euphorocera*) *scutellaris*	Parasite	Diptera	Tachinidae
Thysanomyia sp.	Parasite	Diptera	Tachinidae
Belvosia sp.	Parasite	Diptera	Tachinidae
Drino macarensis	Parasite	Diptera	Tachinidae
Polistes erythrocephalus	Predator	Hymenoptera	Vespidae
P. versicolor	Predator	Hymenoptera	Vespidae
P. carnifex	Predator	Hymenoptera	Vespidae
P. canadensis	Predator	Hymenoptera	Vespidae
Polybia sericea	Predator	Hymenoptera	Vespidae
Podisus sp.	Predator	Hemiptera	Pentatomidae
Zelus sp.	Predator	Hemiptera	Reduviidae
Alcaeorrhynchus grandis	Predator	Hemiptera	Pentatomidae
Bacillus thuringiensis	Pathogen	Eubacteriales	Bacillaceae
Baculovirus erinnyis	Pathogen	GV	Baculoviridae
Prepupae and pupae			
Calosoma sp.	Predator	Coleoptera	Carabidae
Pupae			
Cordyceps sp.	Pathogen	Sphaeriales	Hypocreaceae

Trichogramma spp. should be released when hornworm eggs are newly laid and are green or yellow. *E. ello* eggs should not be left to develop much before releasing the parasites, because once the larvae's cephalic capsule has started forming, the *Trichogramma* spp. will not parasitize them.

CIAT research demonstrates that *Trichogramma austrilicum* shows highly active parasitism on *E. ello* egg clutches (CIAT 1977).

Telenomus sphingis parasitizes the eggs of *E. ello* and *E. alope* and has a significant role in regulating their populations. The biological cycle of *T. sphingis,* from egg to adult, lasts 11 to 14 days. A female lays as many as 228 eggs, which give rise to an average of 99 adults.

Natural enemies of *E. ello* larvae

Five species of predators, several of parasitoids, and one pathogenic virus attack the larvae of this pest:

Predators. Two wasps and a bug are the most used:

- *Polistes erythrocephalus*, *P. canadensis*, and *P. carnifex*. The adults' capacity for predation depends on the number of their own larvae that they have in their nests. At CIAT, each *Polistes* larva was assessed as consuming 0.47 of an *E. ello* larva per day (CIAT 1977; Martín 1985).

- Cassava fields may be colonized with *Polistes* nests placed in stands or huts. To establish their colonies, adults prefer cool shaded places that are close to water. Hence, building bamboo and palm leaves are used to construct the stands. A hut every 4 ha and 20 nests per hut are recommended. The nests should contain more than 50 cells to ensure that the numbers of females and males are sufficient to favor the establishment of new colonies.

- *Podisus* spp. (Hemiptera: Pentatomidae). The most common species are *P. obscurus* (Dallas) and *P. nigrispinus*. Their importance lies in the ease of mass-rearing them and their capacity for predation. Throughout its life, a *P. obscurus* bug can consume between 339 and 1023, with an average of 720, first- and second-instar larvae. The biological cycle lasts from 65 to 119 days, averaging 97 days (Arias and Bellotti, 1989b).

Parasitoids. Several species have been used with good results:

- *Apanteles = Cotesia americanus* and *C. congregatus*. These braconids attack the larvae, ovipositing their eggs within the hornworms' bodies. The eggs hatch and the tiny larvae develop inside the host hornworms until they pupate in the host's epidermis, forming a white cottony mass or cocoon.

- The releases of *Apanteles* carried out at CIAT resulted in increased parasitism of hornworm larvae by more than 50% (CIAT 1977). On a field scale, the environment influences the effectiveness of the parasitoids. For example, in the Atlantic Coast of Colombia, in samplings carried out by CIAT, *Apanteles* spp. and *Telenomus sphingis* were found to be more effective than in the country's hinterland (Valle del Cauca and Quindío). In contrast, *Trichogramma* spp. are less effective in the Atlantic Coast than in the hinterland (Gallego, 1950; B Arias 1990, unpublished data).

  The parasite can be mass-reared for use in biological control programs.

- *Drino* sp., *Belvosia* sp., and *Chetogena (Euphorocera) scutellaris* are dipterans (flies) that parasitize *E. ello* larvae. *Chetogena scutellaris* is particularly important, as it can be mass-reared in the laboratory and possesses a rapid biological cycle.

Other biocontrol agents

Hornworm larvae are also attacked by the granulosis virus *Baculovirus erinnyis* (EeGV) and by the bacterium *Bacillus thuringiensis*. The latter is available commercially (thus facilitating its use) under the trade names DiPel®, Thuricide, Bactospeine, and Biotrol.

Bacillus thuringiensis. Trials conducted at CIAT showed that this bacterium is effective against all larval stages (particularly the first and second instars). It is applied in doses of 3 to 4 g of commercial product per liter of water for soil applications, and of 800 to 1000 g/L for aerial applications. This product has the advantage of not affecting natural enemies of *E. ello* or other insects (Arias and Bellotti 1977).

Baculovirus erinnyis *(EeGV).* This virus is both highly specific and virulent for the pest. Egg parasites such as *Trichogramma* sp. are more abundant in areas where *B. erinnyis* is used. These two beneficial agents are the most efficient controllers of *E. ello* (Arias et al. 1989a; Torrecilla et al. 1992).

The baculovirus can be obtained from infected insects found in the field, or a base solution, maintained in the freezer, can be used. The latter is prepared from *E. ello*, that is, larvae that have died from the disease (Arias and Bellotti 1987; Torrecilla et al. 1992).

The baculovirus begins to act on hornworm larvae when these ingest contaminated leaves. After 4 days, the sick larvae start to lose their capacity for locomotion and feeding, their bodies becoming white and bleached. Death occurs from day 7 onwards when they hang, head downwards, from the leaves (Torrecilla et al. 1992).

Findings obtained from different studies conducted with *B. erinnyis* point out its advantages over most biological control agents. The latter tend to decline in numbers when they do not have their hosts in the field. The virus, however, can be stored for several years when no pest is present, to be used when the opportunity arises (Arias and Bellotti 1987; Torrecilla et al. 1992).

Usually, larvae attacked by the virus become slow, permanently regurgitate, and present residues of excrement adhering to the anal area. The black larvae take on a shiny tone and become extremely flaccid, finally hanging from their anal pseudopodia. Green and yellow larvae also develop brown spots in the folds of some segments or on the central parts of these, as if they had been burnt with a cigarette. Finally, the dead larvae dry up (Arias and Bellotti 1987; Torrecilla et al. 1992).

In the field, the larvae affected by this virus break apart, thus spreading the pathogen and triggering a disease that becomes endemic and able to wipe out the pest. After the larvae have died, they decompose through the joint activities of other microorganisms, especially bacteria, and give off repugnant odors. Hence, larvae collected for use to prepare base solutions or to process or purify the virus must be refrigerated (Torrecilla et al. 1992).

A base solution is prepared with macerated dead larvae. The solution is sprayed directly on the plants. To distribute the virus effectively throughout the crop, 20 to 70 cc in 200 liters of water is needed per hectare (Torrecilla et al. 1992).

To safely manage the virus, recommendations are to (Torrecilla et al. 1992):

- Keep *B. erinnyis* in the freezer either as dead larvae or in solution (liquefied mixture), using plastic bags or lidded glass bottles.
- Withdraw from the freezer only when it is needed and in the quantities required.
- In preparing the solution, avoid using live larvae, larvae that have died from other causes, or larvae that are already decomposing.
- Spray or pulverize only in the early hours of the morning.
- Avoid spraying when larvae are large.
- Visit the cassava plot periodically to detect the pest when it appears.

Recommendations for controlling cassava hornworm

During the first stages of their life cycle, larvae remain hidden under the lower sides of terminal leaves. Hence, when passing through the fields, these parts of the plants must be closely examined. When 5 to 7 first- or second-instar larvae per plant are found, the product should be applied. This level is flexible, depending on the abundance of natural enemies, climatic conditions, cassava variety, and plant age and vigor.

The number of plants to check per hectare depends on the area planted to the crop and on the availability of time. A minimum of five plants per hectare would be acceptable. For plantings of more than 15 ha, having as a trained worker, known in Spanish as a *plaguero*, to permanently check the fields is most advisable.

We emphasize that the success of integrated control depends on the timely application of the different techniques. Insecticides, for example, are valuable components of that control but should be resorted to only when strictly necessary.

Sometimes, beneficial insects are not sufficient to control the hornworm or its larvae when these have reached third instar or larger. In this case, applications of microbial insecticides would not have the expected effectiveness. In such a case, Dipterex 80 SP (trichlorfon) can be applied in doses of 3 g of commercial product per liter of water for soil applications, and 600 to 800 g/ha for aerial applications.

Ultraviolet light traps, particularly black-light lamps (BL type) and blue-black light lamps (type BLB) can be used to attract and capture adult hornworms (Bellotti et al. 1983). Although light traps do not constitute a control method, they allow researchers to discover the fluctuations in population sizes of *E. ello* adults and, hence, better plan the application of IPM.

Preliminary experiments led to the capture of as many as 3094 adults in one night, with the largest number of individuals being trapped between midnight and 2 a.m. This information is important because, in

sites where energy is not available, the traps need only work between midnight and 2 a.m., using batteries or combustion motors (Bellotti et al. 1983).

In fields where the pest is only beginning to attack, manually collecting larvae and pupae is highly effective for reducing hornworm populations.

Options for Controlling Cassava Pests

Table 12-2 summarizes the control options currently available for managing the principal cassava pests. Insects normally appear as pests when the plant's levels of resistance either do not exist or are very low. However, for these pests, a large number of biological control agents may exist. The situation may also arise in which natural controllers are limited. Fortunately, highly acceptable levels of resistance have been found.

In most cases, the two control tools are available, with one being more efficient than the other. For successful control in this crop, the two should, ideally, be combined, together with adequate agronomic practices, thus minimizing pesticide use.

A successful program of IPM for cassava should harmonize with the environment. Pest management technologies should be available at low cost to farmers in developing countries (Bellotti 2000).

Table 12-2. Options to control principal cassava pests.

Pest	Control option	References
Hornworm	Biocontrol: Baculovirus as pesticide; monitoring adult populations with light traps and egg count in the field.	Arias and Bellotti 1987; Bellotti et al. 1992, 1999; Braun et al. 1993; Schmitt 1988
Mites	HPR[a]: Moderate levels of resistance available in cassava clones; an effective program for incorporating resistance into commercial cultivars is needed. *Biocontrol*: A major complex of Phytoseiidae predators that can reduce mite populations is available; other entomopathogens (e.g., *Neozygites* and viruses) have been identified and evaluated.	Bellotti and Riis 1994; Braun et al. 1989; Byrne et al. 1982, 1983; CIAT 1999; Bellotti et al. 1999; Yaninek et al. 1991
Whitefly	Resistance: High levels have been found in some clones and hybrids. Biocontrol: Enemies, especially parasitoids, have been identified and are being evaluated; some entomopathogens give possibilities of control.	Arias 1995; Bellotti and Riis 1994; Bellotti et al. 1999; Castillo 1996; CIAT 1999
Mealybugs	*Resistance*: No adequate levels have been found in *M. esculenta* germplasm. Some wild *Manihot* species have potential for resistance. Biocontrol: three parasitoids (*Acerophagus coccois, Aenasius vexans,* and *Apoanagyrus diversicornis*) provide good control for *Phenacoccus herreni.*	Bellotti et al. 1999; Bento et al. 1999; Van Driesche et al. 1990
(*Phenacoccus manihoti*)	The parasitoid *Anagyrus lopezi* provides very good control in most cassava-growing areas of Africa and Brazil.	Herren and Neuenschwander 1991; Neuenschwander 1994
Thrips	HPR[a]: Pubescent cultivars have very good resistance and are available to farmers.	Bellotti and Kawano 1980; Bellotti and Schoonhoven 1978c
Subterranean burrower bug (*Cyrtomenus bergi*)	HCN contents in cassava: Cultivars with high contents in roots present less damage. Biocontrol: Natural enemies such as fungal and nematoid entomopathogens have given promising results. *Intercropping*: Intercropping cassava with *Crotalaria* reduces damage.	Barberena and Bellotti 1998; Bellotti and Riis 1994; Bellotti et al. 1999; Caicedo and Bellotti 1994; Riis 1997
Stemborers (*Chilomima clarkei*)	Farming practices: Keeping fields clean and destroying infested stems. Transgenesis: Possible use of transgenic plants (*Bt*) is being studied.	Bellotti and Schoonhoven 1978a, 1978b; Gold et al. 1990; Lohr 1983
Lace bug	HPR[a]: Research indicates some level of resistance present in landrace varieties. Biocontrol: Natural enemies have been identified, but research on their effectiveness is lacking.	Bellotti et al. 1999; Cavalcante and Ciociola 1993; CIAT 1990; Farías 1985

a. HPR = host-plant resistance.

SOURCE: Bellotti 2000.

Biotechnology

The biotechnology tools available usually offer a potential to develop improved varieties resistant to pests, thus increasing the effectiveness of natural controllers, including the parasitoids and other entomopathogens mentioned here. The new generation of genetic technologies for pest management is currently being integrated with traditional IPM. It offers alternative technologies for controlling stemborers, leafcutting ants, grasshoppers, white grubs, and other pests difficult to control. This research is already under way and may be available to farmers in the near future (Bellotti 2000).

Pesticides

Few pesticides are used in traditional cassava agroecosystems, because of their high cost and the crop's long cycle, which would make several applications necessary. Some farmers in the Neotropics respond to pest outbreaks with pesticides (Bellotti 2000). For cassava production in large plantings, the trend is to increasingly apply more pesticides to control outbreaks, as in certain areas of Colombia, Venezuela, and Brazil (Bellotti 2000).

The possibility is real that chemical pesticides can be replaced with bioplaguicides in cassava pest management. One example is the effectiveness of the baculovirus against the hornworm and its successful implementation, especially for large plantings (Bellotti 2000).

Entomopathogens are being found for mites, mealybug, whitefly, hornworm, white grubs, subterranean burrower bug, grasshoppers, and others. Research must also be conducted to develop bioplaguicides and other methodologies for their effective implementation. Such activity requires collaboration with the bioplaguicide industry, a process that has already started in Colombia with the production of *Baculovirus erinnyis* (Bellotti 2000).

Agronomic practices

Traditional farmers in most cassava-growing regions have depended on a set of cultural practices that enable them to effectively reduce pest populations (Lozano and Bellotti 1985). Intercropping is a common practice among small farmers. It reduces both the populations of whitefly, hornworm, and subterranean burrower bug, and the damage they cause (Bellotti 2000).

However, farmers may be reluctant to adopt these practices if the intercrop species are not commercially acceptable or if the cassava crop yield is considerably reduced. In large plantings, where mechanization is a production practice, intercropping may not be adoptable. Other cultural practices that may reduce pest populations are varietal mixtures, burning of harvest residues, crop rotation, planting time, and use of high-quality, pest-free, planting materials (Bellotti 2000).

Use of natural enemies

In Africa, classical biological control has been highly successful for managing introduced pests. The management of many cassava pests in the Neotropics requires greater commitment from farmers to effectively implement solutions (Bellotti et al. 1999). Numerous studies in cassava fields in several Neotropical regions have revealed that complexes abound of natural enemies of pests important to that crop. CIAT maintains a taxonomic reference collection, with a systematized database of cassava pests and their natural enemies. The information is available to growers, agricultural researchers, outreach programs, taxonomists, and museums (Bellotti 2000).

Results from explorations and research indicate that natural biological control frequently occurs in the Neotropics. This phenomenon was expected because the diversity of cropping systems and perenniality of the cassava crop would induce a balanced association among pests and their natural enemies (Bellotti 2000).

Disruption of this system (e.g., through pesticide use) may cause pest outbreaks. As described above, populations of the green cassava mite (*M. tanajoa*) in northern South America are regulated by a complex of phytoseiid predator mites. Once this complex is disturbed, yields drop (Bellotti 2000).

The virulence of natural enemies can be increased through genetic engineering, thus permitting use of this abundant complex (Bellotti 2000).

Host-plant resistance

The germplasm bank held at CIAT offers entomologists and breeders more than 6000 cassava varieties in which a group of genes for pest resistance may be found. As mentioned above, variable levels of resistance to mites, whitefly, thrips, subterranean burrower bug, lace bug, and stemborer have been identified (Bellotti 2000).

The innovative biotechnological tools that are available allow efficient and easy access to resistant genes and faster manipulation of molecular levels. Numerous materials from the germplasm bank are continually planted in the field and systematically evaluated for pest resistance (Bellotti 2000).

CIAT has various techniques for mass-rearing most of the principal cassava pests. Also available are damage descriptions and population scales for identifying susceptible and resistant germplasm. Field evaluations of germplasm for resistance need to be carried out, regardless of whether infestations are natural or artificial, because certain symptoms of damage caused by cassava pests are not truly expressed by plants maintained in the screenhouse or greenhouse (Bellotti 2000).

Varieties that possess multiple resistance (i.e., resistance to more than one pest) have been identified. For example, M Ecu 72 contains high levels of resistance to whitefly and thrips, and moderate resistance to mites. One challenge that geneticists and breeders may face is to include resistance to both diseases and arthropods within the one variety (Bellotti 2000).

The principal sources of resistance to pests may be found in the more than 100 wild *Manihot* species so far identified (Allem 1994). Small collections of these are held at some institutes, including CIAT, EMBRAPA (Brazil), and IITA (Bellotti 2000).

The genetic molecular cassava map is being developed (Fregene et al. 1997). This will become a very useful tool for developing, using other *Manihot* species, transgenic cassava plants with resistance to pests (Bellotti 2000).

Projects on IPM in cassava are few. Guides and strategies for the appropriate implementation of alternative controls are not available for small farmers in traditional production systems (Bellotti 2000). Such a lack is also strongly felt in large cropping systems, where the implementation of an effective IPM system, based on biological control and resistant varieties, is decisive in maintaining high yields. This is especially true in the Neotropics, where a large complex of arthropod pests and diseases exist (Bellotti 2000).

An effective proposal for cassava growers is one that overcomes the slow dissemination of technology, for example, use of participatory methods with farmers and inclusion of the private sector in planning research and determining its objectives. The successful implementation of a pilot IPM project in a cassava crop developed with traditional farmers in Northeast Brazil is a real example where such methodology was successfully applied (Bellotti 2000).

References

The following acronyms are used to save space:

CIAT = Centro Internacional de Agricultura Tropical
SOCOLEN = Sociedad Colombiana de Entomología

Allem AC. 1994. The origin of *Manihot esculenta* Crantz (Euphorbiaceae). Genet Resour Crop Eval 41:133–150.

Arias B. 1995. Estudio sobre el comportamiento de la "mosca blanca" *Aleurotrachelus socialis* Bondar (Homoptera: Aleyrodidae) en diferentes genotipos de yuca, *Manihot esculenta* Crantz. MSc thesis. Universidad Nacional–Palmira, Colombia. 181 p.

Arias B; Bellotti AC. 1977. Eficiencia del *Bacillius thuringiensis* sobre el gusano cachón *Erinnyis ello* en yuca en un programa de control biológico. In: Proc IV Congress of SOCOLEN. Bogotá, DC, Colombia.

Arias B; Bellotti AC. 1987. Control de *Erinnyis ello* (L.) (Lep.: Sphingidae) gusano cachón de la yuca (*Manihot esculenta* Crantz) con *Baculovirus erinnyis* NGV. Rev Colomb Entomol 13(2):29–35.

Arias B; Bellotti AC; García F; Heredia A; Reyes JA; Rodríguez NS. 1989a. Control de *Erinnyis ello* (L.) (gusano cachón de la yuca) mediante el uso de *Baculovirus erinnyis* en el Patía (Cauca). Entomólogo (Bol SOCOLEN, Bogotá) 62:1–2.

Arias B; Bellotti AC. 1989b. Potencial de predación de *Podisus obscurus* (Dallas) sobre *Erinnyis ello* (L.), el gusano cachón de la yuca. In: Abstracts [of the] Proc XVI Congress of SOCOLEN, Medellín, Colombia. SOCOLEN, Bogotá, DC, Colombia. 166 p.

Barberena MF; Bellotti AC. 1998. Parasitismo de dos razas del nemátodo *Heterorhabditis bacteriophora* sobre la chinche *Cyrtomenus bergi* (Hemiptera: Cydnidae) en el laboratorio. Rev Colomb Entomol 24(1/2):7–11.

Bellotti AC. 2000. Las plagas principales del cultivo de la yuca: Un panorama global. In: Symposium on "Avances en el Manejo de Plagas". Proc XXVII Congress of SOCOLEN, Medellín, Colombia, July 2000. SOCOLEN, Bogotá, DC, Colombia. p 189–217.

Bellotti AC; Kawano K. 1980. Breeding approaches in cassava. In: Maxwell FG; Jennings PR, eds. Breeding plants resistant to insects. Wiley, NY, USA. p 314–335.

Bellotti AC; Riis L. 1994. Cassava cyanogenic potential and resistance to pests and diseases. Acta Hortic 375:141–151.

Bellotti AC; Schoonhoven A van. 1978a. Cassava pests and their control. CIAT, Cali, Colombia. 71 p.

Bellotti AC; Schoonhoven A van. 1978b. Mite and insect pests of cassava. Annu Rev Entomol 23(1):39–67.

Bellotti AC; Schoonhoven A van. 1978c. Plagas de la yuca y su control. CIAT, Cali, Colombia. p 55–59.

Bellotti AC; Reyes JA; Arias B. 1983. Manejo de plagas en yuca. In: Reyes JA, comp. Yuca: Control integrado de plagas. CIAT, Cali, Colombia. p 265–281.

Bellotti AC; Arias B; Guzmán OL. 1992. Biological control of the cassava hornworm *Erinnyis ello* (Lepidoptera: Sphingidae). Fla Entomol 75:506–515.

Bellotti AC; Smith L; Lapointe SL. 1999. Recent advances in cassava pest management. Annu Rev Entomol 44:343–370.

Bento JMS; Bellotti AC; Castillo JA; de Morães GJ; Lapointe SL; Warumby JF. 1999. Introduction of parasitoids for control of cassava mealybugs in northeastern Brazil. Bull Entomol Res 89(5):403–410.

Braun AR; Bellotti AC; Guerrero JM; Wilson LT. 1989. Effect of predator exclusion on cassava infested with tetranychid mites (Acari: Tetranychidae). Environ Entomol 18(4):711–714.

Braun AR; Bellotti AC; Lozano JC. 1993. Implementation of IPM for small-scale cassava farmers. In: Altieri MA, ed. Crop protection strategies for subsistence farmers. Westview, Boulder, CO, USA. p 103–115.

Byrne DH; Guerrero JM; Bellotti AC; Gracen VE. 1982. Yield and plant growth responses of *Mononychellus* mite resistant and susceptible cassava cultivars under protected vs infested conditions. Crop Sci 22(5–6):486–550.

Byrne DH; Bellotti AC; Guerrero JM. 1983. The cassava mites. Trop Pest Manage 29(4):378–394.

Caicedo AM; Bellotti AC. 1994. Evaluación del potencial del nematodo entomógeno *Steinernema carpocapsae* Weiser (Rhabditida: Steinernematidae) para el control de *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae) en condiciones de laboratorio. Rev Colomb Entomol 20(4):241–246.

Castillo J. 1996. Moscas blancas (Homoptera: Aleyrodidae) y sus enemigos naturales sobre cultivos de yuca (*Manihot esculenta* Crantz) en Colombia. MSc thesis. Universidad del Valle, Cali, Colombia. 173 p.

Cavalcante MLS; Ciociola AI. 1993. Variabilidade quanto au grau de resistência de cultivares de mandioca ao percevejo de renda em Pacajus, CE. In: Relatório Anual de Pesquisa, 1980 a 1992, vol 2. Empresa de Pesquisa Agropecuária do Ceará (EPAC), Fortaleza, Brazil. p 295–304.

CIAT. 1977. Informe Anual 1976. Cali, Colombia.

CIAT. 1990. Annual report [of the] Cassava Program, 1989. Cali, Colombia. 385 p.

CIAT. 1999. Annual Report: Integrated pest and disease management in major agroecosystems. Cali, Colombia. 136 p.

DeBach P. 1964. Biological control of insect pests and weeds. Reinhold Publishing, NY, USA. 844 p.

Farías ARN. 1985. *Hyaliodes vitreus* (Hemiptera: Miridae), un predador de *Vatiga illudens* (Drake, 1773) (Hemiptera: Tingidae) em mandioca, na Bahia. Rev Brasil Mandioca 4(1):123–124.

Fregene M; Angel F; Gómez R; Rodríguez F; Chavarriaga P; Roca W; Tohme J; Bonierbale M. 1997. A molecular genetic map of cassava (*Manihot esculenta* Crantz). Theor Appl Genet 95:431–441.

Gallego M, L. 1950. Estudios entomólogicos: El gusano de las hojas de la yuca (*Erinnyis ello*). Rev Fac Nac Agron (Colomb) 11:84–110.

Gold CS; Altieri MA; Bellotti AC. 1990. Effects of intercropping and varietal mixtures on the cassava hornworm, *Erinnyis ello* L. (Lepidoptera: Sphingidae), and the stemborer, *Chilomima clarkei* (Amsel) (Lepidoptera: Pyralidae), in Colombia. Trop Pest Manage 36(4):362–367.

Herren HR; Neuenschwander P. 1991. Biological control of cassava pests in Africa. Annu Rev Entomol 36:257–283.

Lohr B. 1983. Biología, ecología, daño económico y control de *Chilomima clarkei* (Amsel) (Lepidoptera, Pyralidae) barrenador de la yuca. In: Reyes JA, comp. Yuca: Control integrado de plagas. CIAT, Cali, Colombia. p 159–161.

Lozano JC; Bellotti AC. 1985. Integrated control of diseases and pests of cassava. In: Cock JA; Reyes JA, eds. Cassava: research, production and utilization. CIAT, Cali, Colombia. p 575–585.

Martín CA. 1985. Biología y comportamiento de *Polistes erythrocephalus* Ltr. (Hymenopotera: Vespidae), predador del gusano cachón de la yuca, *Erinnyis ello* (L.), (Lepidoptera: Sphingidae). BSc thesis. Universidad Nacional de Colombia–Palmira, Colombia. 124 p.

Neuenschwander P. 1994. Control of cassava mealybug in Africa: lessons from a biological control project. Afr Crop Sci J 2:369–383.

Riis L. 1997. Behaviour and population growth of the burrower bug, *Cyrtomenus bergi* Froeschner: effects of host plants and abiotic factors. Dissertation. Royal Veterinary Agricultural University, Copenhagen, Denmark. 167 p.

Schmitt AT. 1988. Uso de *Baculovirus erinnyis* para el control biológico del gusano cachón de la yuca. Yuca Bol Inf 12:1–4.

Torrecilla SM; Nunes F, AR; Gómez EJ; Pegoraro RA. 1992. Manejo integrado del 'marandová' de la mandioca en el Cono Sur, Unidad 5. Unidades de aprendizaje para la capacitación en tecnología de producción de mandioca. CIAT; BID; CNPMF; EMATERS; UNESP. Cali, Colombia.

Van Driesche RG; Bellotti AC; Castillo JA; Herrera CJ. 1990. Estimating total losses from parasitoids for a field population of a continuously breeding insect, cassava mealybug, *Phenacoccus herreni* (Homoptera: Pseudococcidae) in Colombia, S.A. Fla Entomol 73:133–143.

Yaninek JS; Mégev B; de Morães GJ; Bakker F; Braun A. 1991. Establishment of the Neotropical predator *Amblyseius idaeus* (Acari: Phytoseiidae) in Benin, West Africa. Biocontrol Sci Technol 1(4):323–330.

CHAPTER 13

Potential for Biological Control in the Management of Cassava Pests*

Elsa Liliana Melo and Carlos Alberto Ortega[1]

Biological Control

Biological control, in the ecological sense, as a phase of natural control, may be defined as the regulation of the population density of a pest organism by natural enemies (parasites, parasitoids, predators, or pathogens) at a level that would be equal or greater than would have been reached by means of another alternative. Applied biological control supposes professional activity or human manipulation that promotes the effectiveness of natural enemies (DeBach 1977).

In a broad sense, biological control may also be defined as mortality or suppression of pest organisms by any biotic factor. In this wider sense, it is the direct action of parasites, parasitoids, predators, and pathogens (i.e., natural enemies) and of competition with other species for natural resources (i.e., antagonists) that regulate an organism's population density to a level lower than it would have been in the absence of that control. It does not include plant resistance, interference with the pest by semiochemicals (e.g., pheromones, allomones, kairomones, and synomones), genetic engineering of the pest, natural chemical extracts, or mechanical control by humans. It does include the manipulation of natural enemies and antagonists through, for example, importation, mass-rearing, and release (Cave 1995a).

Research on biological control includes baseline surveys of any application of the method. These do not necessarily report immediately useful results or direct methods for using, manipulating, or conserving natural enemies. In the first phases, the fundamental aspects studied are taxonomy, biology, physiology, genetics, ecology, demography, behavior, and nutrition of pests and their enemies (DeBach 1975).

If necessary, a pest and its enemies are identified by a specialist, as the organism's name and classification are key to all existing knowledge on it, and thus understanding and controlling it if it is pest, or using it if it is a natural enemy (Cave 1995b).

Natural Enemies

In biological control, various natural enemies participate, for example, parasites, parasitoids, predators, and microorganisms. These organisms must be able to respond quickly to the pest's population dynamics, so that proportionately more natural enemies are present as the pest population increases. This characterizes the theoretically ideal natural enemy, as well as certain biological and ecological criteria (Cave 1995c).

Predators

Predators are carnivorous organisms that, in either immature or adult state, actively seek and capture numerous prey, consuming them either partially or totally. Perhaps half of all insects and mites are predators. As they are so numerous, determining the most effective predators is difficult. They are classified as either generalists or specialists, according to eating habits and behavior. The principal arthropod predators belong to the following orders: Odonata, Orthoptera, Dermaptera, Hemiptera, Neuroptera, Coleoptera, Diptera, Hymenoptera, Araneae, and Acari. Families that stand out are Mantidae, Labiduridae, Pentatomidae, Chrysopidae, Carabidae, Staphylinidae, Coccinellidae, Elateridae, Cecidomyiidae, Syrphidae, and Phytoseiidae (Banegas and Cave 1995).

---

* This chapter is a revision of the version originally published in the Proceedings of the XXVII Congress of SOCOLEN, 2000.

1. Advisors in Plant Health, Biotechnology Laboratories and Annexed Services (LABIOTSA), Quito, Ecuador. E-mails: meloelsa@gmail.com and caortegao@gmail.com

Parasites

A parasite is an organism that lives at the expense of another organism—the host (Australian Museum 2005). In general parasites share the following features:

- Parasites are usually smaller than their host. Parasites use both invertebrate and vertebrate hosts.
- Adult parasites may live on the host (e.g., lice), in the host (e.g., tapeworms) or feed on a host occasionally (e.g., mosquitoes).
- Parasites generally do not kill the host but may harm the host indirectly by spreading pathogens. This may affect the host's behavior, metabolism or its reproductive activity.
- Many parasites have hooks, claws or suckers to attach to their host. Generally parasites have either a sucker (e.g., leeches) or piercing and sucking type mouthparts (e.g., fleas) for feeding.
- Both adults and young can be parasitic. In some cases the young are parasites but the adult is not.

Parasitoids

A parasitoid is an organism that has young that develop on or within another organism (the host), feeding on a single host and killing it at the end of their cycle. The adult state lives free and is not parasitic. Among the characteristics that make parasitoids promising for biological control are:

- Specificity (e.g., Aphelinidae and Encyrtidae)
- Ease of breeding in large quantities (e.g., *Trichogramma* spp., *Cotesia flavipes*, *Encarsia formosa,* and *Telenomus remus*)
- The power of flight, which facilitates dispersion
- High fertility, short generational time, and evolutionary rates that are comparable with those of the pests

Parasitoid species can be found in five of the insect orders, but most are in two: either the Hymenoptera or Diptera (Díaz and Hanson 1995). Important families include Aphelinidae, Platygastridae, Eulophidae, and Encyrtidae.

Entomopathogens

As their name says, entomopathogens cause diseases in insects, and are grouped as microbiological controllers. According to Castillo et al. (1995), the expression "microbiological control" refers to the use of microorganisms (which, in the broad sense, includes nematodes) to control pests.

Recently, the use of microorganisms to effectively control insect pests in different crops has increased, most likely as a result of the discovery and development of new species and strains of entomopathogens (Lacey and Brooks 1997). Insects associate with microorganisms in diverse ways such as symbiosis, mutualism, and parasitism. Mutualism abounds among insects; an example is the association of protozoa with termites, although the former are not pathogenic to the host insects. In contrast, entomopathogens cause infections, parasitism, or toxemia in insects (Lacey and Brooks 1997).

Five principal groups of microbiological agents exist: viruses, fungi, nematodes, bacteria, and protozoa.

Viruses. Entomopathogenic viruses are infectious entities whose genome, constituting nucleic acid, DNA, or RNA, is replicated in host tissues. A major viral family for insect control is the Baculoviridae. Baculoviruses contaminate the insect through the oral pathway. Normally, virions (infective units of viruses) are found on plant leaves and stems, and are ingested by the insect as it eats. The first cells to be affected are the epithelial ones of the intestine. The virus then attacks other tissues such as fatty bodies, intestinal epidermis, hemocytes, trachea, and silk glands. Infected larvae become lethargic, stop eating, and finally become paralyzed. Dead insects become the most important sources of inoculum for maintaining the epizootic (Castillo et al. 1995).

Fungi. Entomopathogenic fungi kill the host relatively quickly by penetrating and proliferating within its body. The insect dies as the fungus either deprives it of soluble nutrients from the hemolymph, invade or digest its tissues, or releases toxins that poison it. Not all fungi associated with insects are pathogenic. Some pathogens are obligate, but most are facultative. Saprophytic and other symbiotic fungi also exist (Ferron 1985).

More than 700 species of entomopathogenic fungi exist, distributed across different taxonomic groups, and all with potential for use in regulating insects (Hajek and St Leger 1994). The most widely accepted classification system of fungi was proposed by Ainsworth in 1973 (cited by Tanada and Kaya 1993). It

separates fungi into two divisions: Myxomycota, which are plasmodial (i.e., asexual, pseudopodial, and producing masses of multinucleate protoplasm that resemble amebas); and Eumycota, which are nonplasmodial and frequently mycelial in form. Entomopathogenic fungi are found in the division Eumycota and in the following subdivisions:

- Mastigomycotina: mobile cells or zoospores; perfect stage as oospores
- Zygomycotina: cells not mobile; perfect stage as zygospores
- Ascomycotina: perfect stage as ascospores
- Basidiomycotina: perfect stage as basidiospores
- Deuteromycotina: cells not mobile; no perfect stage

Most entomopathogenic fungi are found in the subdivisions Zygomycotina, class Zygomycetes, order Entomophthorales (e.g., *Neozygites* genus); and Deuteromycotina, class Hyphomycetes, order Moniliales (includes the genera *Aspergillus*, *Beauveria, Fusarium, Hirsutella, Metarhizium, Paecilomyces,* and *Verticillium*).

Researchers of entomopathogenic fungi have carried out studies that indicate an apparently logical way to demonstrate the virulence or pathogenicity of these fungi in different insects. Thus, they can enter in an integrated pest management (IPM) program (Sánchez 1996).

Nematodes. The phylum Nematoda is, after Arthropoda, the most diverse of the animal kingdom. They can be found in a wide variety of habitats. They are round worms that lack respiratory and circulatory systems. The insect-nematode association ranges from accidental to obligate and from commensal to parasitic (Stock 1998).

Nematodes of the families Steinernematidae and Heterorhabditidae are obligate parasites of a broad range of insect species. In each family, only one genus exists, respectively, the *Steinernema* and *Heterorhabditis*. Their members live in mutualism with the bacteria *Xenorhabdus* sp. and *Photorhabdus* sp., respectively (Sáenz 1999).

These bacteria, which are lethal for their insect hosts, make the nematodes an adequate organism for biological control. The infective state is the juvenile of the third nymphal stage (IJ3), which either enters through natural apertures such as the mouth, anus, or spiracles, or penetrates the insect's cuticle to reach the hemocele, where it releases the symbiont. The bacterium proliferates and produces enzymes (lipases and proteases) that degrade the host's tissues. Together, the nematodes and bacteria kill the insect within 48 h. The juveniles then consume the bacteria and the insect's degraded tissues.

Nematode development is favored by the bacterium producing antibiotics, preventing the proliferation of secondary pollutants. Between one and three generations of the nematode are produced in the host insect, depending on its size. All individuals of *Steinernema* are sexually differentiated. In *Heterorhabditis,* however, those of the first generation are hermaphrodite and those of the second are differentiated.

The bacteria *Xenorhabdus* and *Photorhabdus* are Gram-negative bacilli of the family Enterobacteriaceae (Akhrust and Boemare 1990). In *in vitro* culture, they present two phases:

- P1, where they live in infective nematodes of IJ3 form, producing antibiotics and flagella
- P2, where they live in cadavers of old insects or nematodes

The bacterium-nematode association is mutualistic: the bacterium cannot survive alone in the soil and the nematode cannot develop well without the bacterium. Through mutual assistance, they evade the host's immune response, thus guaranteeing the survival of both. However, more research is needed on this mechanism. Meanwhile, the pathogenic potential of the nematode-bacterium complex has been used for the biological control of several pests (Stock 1998).

Bacteria. Bacteria are found in all dead insects, but only some are the primary cause of mortality; others sometimes cause mild infections. The bacteria enter the insect through its food and remain confined by the intestine's peritrophic membrane. They cause general septicemia, but are not located in any specific tissue. Little is known of the role that bacterial pathogens play in controlling the insect pest. Epizootics occur under reported conditions of high-density populations of the host but, under other circumstances, either occur rarely or are unrecognized.

These bacteria separate into facultative and obligate pathogens. Entomopathogenic bacteria belonging to the genus *Bacillus* (e.g., *B. thuringiensis,*

B. cereus, B. popilliae, and *B. larvae*) are the most promising for controlling insect pests (Castillo et al. 1995).

Protozoa. Protozoa are considered important factors in the natural regulation of the population density of certain insects. However, they have not been much applied as microbial agents, as entomophilic species already cause chronic or debilitating infections in a wide range of hosts (Castillo et al. 1995).

Biological Control of Cassava Pests

The most common natural enemies of cassava pests belong to four groups: parasites, parasitoids, predators, and pathogens. Of these, entomopathogenic fungi, nematodes, and viruses stand out as being the most studied. At CIAT, a list of natural enemies was compiled, which included 76 parasites/parasitoids, 138 predators, and 38 pathogens (Table 13-1). Possibly, more species are still unreported.

Table 13-2 shows some of the major natural enemies that control the cassava pests. Below are discussed significant pests: cassava green mite, cassava mealybug, cassava subterranean burrower bug, whitefly, cassava hornworm, white grubs, stemborers, and lace bugs.

Cassava green mite

The cassava green mite (CGM), *Mononychellus tanajoa* (syn.: *Mononychellus progresivus*), is probably native to Northeast Brazil, where it was reported for the first time in 1938. The indigenous people knew its characteristic symptom of damaged young leaves and meristems, calling it *tanajoa* or "plant disease or problem" (Bellotti and Schoonhoven 1978; Bellotti et al. 1999). In the 1970s, *M. tanajoa* was introduced accidentally to the African continent, first appearing in Uganda (Nyiira 1972). This pest spread throughout the African cassava belt within 10 years, perhaps through the exchange of planting material (Yaninek and Herren 1988). This mite is currently the principal cassava pest in Africa, causing yield losses between 13% and 80% (Herren and Neuenschwander 1991).

To develop a biological control program to combat CGM—a pest of great importance in the subhumid areas of Africa and Brazil—studies were conducted on the taxonomy and geographical distribution of predator mites of the family Phytoseiidae in the cassava crop (Bellotti et al. 1983b). Geographical priority was assigned to the exploration of natural enemies based on agrometeorological homology of those regions in the Americas and Africa affected by CGM (Bellotti et al. 1983b; Yaninek and Bellotti 1987). Agrometeorological homology maps were prepared, based on the microregional classification of the cassava crop as proposed by Carter et al. (1992).

Table 13-1. Natural enemies (no.) of cassava pests.

Pest	Biocontrollers (Enemy type)		
	Parasites/ Parasitoids	Predators	Pathogens
Mites			
Mononychellus tanajoa		60	2
Tetranychus urticae			
Hornworm	18	15	15
Whitefly	17	5	6
Lace bug			1
Mealybug	25	46	2
Fruit fly	3		
Stemborers			
Chilomima clarkei	5	2	5
Lagochirus sp.	2		
Scale insects			
Aonidomytilus albus	2	9	2
Saissetia miranda	2		
Cydnidae		1	2
Gall fly	2		1
White grubs			2
Total	**76**	**138**	**38**

According to Braun et al. (1993), during explorations in the cassava-cropping areas of South America between 1983 and 1990, a total of 40 phytoseiid species were found in cassava and neighboring plants, living in association with the complex of phytophagous mite species. Maximum diversity was verified in Colombia. Of these 40 species, 18 were the most frequently found in the crop (CIAT 1990). Currently, CIAT has a database that stores records belonging to 2416 samples collected from different countries during various exploration periods. In all, 4300 records had been collected and identified by CIAT or international taxonomists. Of these specimens, the project conserves 2368 slides.

During the operation of the "CGM Biological Control" Project, 31 countries of the Americas and other continents were sampled. In Colombia, 1576 samples were recorded, meeting the project's objective.

Table 13-2. Major natural enemies of the most important cassava pests.

Pest	Type of natural enemies		
	Parasitoids	Predators	Entomopathogens
Cassava hornworm			
Erinnyis ello	*Trichogramma* sp. (E)[a] *Telenomus* sp. (E) *Sphingid* sp. (E) *Cotesia americana* (L) *Euplectrus* sp. (L) *Apanteles flaviventris* (L) *Drino* sp. (L) *Euphorocera* sp. (L) *Sarcodexia innota* (L) *Thysanomia* sp. (L) *Belusia* sp. (L) *Forcipomyia eriophora* (L)	*Chrysopa* sp. (E) *Podisus nigrispinus* (L) *P. obscura* (L) *Polistes canadensis* (L) *P. carnifex* (L) *P. erythrocephalus* (L) *P. versicolor* (L) *Zelus* sp. (L) *Polybia emaciate* (L) *P. sericea* (L) *Calosoma* sp. (L) Spiders (several species) (L)	*Bacillus thuringiensis* (L) Baculovirus of *E. ello* (L) *Metarhizium anisopliae* (L) *Beauveria bassiana* (L) *Paecilomyces* sp. (L) *Nomuraea rileyi* (L) *Cordyceps* sp. (P)
Cassava mealybug			
Phenacoccus herreni	*Apoanagyrus diversicornis* *Anagyrus insolitus* *Anagyrus* sp. ca. *putonophilus* *Epidinocarsis elegeri* *Prochiloneurus dactylopii* *Chartocerus* sp. *Acerophagus coccois*	*Ocyptamus* sp. *Sympherobius* sp. *Hyperaspis* sp. *Cleothera onerata* *Nephus* sp.	*Cladosporium* sp. *Neozygites fumosa*
P. madeirensis	*Eusemion* sp. *Signiphora* sp.	*Kalodiplosis coccidarum* *Curinus colombianus* *Cleothera onerata*	
P. manihoti	*Epidinocarsis lopezi* *Gyranusoidea* sp. *Parapyrus manihoti*	*Diomus* sp. *Exochomus* sp. *E. flaviventris* *Sympherobius maculipennis* *Hyperaspis raynevali* *H. aestimabilis* *Diomus hennesseyi*	
Cassava green mite			
Mononychellus tanajoa		Insects: *Stethorus* sp. *Oligota* sp. *Chrysopa* sp. Phytoseiidae mites: *Typhlodromalus manihoti* *T. aripo* *Neoseiulus idaeus*	 *Hirsutella thompsonii* *Neozygites* sp.
Lace bug			
Vatiga manihotae		*Zelus nugax* (N-A)	
Whitefly complex			
Aleurotrachelus socialis	*Encarsia hispida* *E. bellottii* *Eretmocerus* spp. *Euderomphale* sp. nov. *Signiphora* sp.	*Chrysodina* sp. *Delphastus* sp. *Delphastus* sp. pos. *quinculus* *D. pusillus* *Chrysopa* sp.	*Fusarium* sp. *Verticillium lecanii* *Beauveria bassiana* *Metarhizium anisopliae* *Paecilomyces* sp. *Cladosporium* sp.
Bemisia tuberculata	*Eretmocerus* spp. *Encarsia pergandiella* *E. hispida* *Euderomphale* sp. nov. *Metaphycus* sp.		
Trialeurodes variabilis	*Encarsia pergandiella* *E. hispida* *Eretmocerus* sp.		

(Continued)

Table 13-2. (Continued.)

Pest	Type of natural enemies		
	Parasitoids	Predators	Entomopathogens
Aleurodicus dispersus	*Aleuroctonus vittatus* *Eretmocerus* spp.		
Other whiteflies:	*Encarsia sophia* *E. luteola* complex *E. strenua* complex *Amitus macgowni*		
Subterranean burrower bug			
Cyrtomenus bergi		*Nerthra* sp.	*Heterorhabditis bacteriophora* *Steinernema carpocapsae* *Metarhizium anisopliae* *Beauveria bassiana* *Paecilomyces lilacinus*
White grubs			
Phyllophaga spp.; *Anomala* spp.			*Heterorhabditis* spp. *Steinernema* spp. *Metarhizium anisopliae*
Stemborers			
Chilomima clarkei *Lagochirus* spp.		*Bracon* sp. *Apanteles* sp. *Brachymeria* sp.	*Bacillus thuringiensis* *Spicaria* sp. Virus (not ident.)

a. Developmental stage at which the cassava pest are attacked: E = egg; L = larva; N = Nymph; P = pupa; A = Adult.

The most sampled areas were in Colombia, Venezuela, Ecuador, and Brazil. About 87 species were found, of which 25 were new. On cassava, 66 phytoseiid species were collected, with 13 being the most common (Melo 2000).

Typhlodromalus manihoti was collected the most frequently, being found in more than 50% of the sampled fields, followed by *Neoseiulus idaeus*, *T. aripo*, *Galendromus annectens, Euseius concordis*, and *E. ho*. To control *M. tanajoa* in Africa, *T. aripo* and *N. idaeus* showed the most promise (Yaninek et al. 1991, 1993). Since 1984, numerous phytoseiids species have been sent from Colombia and Brazil to Africa.

Of the species that were mass released and established, none came from Colombia. However, three successful species were from Brazil: *T. manihoti, T. aripo,* and *N. idaeus* (Yaninek et al. 1991, 1993; Bellotti et al. 1999). *Typhlodromalus aripo* appeared to be the most promising as it dispersed rapidly to more than 14 countries. Field evaluations indicated that *T. aripo* reduces the CGM population by 35% to 60%, thus increasing fresh matter production by 30% to 37%.

Field experiments conducted in Colombia (Braun et al. 1989) demonstrated the importance of diversity of phytoseiid species for controlling the CGM. In Colombia, fresh and dried roots production was reduced by 33% when natural enemies were eliminated. Neither did acaricide applications increase production, thus indicating the effectiveness of biological control.

The explorations also identified some predator insects of the CGM, especially the staphilinid *Oligota minuta* and the coccinellid *Stethorus* sp. *Oligota minuta* has been classified as the dominant predator of *M. tanajoa* populations. Research conducted at CIAT and in Uganda agrees that *Oligota* populations are located among the fifth and eighth leaves, that is, where the pest is found in highest numbers. One larva can consume from 49 to 70 mites and from 44 to 61 of their eggs. One adult consumes, over 7 to 16 days, between 97 to 142 eggs and adults.

The other insect predator, *Stethorus* sp., is found more in association with another pest: the spider mite *Tetranychus urticae*. In severe attacks in the field, 98% of predators were *Stethorus* sp. and only 2% were *Oligota* sp. (CIAT 1982).

These phytoseiids and predator insects are being intensively studied in the laboratory and field. So far, studies have shown that phytoseiid mites are more efficient than predator insects (Byrne et al. 1983), although laboratory and field studies have shown that the neuropteran predator *Chrysopa* sp., which consumes the pest at different stages, is also very effective.

Other natural enemies of the pest mites are pathogenic fungi belonging to the genera *Neozygites* (Zygomycetes: Entomophthorales) and *Hirsutella* (Hyphomycetes: Moniliales). The former is a pathogenic fungus that appears sporadically in Colombia and Northeast Brazil (*Neozygites* sp. cf. *floridana*) and causes as much as 100% mortality in CGM in 1–2 weeks (Delalibera et al. 1992). Some strains are specific to the *Mononychellus* genus (Moraes and Delalibera 1992).

This pathogen has been also found in Africa, but has never been observed as causing dramatic mortality in this pest (Yaninek et al. 1996). This suggests that isolates from Brazil are more virulent than those of Africa. Because the taxonomy of this genus is not well known and it is necessary to differentiate the African isolates from the candidates for release, molecular analysis of these has started. Results indicate that the isolates can be differentiated, although the technique needs to be standardized to measure genetic distance (Bohórquez 1995).

Hirsutella sp. was evaluated in Africa and shown to be very effective. Its potential is such that it could be used as a biological control agent (Odongo et al. 1988; Yaninek et al. 1996).

Cassava mealybug

One way to control mealybug pests (*Phenacoccus herreni* and *P. manihoti*) is to use natural enemies, finding them through explorations. The management of the cassava mealybug is an example of classical biological control (Herren and Neuenschwander 1991). A complex of mealybug species exists, as mentioned in previous chapters, including *P. herreni*, which is found in the Americas. Of its parasites, two species of *Anagyrus* (Encyrtidae) stand out: *A. insolitus* and *A.* sp. ca. *putonophilus*. Several parasitoids show a specialty or preference for *P. herreni*. Among those identified in northern South America are *Acerophagus coccois*, *Apoanagyrus diversicornis*, *Ap. elegeri, Anagyrus putonophilus, A. insolitus,* and *Aenasius vexans*. Three of these (*Ap. diversicornis, Ac. coccois,* and *Ae. vexans*) were identified as effective for controlling *P. herreni* (van Driesche et al. 1988, 1990).

Collaborative efforts by CIAT and EMBRAPA ensured that *Ap. diversicornis, Ac. coccois*, and *Ae. vexans* were exported from CIAT and released in Northeast Brazil, mainly in the states of Bahia and Pernambuco, during 1994 to 1996. Before introduction, EMBRAPA scientists had carried out field surveys to measure damage and collect natural enemies. By the end of 1996, more than 35,000 individuals of the three parasitoid species had been released.

In Bahia, *Ap. diversicornis* had dispersed 130 km in 6 months, 234 km in 14 months, and 304 km in 21 months, after release. *Acerophagus coccois* had also established successfully, being recovered in high numbers at distances of almost 180 km from the release site 9 months later. *Aenasius vexans*, however, was constantly recaptured at its release site in Pernambuco, having dispersed only 40 km in 5 months (Bento et al. 1999). Comparative studies of the life cycles of the three parasitoids show that each could complete two cycles for one cycle of *P. herreni*, a favorable ratio in biological control.

Aenasius vexans and *Ap. diversicornis* show a marked preference for *P. herreni*, even though laboratory studies indicated that they also parasitize other species of mealybug (Bellotti et al. 1983a, 1994; Bertschy et al. 1997). *Acerophagus coccois* shows equal preference for either *P. herreni* or *P. madeirensis.* All three parasitoids are attracted by infestations of *P. herreni* (Bertschy et al. 1997). *Apoanagyrus diversicornis* prefers third-instar nymphs, while *Ac. coccois*, which is much smaller, parasitizes with equal frequency male cocoons, adult females, and second-instar nymphs. Oviposition by *Ap. diversicornis* causes 13% mortality among third-instar nymphs (van Driesche et al. 1990). *Aenasius vexans* prefers with equal frequency second and third instars and adult females (CIAT 1990).

Some field studies of natural populations of *Ap. diversicornis* and *Ac. coccois* determined the percentage of parasitism by using plant traps as hosts of *P. herreni* around the cassava crop (van Driesche et al. 1988). With the combined action of the two parasitoids, *P. herreni* mortality was estimated at 55% (van Driesche et al. 1990).

In 1980, the cassava mealybug found in the Americas and that in Africa were reported as comprising different species. One presented males, which led to the description of a new species, *P. herreni*. At the same time, *P. manihoti* was located in Paraguay by Bellotti (Herren and Neuenschwander 1991). In addition to the pest, they found 15 natural enemies, two of which were sent for release in Africa. These were a coccinellid predator, *Cleothera onerata*, which, however, had difficulties surviving the rainy seasons; and the other was the parasitoid

Epidinocarsis lopezi, which was released by air and proved to be more effective. Its establishment was achieved in 25 countries of the cassava belt. The mealybug is now under control in 90% of the region (Wigg 1994).

The predators reported as attacking the mealybug (Table 13-1) include *Cleothera onerata* (as mentioned above), *Sympherobius* sp., the dipteran *Ocyptamus* sp., *Hyperaspis* sp., *Nephus* sp., and *Diomus hennesseyi*. The only natural enemy of *P. manihoti* found in Zaire was the predator butterfly *Spalgis lemolea* (Bennett and Greathead 1978; Leuschner and Nwanze 1978).

Entomopathogenic fungi also have been found in association with the cassava mealybug, for example, *Cladosporium* sp. and *Neozygites fumosa* (CIAT 1990).

Cassava subterranean burrower bug

CIAT has carried out baseline surveys on the cassava subterranean burrower bug, *Cyrtomenus bergi* (Hemiptera: Cydnidae), studying such aspects as biology, behavior, population fluctuation, and host preference (Arias and Bellotti 1985). Trials have also carried out on chemical control and cropping with the legume *Crotalaria juncea* (Castaño et al. 1985). Insecticides are not recommended, not only because they are costly, but also because they destroy the natural enemies that control the populations of other cassava pests (Caicedo and Bellotti 1994).

Native nematodes have been found in association with *C. bergi* and are considered as an alternative to chemical and agronomic control. Eight sites around Manizales, Pereira, and Santander of Quilichao have been explored and, in all samples, nematodes were found. Geographical races of *Heterorhabditis bacteriophora* were identified in 37% of isolates recovered from both soil and dead burrower bugs in the field under various climatic and physicochemical soil conditions (Caicedo and Bellotti 1996).

In the interest of control, a search and identification of native isolates of entomopathogenic nematodes (EPNs) were carried out in 2003, collecting soil samples from Quindío, Risaralda, Caldas, and Cauca. To extract EPNs, traps comprising larvae of the insect *Galleria mellonella* (Lepidoptera: Pyralidae) were used. The nematode larvae's pathogenicity was then verified, following the Koch postulates. They were then multiplied, stored, and identified. From 284 soil samples—300 g each—collected from 15 crops at 23 sites, 11 were positive for fungi, 13 for mites, and 17 for entomopathogenic and saprophagous nematodes. From the latter, 20 subsamples were selected according to their morphological characteristics and behavior containing only entomonematodes and they were sent to Germany for identification.

Using the PCR molecular technique, two samples from Cauca (in *Manihot esculenta*) and Risaralda (in *Inga* spp.), respectively, were identified as *Steinernema kraussei* Steiner (Rhabditida: Steinernematidae). This was the first report of these nematodes for Colombia (Melo et al. 2009).

Caicedo (1993) reported that, when she used an isolate of the *S. carpocapsae* strain All, the most susceptible stage of the *C. bergi* proved to be the adult, which presented a 60% parasitism for the entire evaluated doses (2000, 4000, 6000, 8000, and 10,000 EPNs/ml). Over time (2, 5, 8, and 10 days), the nematodes caused 100% parasitism, but mortality was always lower than parasitism. The best dosages for mortality were determined to be LD_{50} of 193 EPNs/ml and LD_{90} of 403 EPNs/ml. On evaluating native isolates found in the samples, the fifth state of the pest was the most susceptible, with 90% succumbing to the isolate from Cauca (SQC92) and 100% to that from Risaralda (LFR92). The next most susceptible state was the adult, with 85% and 100%, respectively, succumbing.

Although the nematodes were able to parasitize all states of the pest, 100% parasitism by isolate LFR92 was effective only at 702 EPNs/ml and by isolate SQC92 at 826 EPNs/ml. Mortality, using LD_{50} and the same strains, needed 800 and 870 EPNs/ml, respectively (Barberena 1996). At the end of 2002, soil samples were collected from the same sites where the EPN strains were initially found. The *Heterorhabditis* sp. strain CIAT was found at La Colonia, Department of Risaralda. Moreover, native and introduced strains of *Steinernema* and *Heterorhabditis* were evaluated on stages 5 and adult of the pest (5000 EPNs/ml). Values of 100% parasitism and 22% mortality were obtained for isolate *Steinernema* sp. strain SNI (CENICAFE) of the adult pest.

Greenhouse experiments were carried out on *C. bergi* applying *S. carpocapsae*, *Steinernema* sp. strain SNI, and *Heterorhabditis* sp. strain HNI, using a concentration of 1000 EPNs/ml. Values for parasitism on the pest were 21%, 18%, and 18%, respectively,

with no mortality. At a higher concentration (25,000 EPNs/ml), parasitism was 55% for *S. carpocapsae* and 45% for *Heterorhabditis* sp. strain HNI, and mortality 29% and 9%, respectively. In another experiments, entomonematodes *S. riobravis*, *Steinernema* sp. strain SNI, and *Heterorhabditis* sp. strain CIAT were evaluated against the third pest stage, with higher concentration (100,000 EPNs/ml). Pest mortality was 33%, 28%, and 26%, respectively.

During this research, on dissecting the burrower bugs, melanization of the EPNs was observed. With the collaboration of the chemistry laboratory at the University of Caldas, phenoloxidase activity was detected. It is probably the pest's immune response to attack from EPNs, injecting them, whether dead or alive. This finding is considered sufficiently important to further study of this line of inquiry to understand how this humoral response, typical in Diptera, appears in this hemipteran (CIAT 2003).

Two EPNs—the native *S. feltiae* (strain sampled at Villapinzón) and the introduced *Heterorhabditis bacteriophora* strain E-Nema—were evaluated for their parasitism on six developmental stages of *C. bergi*. Results were 45.2% and 46.8% infection for *S. feltiae* and *H. bacteriophora*, respectively, on all developmental stages of the pest at applied doses. Despite the lack of statistical differences between strains, the trend was greater infectivity for the fourth instar (48.4%) and adult (46.9%). Isolates of *S. feltiae* induced a mortality rate of 21.4% and those of *H. bacteriophora* 20.0%. Despite the higher infection rate, *H. bacteriophora* nevertheless showed a lower mortality rate.

Commercial concentrations—at 1000 and 500 EPNs/ml of *S. feltiae* and *H. bacteriophora*, respectively—were applied to fifth instars and adults of the pest, and destructive evaluations were made 15 and 30 days after infection (dai). Only the adults were infected, at 93.9% with *S. feltiae* and 72.1% with *H. bacteriophora*, with no distinction of strain or evaluation time. For mortality, at 15 dai, *H. bacteriophora* accounted for 41.2%, and *S. feltiae* 8.6%. However, at 30 dai, they equalized at 62.7%. Dissection of pest individuals revealed melanized EPNs, probably because of *C. bergi*'s immunological response to the EPNs. At 30 dai, *S. feltiae* was shown to be more susceptible (37.5%) than *H. bacteriophora* (13.17%).

Considering the behavior of *S. feltiae* isolates, which was more affected by the pest's defense, the nematode-bacterium complex probably had difficulty developing and thus needed more time to kill the insect. Or, this increased exposure enabled more nematodes to enter and overcome the host's defenses.

Other studies have been conducted to find the best methodology for mass-rearing nematodes, using *H. bacteriophora,* which is considered as promising for its high virulence, its capacity to search, and facility to reproduce (Gaugler and Kaya 1990). Results indicated that the best production was obtained by breeding *in vivo* and *in vitro*. Two races of this species were also evaluated for their capacity to parasitize the entire pest's developmental stage. The fifth stage proved to be the most susceptible. On increasing nematode dose, parasitism also increased (Barberena 1996).

Other entomopathogens used for controlling *C. bergi* are fungi. Bioassays were carried out in the laboratory and suspensions of conidia of the fungus *Beauveria bassiana* were evaluated, together with *Metarhizium anisopliae* and *Paecilomyces lilacinus* (Deuteromycotina: Hyphomycetes), combining three substrata and two inoculation methods. Immature stages of the pest are the most susceptible to *M. anisopliae,* which induces higher mortality rates than either *B. bassiana* or *P. lilacinus* (Sánchez and Bellotti 1997a).

Isolates of *M. anisopliae* from CIAT applied in the laboratory also showed mortality rates ranging from 45% to 60% (Jaramillo 2004). Results showed that *C. bergi* can be controlled by using a combination of *M. anisopliae* (1E+08 conidia/ml) and sublethal doses (30 ppm) of Imidacloprid over 25 dai. The mortality rate was >80%. These greenhouse results were better than those obtained when only the insecticide was applied at commercial doses (Table 13-3). This is therefore an important alternative for IPM programs in Colombia and other Latin American countries, as it would encourage farmers to reduce their use of highly toxic synthetic insecticides such as chlorpyrifos and carbofuran, which are heavily used in Colombia (Jaramillo 2004).

Research indicates the potential that entomopathogenic nematodes and fungi have for the biological control of *C. bergi*, with recent studies indicating one possible solution. However, such research has been conducted only in laboratories or greenhouses. Field studies must be carried out before acceptable technologies can be recommended (AC Bellotti 2002, pers. comm.).

Table 13.3. Mortality average corrected (CM) (%) (± SD) of *Cyrtomenus bergi* nymph treated with *Metarhizium anisopliae* (1E+08 conidia/ml) and two doses of Imidacloprid (300 y 30 ppm) alone and combined with *M. anisopliae*.

Treatment	Percentage MS (± SD)					
	Day 5	Day 10	Day 15	Day 20	Day 25	Day 30
M. anisopliae + Imidacloprid 30 ppm	9.2 ±3.6 ab	22.4 ±6.0 a*	34.9 ±4.0 a*	61.2 ±5.4 a*	79.4 ±3.5 a*	87.1 ±2.9 a*
M. anisopliae	6.7 ±2.2 ab	13.5 ±3.9 a*	20.4 ±4.0 ab*	43.5 ±8.1 ab*	58.0 ±6.8 b*	66.5 ±5.2 b*
Imidacloprid 300 ppm	6.7 ±2.6 ab	10.8 ±4.2 Ab	20.6 ±3.6 ab*	35.6 ±5.1 bc*	52.2 ±4.8 b*	52.7 ±5.6 bc*
Imidacloprid 30 ppm	7.6 ±1.8 a*	15.2 ±4.0 a*	15.2 ±4.0 b*	18.8 ±4.0 c*	25.1 ±5.6 c*	37.4±5.9 c*

MS = Mean square; SD = Standard deviation.

A potential predator of *C. bergi* is the *Nerthra* bug (Hemiptera: Gelastocoridae), which was observed in a peanut field (MP Hernández 2002, pers. comm.).

Whitefly

Recently, in Colombia, whiteflies have caused adverse effects in areas where cassava is cultivated. Given this situation and the ignorance of the roles that biological control agents play, a study was begun of the parasitoid species that associate with this insect and their distribution. The study was conducted in different regions of Colombia: Cauca, Valle del Cauca, and the Atlantic Coast (Table 13-4) (CIAT 1995). Samples of whitefly were duly collected and processed in the laboratory, identifying and analyzing each species of both parasitoids and whitefly.

To date, various species of whitefly and their parasitoids have been found in different areas or sites, demonstrating the variability of parasitoids and their intrinsic relationship with any given whitefly species, or their presence as hyperparasitoids. The following whiteflies were identified as being predominant in the crop: *Aleurotrachelus socialis*, *Bemisia tuberculata*, *Trialeurodes* sp., and *Tetraleurodes* sp.

The parasitoids found in association with whiteflies were *Eretmocerus* sp. (Aphelinidae); the *Encarsia*

Table 13-4. Whitefly species and their parasitoids collected from three geographical regions of Colombia.

Region	Whitefly species	Parasitoid species
Atlantic Coast	*Aleurotrachelus socialis*	*Encarsia* sp. *Eretmocerus* sp.
	Bemisia tuberculata	*Encarsia* sp. *Eretmocerus* sp. *Metaphycus* sp.
	Trialeurodes sp.	*Encarsia* sp.
	Tetraleurodes sp.	*Eretmocerus* sp.
Valle del Cauca	*Aleurotrachelus socialis*	*Encarsia* sp. *Eretmocerus* sp. *Bemisia tuberculata*
Cauca	*Aleurotrachelus socialis*	*Encarsia bellottii* *Eretmocerus* sp. *Signiphora aleyrodis*
	Bemisia tuberculata	*Encarsia pergandiella* *Eretmocerus* sp. *Euderomphale* sp. *Signiphora aleyrodis*
	Trialeurodes sp.	*Encarsia hispida* *Encarsia pergandiella* *Eretmocerus* sp.

pergandiella species group (Aphelinidae); *E. hispida*, *E. bellottii*, *Metaphycus* sp. (Encyrtidae), and *Euderomphale* sp. (Eulophidae). *Signiphora aleyrodis* (Signiphoridae) is a possible hyperparasitoid (Trujillo et al. 1999). Other parasitoids identified were *E. sophia,* the *E. luteola* species group, the *E. strenua* species group (with the last two forming a species complex), and *Amitus macgowni* (HE Trujillo 2002, pers. comm.).

The greatest wealth of parasitoid species in Colombia (mainly of the *Encarsia, Eretmocerus*, and *Amitus* genera) was most frequently associated with *A. socialis*, *B. tuberculata*, and *Trialeurodes variabilis* (Castillo 1996).

Aleurotrachelus socialis, *B. tuberculata*, and *T. variabilis* are the whitefly species that usually attack the cassava crop in Colombia. Temperatures and humidity were not related to populations of the three species, although *A. socialis* was found primarily in those sites where temperatures were about 35 °C. More than 10 species of microhymenopteran parasitoids—natural enemies associating with whitefly species—were collected and identified. Most were newly recorded for Colombia (Castillo 1996). Three were identified as *Encarsia hispida, E. pergandiella*, and *E. bellottii* (Evans and Castillo 1998). Only one *Eretmocerus* and one *Amitus* sp. (*A. macgowni*) were identified. Predominant species were *E. hispida, Amitus* sp., and *Eretmocerus* sp. The highest levels of parasitism on whiteflies *A. socialis, B. tuberculata*, and *T. variabilis* were 15.3%, 13.9%, and 12.1%, respectively, although rates varied with geographical region (Castillo 1996).

The species complex of parasitoids associated with each whitefly species was, to some extent, influenced by geographical area. In the Caribbean coast, *A. socialis* was more frequently parasitized by *Eretmocerus* spp. (67%), whereas in Cauca and Valle del Cauca, the *Encarsia* genus complex was more predominant. For example, in Valle del Cauca (1000 m above sea level), 99.6% of parasitism of *A. socialis* was by *Encarsia* spp. versus 0.4% by *Eretmocerus* spp. (Figure 13-1) (Trujillo et al. 1999). The most numerous complex of parasitoid species was associated with *B. tuberculata*.

Greenhouse studies (Ortega 1999) showed that *E. hispida* preferred parasitizing the third instar of *A. socialis* (75.3%) to the other instars, with rates being 15.6%, 44.7%, and 43.1% for the first, second, and fourth instars, respectively. Another results also indicated that the third instar of the whitefly is also

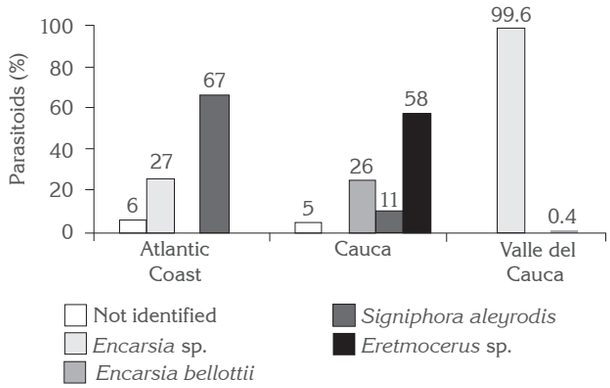


Figure 13-1. Parasitoid species collected on the whitefly *Aleurotrachelus socialis* from three areas of Colombia.

preferred by the parasitoid *E. hispida,* which showed an average parasitism rate of 21.1%, 35.2%, 46.4%, and 21.9% on the first through to the fourth instar, respectively. The highest parasitism rate was presented on the third instar. Evaluations were made 48, 72, 96, and 216 h after the parasitoids were released. The peak for parasitism occurred between 72 and 96 h, with 34.7% and 32.7%, respectively (Ortega 1999).

Although the parasitoid demonstrates facility to parasitize under controlled conditions, results under natural conditions may be less efficient. More research is needed in this area (CIAT 1999).

In Colombia, entomopathogenic fungi (*B. bassiana, Verticillium lecanii*, and *M. anisopliae*), recognized worldwide as whitefly pathogens, have been evaluated in the laboratory, but as yet have not been found parasitizing in the field. Laboratory results showed that, with *B. bassiana*, mortality rates were 28%, 55%, and 39% for nymphs of first, second, and third instars of *A. socialis*, respectively. The second instar was the most susceptible. *Beauveria bassiana* and *M. anisopliae* caused mortality rates of 18.1% and 18.8%, respectively, when applied in the morning, and 12.4% and 5.7% when applied in the afternoon (Sánchez and Bellotti 1997b).

Cassava hornworm

Several parasitic insects, predators, bacteria, fungi, and viruses make biological control of the cassava hornworm *Erinnyis ello*; also known as the ello sphinx moth, possible without having to resort to insecticidal applications that would otherwise break the balance existing between this pest and its natural enemies (Herrera 1999). More than 40 species of parasites,

predators, and pathogens of the pest's eggs, larvae, and pupae have been identified (CIAT 1989; Bellotti et al. 1999).

Eight species of microhymenopterans from the families Trichogrammatidae, Scelionidae, and Encyrtidae parasitize *E. ello* eggs. These include *Trichogramma minutum, Telenomus sphingis, T. dilophonotae, Ooencyrtus* sp., and *O. submetallicus* (CIAT 1989). Some *Trichogramma* and *Telenomus* species have been reported as parasitizing 94% to 99% of eggs (Bellotti and Schoonhoven 1978). The dipteran Tachinidae flies and hymenopteran Braconidae wasps, especially the *Cotesia* genus, also attack the pest (Bellotti et al. 1992, 1994).

The most common egg predators are the *Chrysoperla* spp. Other important predators, attacking larvae, include *Polistes* spp. (Hymenoptera: Vespidae), *Podisus* spp. (Hemiptera: Pentatomidae), and several species of spiders (Bellotti et al. 1992).

For microbial control, sprays of the bacterium *Bacillus thuringiensis*, in doses of 2 to 3 g of commercial product per liter of water, provide effective control. Control is more effective with first, second, and third instar larvae of the pest (Arias and Bellotti 1977; Herrera 1999).

The key to effective use of biological control agents is the ability to synchronize the release of a large number of predators or parasitoids during the pest's early developmental stages, preferably the egg or first to third instars. Parasitoids and predator efficiency is limited by poor functional response during short-term (15 days) hornworm outbreaks. Successful control requires the monitoring of populations in the field to detect immigrant adults or early instars. This can be done with black light lamps (type T20T12BLT) that trap adults in flight, or recognizing the presence of eggs or larvae (Braun et al. 1993). The difficulty of synchronizing mass releases of parasitoids and predators with peak populations of the pest suggests the need for an inexpensive, storable, biological pesticide.

A baculovirus has been identified as killing larvae, as being easy to manipulate, and inexpensive to store. This methodology was first implemented in commercial crops in Brazil, against populations of first-instar larvae. The result was almost complete control (Schmitt 1988). In Venezuela, the virus replaced insecticides in large plantations (7000 ha) where the hornworm is endemic. Control was 100% when 70 ml/ha were applied to larvae of first and second instars. The direct expense for storing, applying, processing, and collecting was U$4/ha (CIAT 1995; Laberry 1997).

Entomopathogenic fungi also exist, although surveys showed that the number of insects affected by these in cassava crops was low, being found in only one of five areas evaluated. Under laboratory conditions, a strain of *B. bassiana* caused the highest mortality rate in *E. ello* (31.6% to 87.5%), with the third instar being the most susceptible. The fungus's action does not transmit from one generation to another. When two strains of *B. bassiana* and *M. anisopliae* are mixed and applied to third-instar larvae, the mortality rate was 90%. No antagonism was presented, with individual dead larvae showing typical symptomatology (Múnera et al. 1999).

In April 1979, during an outbreak of *E. ello* in the cassava-producing area of Quindío, Risaralda, and northern Valle del Cauca, pupae of this insect were collected, showing infection by a fungus of the *Cordyceps* genus (class Ascomycetes). In this same area, the pathogen had contained the attack by the pest's third generation. The fungus can be cultivated under laboratory conditions in oat-agar medium (CIAT 1989).

White grubs

Nematodes *Steinernema* sp. strain SNI, *Heterorhabditis* sp. strain HNI, and *Heterorhabditis* sp. strain CIAT were evaluated under the controlled laboratory conditions. On third-instar larvae of *Phyllophaga menetriesi*, penetration by the nematodes was 74.5%. The highest was for *Steinernema* sp. at 80.0%, compared with 52.9% for *Heterorhabditis* sp. strain CIAT. Overall, the mortality rate was 10.5%. Further experiments were carried out with three other strains of entomonematodes (SNI, HNI, and H-CIAT), using two concentrations (7000 and 13,000 EPNs/ml) and two periods of evaluation (5 and 10 days). *Heterorhabditis* strain HNI-13-5 induced the highest mortality rate at 31.6%, and strains HNI-13-10 and H-C-7-5 both induced a rate of 21%. Treatments with *Steinernema* strains SNI-13-5 and SNI-7-10 showed no mortality. That is, mortality rates from treatments with the highest percentages of penetration (*Steinernema* sp.) were lower than those of *Heterorhabditis* sp., which, with less parasitism, caused higher mortality.

Later tests with *Phyllophaga* sp. evaluated the infectivity and mortality produced by seven strains of

EPNs: *Steinernema riobravis* (Sr), *S. carpocapsae* strain All (Sc), *S. arenarium* (Sa), and *S. feltiae* (Sf); and *Heterorhabditis bacteriophora* strains Hb1 and Hb2, and *Heterorhabditis* sp. strain HNI. The concentration was 10,000 EPNs/ml. The highest values for infectivity occurred with the *Heterorhabditis* strains Hb2 (70.8%), HNI (74.0%), and Hb1 (77.1%), whereas *Steinernema* strains had the following rates: Sr at 12.5%, Sc at 13.5%, Sa at 17.7%, and Sf at 35.4%. The survival rate was higher for the *Steinernema* strains Sf (75.0%), Sa (92.7%), Sr (97.9%), and Sc (98.9%) than for the *Heterorhabditis* strains HNI (30.2%), Hb2 (35.4%), and Hb1 (40.6%).

Three species of white grubs were also evaluated (*Anomala* sp., *Phyllophaga* sp., and *P. menetriesi*) against three *Heterorhabditis* strains (*H. bacteriophora* Hb1 and Hb2, and *Heterorhabditis* sp. strain HNI) and two *Steinernema* species (Sr and Sc). The average rates of infection of *Phyllophaga* sp., *Anomala* sp., and *P. menetriesi* by the five strains were 56.7%, 43.7%, and 22.5%, respectively. On comparing the average infection by the strains for the three pest species, those that stood out significantly ($P < 0.05$) were HNI at 66.7% and Hb1 at 60.4%, followed by Hb2 (34.0%), Sc (25.0%), and Sr (18.7%). The average survival rate was highest for *P. menetriesi* at 89.2%, followed by *Anomala* sp. (70.4%) and *Phyllophaga* sp. (56.2%). The total average for the last pest, by strain, presented two ranges: for the *Steinernema* strains 93.1% (Sr) to 86.8% (Sc), and for the *Heterorhabditis* strains 73.6% (Hb2), through 56.9% (Hb1) to 49.3% (HNI).

By other hand, it was demonstrated that certain developmental stages of the pests are more susceptible to these microorganisms. Hence, we evaluated the effect of the entomonematodes *Heterorhabditis* sp. (HNI; from CENICAFE) and *Steinernema feltiae* (Sf; from Villapinzón) on the mortality of different stages of these two species of white grubs: first-instar larva (L1), L2, L3 young, L3 mature, and prepupa. A concentration of 10,000 EPNs/ml was applied to larvae maintained in organic soil, under controlled laboratory conditions (24.5 °C and 70% ± 5% RH); evaluating its effect 10 and 20 days after infection (dai). The EPN strains presented differences for *Anomala inconstans* ($P \leq 0.05$), with the highest mortality rate achieved by strain HNI at 84.7%, compared with Sf at 76.7%, for the different instars. However, L2 was the most susceptible to the first strain (98.3%). No differences were observed between evaluation periods for this species. The highest mortality rate for *P. menetriesi* occurred 20 dai with strain HNI, again with L2 being the most susceptible stage (81.1%).

The susceptibility of white grubs to EPNs was determined as being dependent on both the species and strain of entomopathogen used—important aspects, together with knowledge of the insect's dynamics, to take into account in developing biological control programs for white grubs (Melo et al. 2007). These results are relevant, as the initial stages of white grubs take place close to the soil surface, making control, using these entomonematodes, relatively easy.

More research needs to be conducted on the defense mechanisms that pest larvae use, such as physical barriers, as in the case of *P. menetriesi* (Melolonthidae), where the cuticle is thicker than in *Cyclocephala* (Dynastinae); external melanized callosities that impede entry of parasitoids, as observed in field studies in northern Cauca (Pardo 2000); or, movement through soil to evade antagonists (M Londoño 2002, pers. comm.).

Stemborers

Known control methods were first evaluated in the 1980s, when research on the pest began. The methods that stand out are the treatment of planting stakes, and applications of the bacterium *Bacillus thuringiensis*, the fungus *Spicaria* sp., or a suspension of liquefied larvae killed by disease (probably viral). The mortality rates were as follows: 100% with the solution of macerated larvae, 99% with *B. thuringiensis*, and 88% with *Spicaria* sp. (Lohr 1983; Herrera 1999). The high mobility of the early larva-like instars of the stemborers makes them highly vulnerable and easily controlled by *B. thuringiensis*.

Because adult stemborers are difficult to kill and larvae eat inside the stems, controlling them with insecticides is not practical. Practices that will reduce pest populations are the removal and burning of infested plant parts. Only stakes that have no infestation or damage should be left to stand (Bellotti et al. 1983a).

Several natural enemies have been identified, including hymenopteran parasites and parasitoids such as *Bracon* sp., *Apantales* sp., and *Brachymeria* sp. (Lohr 1983).

Lace bugs

At CIAT, the bug *Zelus nugax* (Hemiptera: Reduviidae) was observed to be an excellent predator of nymphs and adults of cassava lace bugs (*Vatiga* spp.), consuming, during its biological cycle, an average of 496 individuals of the pest.

Controlling lace bugs seems difficult, with few natural enemies having been found (Bellotti et al. 1999). Continuous use of insecticides is expensive and can destroy the natural enemies of other pests. Preliminary surveys and evaluations of the cassava germplasm bank held at CIAT indicate the presence of varietal resistance in the crop. Implementing such technology will, however, require considerable research (CIAT 1990).

Conclusions

In CIAT's cassava entomology program, the staff and students, both national and foreign, have carried out many tasks towards controlling the pests described above, using natural enemies. With these tools, the conditions of such an important crop can be improved for millions of people around the world.

Although the efficiency of infectivity and mortality observed in the laboratory is known to decline dramatically in the field, few studies have been applied on a field scale, particularly those seeking information on the effective application of biocontrol agents to better control subterranean insects such as white grubs. Some successful field studies include those on cassava hornworm and baculoviruses, the mealybug and *Epidinocarsis lopezi* in Africa, and the mite *M. tanajoa* and its predator *T. aripo* in Africa.

The next step is to implement these methodologies with farmers to awaken their interest in responsible environmental management and in using pesticides to a minimum.

While battles have been won, the war continues. Food production should be increased, in a scientific way, to meet requirements of the growing human society, while protecting and conserving natural resources and complying with the parameters of good agricultural practices. Agriculture should continue to perform its function as a motor of change. The "silent revolutionaries", that is, the small farmers, the authorities responsible for formulating policies, scientists, and donors have but only one option: to continue being committed to this task (WD Hopper, cited in Wigg 1994).

References

To save space, the acronym "CIAT" is used instead of "Centro Internaccional de Agricultura tropical".

Arias B; Bellotti AC. 1977. Eficiencia de *Bacillus thuringiensis* sobre el gusano cachón (*Erinnyis ello*) en yuca, en un programa de control biológico. Rev Colomb Entomol 3(3–4):93–97.

Arias B; Bellotti AC. 1985. Aspectos ecológicos y de manejo de *Cyrtomenus bergi* Froeschner, la chinche de la viruela, en el cultivo de la yuca (*Manihot esculenta* Crantz). Rev Colomb Entomol 11(2):42–46.

Akhurst RJ; Boemare NE. 1990. Biology and taxonomy of *Xenorhabdus*. In: Gaugler R; Kaya HK, eds. Entomopathogenic nematodes in biological control. CRC Press, Boca Raton, FL, USA. p 75–90.

Australian Museum. 2009. Predators, parasites and parasitoids. Sydney, Australia. (Available at http://australianmuseum.net.au/predators-parasites-and-parasitoids)

Banegas JA; Cave R D. 1995. Biología y diversidad de depredadores. In: Cave R, ed. Manual para la enseñanza del control biológico en América Latina, 1st ed. Zamorano Academic Press, Zamorano, Honduras. p 39–49.

Barberena MF. 1996. Capacidad parasítica de dos razas del nematodo *Heterorhabditis bacteriophora* Poinar (Rabditida: Heterorabditidae) sobre la chinche de la viruela de la yuca *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae) en condiciones de laboratorio. Thesis. Universidad del Valle, Cali, Colombia. 89 p.

Bellotti AC; Schoonhoven A van. 1978. Cassava pests and their control. CIAT, Cali, Colombia. 71 p.

Bellotti AC; Reyes JA; Varela AM. 1983a. Observaciones de los piojos harinosos de la yuca en las Américas; su biología, ecología y enemigos naturales. In: Reyes JA, ed. Yuca: Control integrado de plagas. CIAT, Cali, Colombia p 313–339.

Bellotti AC; Reyes JA; Arias B; Vargas O. 1983b. Insectos y ácaros de la yuca y su control. In: Reyes JA (ed.). Yuca: Control integrado de plagas. CIAT, Cali, Colombia p 69–94.

Bellotti AC; Arias B; Guzmán OL. 1992. Biological control of the cassava hornworm *Erinnyis ello* (Lepidoptera: Sphingidae). Fla Entomol 75:506–515.

Bellotti AC; Braun AR; Arias B; Castillo JA; Guerrero JM. 1994. Origin and management of Neotropical cassava arthropod pests. Afr Crop Sci J 2(4):407–417.

Bellotti AC; Smith L; Lapointe SL. 1999. Recent advances in cassava pest management. Annu Rev Entomol 44:343–370.

Bennett FD; Greathead PJ. 1978. Biological control of the cassava mealybug (*Phenacoccus manihoti* Matile-Ferrero): prospects and necessity. In: Brekelbaum T; Bellotti A; Lozano JC, eds. Cassava protection workshop, Cali, Colombia, 1977. CIAT, Cali, Colombia. p 181–194.

Bento JMS; Bellotti AC; Castillo JA; de Moraes GJ; Lapointe SL; Warumby JF. 1999. Introduction of parasitoids for control of cassava mealybugs in northeastern Brazil. Bull Entomol Res 89(5):403–410.

Bertschy C; Turlings TCL; Bellotti AC; Dorn S. 1997. Chemically-mediated attraction of three parasitoid species to mealybug-infested cassava leaves. Fla Entomol 80(3):383–395.

Bohórquez A. 1995. Caracterización de poblaciones de *Mononychellus tanajoa* CIAT, 1982. In: Ácaros presentes en el cultivo de la yuca y su control. Guía de estudio. CIAT, Cali, Colombia. 36 p.

Braun AR; Bellotti AC; Guerrero JM; Wilson LT. 1989. Effect of predator exclusion on cassava infested with tetranychid mites (Acari: Tetranychidae). Environ Entomol 18(4):711–714.

Braun A; Alvarez JM; Cuéllar ME; Duque MC; Escobar JR; Franco C; Gaigl A; Guerrero JM; Lenis JI; Melo EL; Mesa NC; Zuñiga R. 1993. Inventario de ácaros fitófagos y sus enemigos naturales en el cultivo de la yuca en Ecuador. In: Braun AR, ed. Bases fundamentales para la investigación sobre los ácaros plaga y sus enemigos naturales en el Ecuador. Working document no. 126. CIAT, Cali, Colombia p 1–51.

Byrne DH; Bellotti AC; Guerrero JM. 1983. The cassava mites. Trop Pest Manage 29(4):378–394.

Caicedo AM. 1993. Evaluación del parasitismo del nematodo entomógeno *Steinernema carpocapsae* Weiser (Rhabditida: Steinernematidae) y reconocimiento de nemátodos nativos para el control de *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae). Agronomy thesis. Faculty of Agricultural Sciences, Universidad Nacional de Colombia–Palmira, Colombia. 101 p.

Caicedo AM; Bellotti AC. 1994. Evaluación del potencial del nematodo entomógeno *Steinernema carpocapsae* Weiser (Rhabditida: Steinernematidae) para el control de *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae) en condiciones de laboratorio. Rev Colomb Entomol 20(4):241–246.

Caicedo AM; Bellotti AC. 1996. Reconocimiento de nematodos entomopatógenos nativos asociados con *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae) en ocho localidades de Colombia. Rev Colomb Entomol 22(1):19–24.

Carter SE, Fresco LO, Jones PG; Fairbairn JN. 1992. An atlas of cassava in Africa. Historical, agroecological and demographic aspects of crop distribution. CIAT, Cali, Colombia. 85 p.

Castaño PO; Bellotti AC; Vargas O. 1985. Efecto del HCN y de los cultivos intercalados en la 'chinche de la viruela' (*Cyrtomenus bergi* Froeschner) y en el daño que causa al cultivo de la yuca. Rev Colomb Entomol 11(2):24–26.

Castillo P; Acosta N; Ciliézar A. 1995. Control microbiológico de plagas artrópodas. In: Cave RD, ed. Manual para la enseñanza del control biológico en América Latina. Zamorano Academic Press, Zamorano, Honduras. p 51–72.

Castillo J. 1996. Moscas blancas (Homoptera: Aleyrodidae) y sus enemigos naturales sobre cultivos de yuca (*Manihot esculenta* Crantz) en Colombia. MSc thesis. Universidad del Valle, Cali, Colombia. 173 p.

Cave RD. 1995a. Perspectivas del control biológico. In: Cave Rd, Ed. Manual para la enseñanza del control biológico en América Latina. Zamorano Academic Press, Zamorano, Honduras. p 7–9.

Cave RD. 1995b. La taxonomía y sistemática en el control biológico. In: Cave RD, ed. Manual para la enseñanza del control biológico en América Latina. Zamorano Academic Press, Zamorano, Honduras. p 17–21.

Cave RD. 1995c. Características deseables de un buen enemigo natural para el control de plagas. In: Cave RD, ed. Manual para la enseñanza del control biológico en América Latina. Zamorano. Academic Press, Zamorano, Honduras. p 23–25.

CIAT. 1982. Ácaros presentes en el cultivo de la yuca y su control. Guía de estudio. Cali, Colombia. 36 p.

CIAT. 1989. Manejo integrado de Erinnyis ello (L.), gusano cachón de la yuca. Guía de estudio para ser usada como complemento de la unidad audiotutorial del mismo tema. Cali, Colombia. 62 p.

CIAT. 1990. Biological control of cassava green mite. In: Cassava Program, Annual report. Cali, Colombia. p 129–179.

CIAT. 1995. Annual report, Cassava Program, 1994. Cali, Colombia. p 144–163.

CIAT. 1999. Annual report, Integrated Pest and Disease Management in Major Agroecosystems. Cali, Colombia. 136 p.

CIAT. 2003. Soil pest-cassava and others crops. In: Annual Report. Integrated Pest and Disease Management in Major Agroecosystems. Cali, Colombia. p 53–70.

DeBach P. 1975. El alcance del control biológico. In: Control biológico de las plagas de insectos y malas hierbas. Compañía Editorial Continental S.A., Mexico. 949 p.

DeBach P. 1977. Ecología del control biológico. In: Lucha biológica contra los enemigos de las plantas. Ediciones Mundi-Prensa, Madrid, Spain. 395 p.

Delalibera Jr I; Sosa-Gómez DR; Moraes GJ; de Alencar JA; Farias-Araujo W. 1992. Infection of *Mononychellus tanajoa* (Acari: Tretranychidae) by the fungus *Neozygites* sp. (Entomophthorales) in Northeastern Brazil. Fla Entomol 75(1):145–147.

Díaz FA; Hanson P. 1995. Biología y diversidad de parasitoides. In: Cave R, ed. Manual para la enseñanza del control biológico en América Latina. Zamorano Academic Press, Zamorano, Honduras. p 27–37.

Evans GA; Castillo JA. 1998. Parasites of *Aleurotrachelus socialis* (Homoptera: Aleyrodidae) from Colombia including descriptions of two new species (Hymenoptera: Aphelinidae: Platygasteridae). Fla Entomol 81(2):171–178.

Ferron P. 1985. Fungal control. In: Kerkut GA; Gilbert LI, eds. Comprehensive insect physiology, biochemistry, and pharmacology, vol 12: Insect control. Pergamon Press, New York. p 313–346. (13 vols.)

Gaugler R; Kaya HK, eds. 1990. Enthomopathogenic nematodes in biological control. CRC Press, Boca Raton, FL, USA. 365 p.

Hajek AE, St Leger RJ. 1994. Interactions between fungal pathogens and insect host. Annu Rev Entomol 39:293–322.

Herren HR; Neuenschwander P. 1991. Biological control of cassava pests in Africa. Annu Rev Entomol 36:257–283.

Herrera CJ. 1999. Manejo integrado de plagas en el cultivo de la yuca. In: Seminar-workshop "Hacia una producción bioracional de la yuca", held at Pivijay, El Carmen de Bolívar, Feb 1999. PMD; IICA; BIOCARIBE S.A., Medellín, Colombia. 45 p.

Jaramillo J. 2004. Control of subterranean burrower bug *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae) using entomopathogenic fungi (Deuteromycotina: Hyphomycetes). MSc thesis in Horticulture. University of Hannover, Germany. 24 p.

Laberry R. 1997. La aplicación de un programa MIP en producción industrial de yuca. In: Proc. Congreso de Fitopatología, Biodiversidad y Micorrizas, held at CIAT, Cali. Asociación Colombiana de Fitopatología y Ciencias Afines (ASCOLFI), Palmira, Colombia. p 136–137.

Lacey LA; Brooks WM. 1997. Initial handling and diagnosis of diseased insects. In: Lacey LA, ed. Manual of techniques in insect pathology. Biological Techniques Series. Academic Press, NY. p 1–15.

Leuschner K; Nwanze K. 1978. Preliminary observations of the mealybug (Hemiptera: Pseudococcidae) in Zaire. In: Brekelbaum T; Bellotti AC; Lozano JC, eds. Cassava protection workshop, Cali, Colombia, 1977. CIAT, Cali, Colombia. p 195–202.

Lohr B. 1983. Biología, ecología, daño económico y control de *Chilomima clarkei* (Amsel) (Lepidoptera, Pyralidae) barrenador de la yuca. In: Reyes JA, ed. Yuca: Control integrado de plagas. CIAT, Cali, Colombia. p 159–161.

Melo EL. 2000. El potencial de control biológico en el manejo de plagas. In: Symposium "Avances en el Manejo de Plagas". Proc XXVII Congress of SOCOLEN, held in Medellín, July 2000. Sociedad Colombiana de Entomología (SOCOLEN), Bogotá, Colombia. p 219–242.

Melo EL; Ortega-Ojeda CA; Gaigl A. 2007. Efecto de nematodos sobre larvas de *Phyllophaga menetriesi* y *Anomala inconstans* (Coleoptera: Melolonthidae). Rev Colomb Entomol 33(1):21–26.

Melo EL; Ortega-Ojeda CA; Susurluk A; Gaigl A; Bellotti AC. 2009. Poblaciones nativas de nematodos entomopatógenos (Rhabditida) en cuatro departamentos de Colombia. Rev Colomb Entomol 35(1):95–100.

Moraes GJ; Delalibera Júnior I. 1992. Specificity of a strain of *Neozygites* sp. (Zygomycetes: Entomophthorales) to *Mononychellus tanajoa* (Acari: Tetranychidae). Exp Appl Acarol 14:89–94.

Múnera DF; De los Ríos J; Bellotti AC. 1999. Patogenicidad sobre *E. ello* (Lepidoptera: Sphingidae) en condiciones de laboratorio por hongos entomopatógenos recolectados en cultivos comerciales de yuca, *Manihot esculenta*, en el Valle del Cauca, Colombia. Rev Colomb Entomol 25(3–4):161–167.

Nyiira ZM. 1972. Cassava: investigations 1972–1973. In: Kawanda Research Station, Uganda: Annual Report (Part 2), Entomology Section. Kampala, Uganda. 6 p.

Odongo B; Kumar R; Odindo MO; Brownbridge M. 1988. The effectives of entomogenous fungus *Hirsutella* sp. (fungi imperfecti) in controlling cassava green mite, *Mononychellus tanajoa* (Acari: Tetranychidae). In: Proc 8th Symposium of the International Society for Tropical Root Crops, Bangkok, Thailand. 354 p.

Ortega GA. 1999. Determinación de la efectividad de *Encarsia hispida* DeSantis (Hymenoptera: Aphelinidae) como parasitoide de la 'mosca blanca de la yuca', *Aleurotrachelus socialis* Endar (Homoptera: Aleyrodidae), bajo condiciones de invernadero. BSc thesis. Universidad Nacional de Colombia–Palmira, Colombia. 57 p.

Pardo LC. 2000. Avances en el estudio de chisas rizófagas (Coleoptera: Melolonthidae) en Colombia, observaciones sobre los complejos regionales y nuevos patrones morfológicos de larvas. In: Symposium "Avances en el Manejo de Plagas". Proc XXVII Congress of SOCOLEN, held in Medellín, Sociedad Colombiana de Entomología (SOCOLEN). Bogotá, Colombia. p 285-306.

Sáenz A. 1999. Los nematodos entomopatógenos: Una alternativa del control biológico. In: Proc XXVI Congress of SOCOLEN. Sociedad Colombiana de Entomología (SOCOLEN), Bogotá, Colombia. p 82–97.

Sánchez D. 1996. Patogenicidad de hongos Hyphomicetes sobre *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae), chinche subterránea de la yuca, en condiciones de laboratorio. Thesis. Faculty of Agricultural Sciences, Universidad Nacional de Colombia-Palmira, Colombia. 100 p.

Sánchez D; Bellotti AC. 1997a. Patogenicidad de hongos Hyphomicetes sobre *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae), chinche subterránea de la yuca. Rev Colomb Entomol 23(1/2):31–37.

Sánchez D; Bellotti AC. 1997b. Evaluación de la patogenicidad de hongos Hyphomicetes sobre mosca blanca de la yuca *A. socialis*. Report on the Cooperative Agreement CIAT–Colciencias, Programa BID para jóvenes investigadores. CIAT, Cali, Colombia. 20 p.

Schmitt AT. 1988. Uso de *Baculovirus erinnyis* para control biológico del gusano cachón de la yuca. Yuca Bol Inf 121:1–4.

Stock SP. 1998. Sistemática y biología de nematodos parásitos y asociados a insectos de importancia económica. In: International Entomopathogenic Nematodes and Insect Pathology Courses. Universidad Nacional del Litoral (UNL). Editorial Esperanza, Santa Fé, Argentina. 106 p.

Tanada Y; Kaya HK. 1993. Insect pathology. Academic Press, San Diego, CA, USA. p 318–387.

Trujillo HE; Arias B; Guerrero JM; Bellotti AC. 1999. Estudio del complejo y distribución de especies de parasitoides de mosca blanca en el cultivo de la yuca (*Manihot esculenta* Crantz) en diversas zonas de Colombia. In: Abstracts XXVI Congress of SOCOLEN, held in Bogotá, DC, Colombia, July 1999. Sociedad Colombiana de Entomología (SOCOLEN), Bogotá, Colombia. 123 p.

van Driesche RG; Castillo JA; Bellotti AC. 1988. Field placement of mealybug-infested potted cassava plants for the study of parasitism of *Phenacoccus herreni*. Entomol Exp Appl 46:117–123.

van Driesche RG; Bellotti AC; Castillo JA; Herrera CJ. 1990. Estimating total losses from parasitoids for a field population of a continuously breeding insect, cassava mealybug, *Phenacoccus herreni* (Hemiptera: Pseudococcidae) in Colombia, S.A. Fla Entomol 73:133–143.

Wigg D. 1994. Los revolucionarios silenciosos. Una reseña de la campaña contra el hambre que llevan a cabo los científicos agrícolas. World Bank, Washington, DC, USA. p 1–11.

Yaninek JS; Bellotti AC. 1987. Exploration for natural enemies of cassava green mite based on agrometeorological critera. In: Rijks D; Mathys G, eds. Seminar on agrometeorology and crop protection in the lowland humid and subhumid tropics, held in Cotonou, Benin, July 1986. World Meteorological Organization, Geneva, Switzerland. p 69–75.

Yaninek, JS; Herren HR. 1988. Introduction and spread of the cassava green mite, *Mononychellus tanajoa* (Bondar) (Acari: Tetranychidae), an exotic pest in Africa, and the search for appropriate control methods: a review. Bull Entomol Res 78:1–13.

Yaninek JS; Mégev B; De Moraes GJ.; Bakker F; Braun A. 1991. Establishment of the Neotropical predator *Amblyseius idaeus* (Acari: Phytoseiidae) in Benin, West Africa. Biocontrol Sci Technol 1(4):323–330.

Yaninek JS; Onzo A; Ojo JB. 1993. Continent-wide releases of Neotropical phytoseiids against the exotic cassava green mite in Africa. Exp Appl Acarol 17(1/2):145–160.

Yaninek JS; Saizonou S; Onzo A; Zannou I; Gnanvossou D. 1996. Seasonal and habitat variability in the fungal pathogens, *Neozygites* c.f. *floridana* and *Hirsutella thompsonii*, associated with cassava mites in Benin, West Africa. Biocontrol Sci Technol 6(1):23–33.

CHAPTER 14

Cassava's Natural Defense against Arthropod Pests*

Paul-André Calatayud[1] *and Diego Fernando Múnera*[2]

Introduction

Higher plants develop physical and chemical mechanisms for their defense against pests. These defenses may be found within healthy plants or are induced through arthropod attack. They are variable in nature, and can be modified by ecological factors.

More frequently, physical mechanisms are present in healthy plants, although they are sometimes induced by pests, as in the case of callus formation. These mechanisms greatly affect the establishment of an arthropod on a plant, especially, those behaviors that prevail when the insect selects and establishes itself on a host plant.

Chemical defense is the most effective and frequent mechanism found in plants (Bell 1974), as the substances of secondary metabolism are those that exercise the most action on the environment. According to Fraenkel (1969), these substances are composed mostly for defensive functions and tend to give the plant repellent or toxic attributes, affecting insect growth.

These substances are qualified as secondary, because each family is restricted to a limited group of plants and because usually they do not appear to intervene in the basic biochemical processes of most plants. Secondary substances include alkaloids, steroids, terpenoids, phenolic compounds (e.g., flavonoids and tannins), hydrocyanic or sulfur-derived compounds (e.g., linamarin and glucosinolates), and other organic compounds whose metabolic functions within plants are not well defined (Robinson 1974; Beck and Reese 1976).

Whittaker (1970) proposed the term *allelochemical* for some secondary substances that are defined, in plant-insect interactions, as substances produced by the plant and which markedly affect the insect's growth, survival, and behavior or biology. An example of allelochemical interactions is the production of phytoalexins, which are synthesized by the plant and are induced by the presence of a foreign body, usually a microorganism. Other interactions include those that attract or repel, or are phagorepellent, inhibiting, or toxic.

Manihot esculenta Crantz (Euphorbiaceae) is reported in the literature as presenting physical and chemical mechanisms against arthropod pests (Bellotti et al. 1999). In this chapter, we present several cases that have been clearly demonstrated.

Physical Mechanisms

For cassava's resistance to thrips, *Frankliniella williamsi* (Thysanoptera, Thripidae), leaf pilosity has been clearly demonstrated as contributing to the plant's defense against these insects. Increased leaf pubescence leads to increased resistance to thrips, as the hairiness interferes with their progress in settling on the plants (Schoonhoven 1974; Bellotti and Schoonhoven 1978).

In contrast, cassava's pilosity does not disturb the cassava mealybug (*Phenacoccus manihoti* Matile-Ferrero; Sternorrhyncha: Pseudococcidae) (Calatayud and Le Rü 2006). In a study on cassava and *P. manihoti* interactions, a common and rapid reaction, also appearing in many other plant species, was

* This paper was first published in Spanish in the Proceedings of the XXVII Congress of SOCOLEN, held in Colombia, 2000.

1. Entomologist, Laboratory of Evolution, Genomes & Speciation, IRD, c/o CNRS, Gif-sur-Yvette, France, & Université Paris-Sud, Orsay, France.
E-mail: calatayud@legs.cnrs-gif.fr
2. Agronomist, Cassava Entomology, CIAT, Cali, Colombia.
E-mail: difemusa@hotmail.com

observed: callus formation (polymer of ß(1,3)-D-glucopyranose; Figure 14-1) on contact with the mealybug's stylets (Calatayud et al. 1996). This reaction constitutes a scarring of the phloem, which thus interrupts sustained feeding by this phloemphagous insect.

Another physical mechanism of plants, which affects feeding behavior in *P. manihoti*, occurs in the plant cell wall. An analysis of the secondary compounds present in the intercellular liquids of cassava leaves has shown that phenolic acids are strongly involved in the mealybug's establishment on the plant (Calatayud et al. 1994a). These acids, precursors in the synthesis of compounds associated with cell-wall pectins, probably constitute significant factors in interactions with the insect's salivary enzymes, thus annoying the insect and changing its feeding behavior. Moreover, the level of these phenolic acids declines strongly during dry times, thus partly explaining increases in natural populations of *P. manihoti* in the field during droughts (Calatayud and Le Rü 1995).

Chemical Mechanisms

An important characteristic of cassava biochemistry is the presence of cyanogenic compounds in leaves, stems, and roots. In plant tissues, the cyano (CN)[3] group links with D-glucose to form cyanogenic glucosides (Conn 1980), mostly linamarin (Figure 14-2) (Butler et al. 1965).

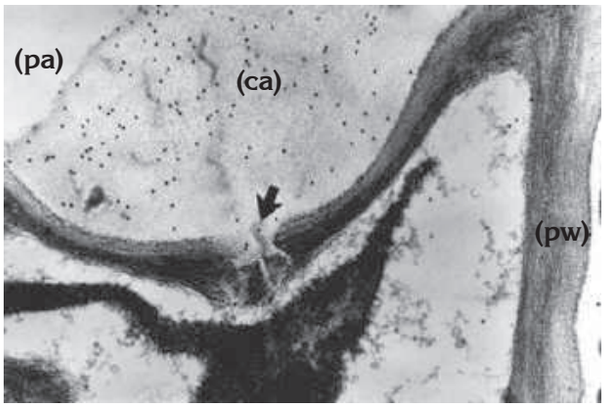


Figure 14-1. Microphotograph of a cross-section of cassava leaf tissue infested by mealybug *Phenacoccus manihoti*. The section, which shows a phloem cell, was treated with the polyclonal antibody specific against the substance ß(1,3)-D-glucopyranose, a constituent of the callus (ca). This reaction makes visible the gold particles carrying the antibody (black points in the callus). The callus results from the cell responding to the perforation (black arrow) that the insect made in the primary cell wall (pw). The callus covers the hole and thus prevents the plasmalemma (pa) from draining and causing cell death. These elements (callus, perforation, plasmalemma) are found within the insect's feeding area. (Calatayud and Múnera 2000; adapted from Calatayud et al. 1996.)

When wounded, cassava tissues excrete hydrocyanic acid (HCN). This property, known as cyanogenesis, results specifically from the action of an endogenous enzyme (ß-glucosidase) on linamarase (Figure 14-2; Conn 1980). The cyanogenesis releases a toxic molecule, thus protecting cassava against pests. However, such protection has yet to be clearly demonstrated (Hruska 1988).

In roots, cyanogenesis can constitute a defense against the subterranean burrower bug, *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae). The HCN released through an attack from this insect on roots was demonstrated to play a repellent role. Cassava varieties with low HCN levels are usually attacked more severely than those with high HCN levels (Castaño et al. 1985; Bellotti and Riis 1994; Riis 1997; Bellotti et al. 1999). Furthermore, high levels of HCN in artificial diets (with levels similar to those found in bitter cassava varieties) were clearly demonstrated to be toxic to the burrower bug (Cortés et al. 2003), indicating that cassava varieties with high levels of HCN are also toxic to *C. bergi*.

However, for several reasons, cyanogenesis in cassava does not constitute a defense mechanism against the mealybug. Linamarin itself is not toxic to *P. manihoti* and seems more like a phagostimulant (Calatayud et al. 1994a, 1994b; Calatayud 2000).

Under natural conditions, the insect has an enzymatic complex capable of hydrolyzing linamarin (Calatayud et al. 1995). However, the linamarase of *P. manihoti* does not seem to come from the insect itself, but from bacteria contained in its digestive tract (Calatayud 2000). The HCN levels found within their digestive tract are not toxic to the insect, as it possesses an effective system of excretion or detoxification (Calatayud et al. 1994b).

Furthermore, the location of linamarase in plant tissues differs from that of its substrate, linamarin (Pancoro and Hughes 1992). This, and the fact that *P. manihoti* stylets, on penetrating, causes almost no

3. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

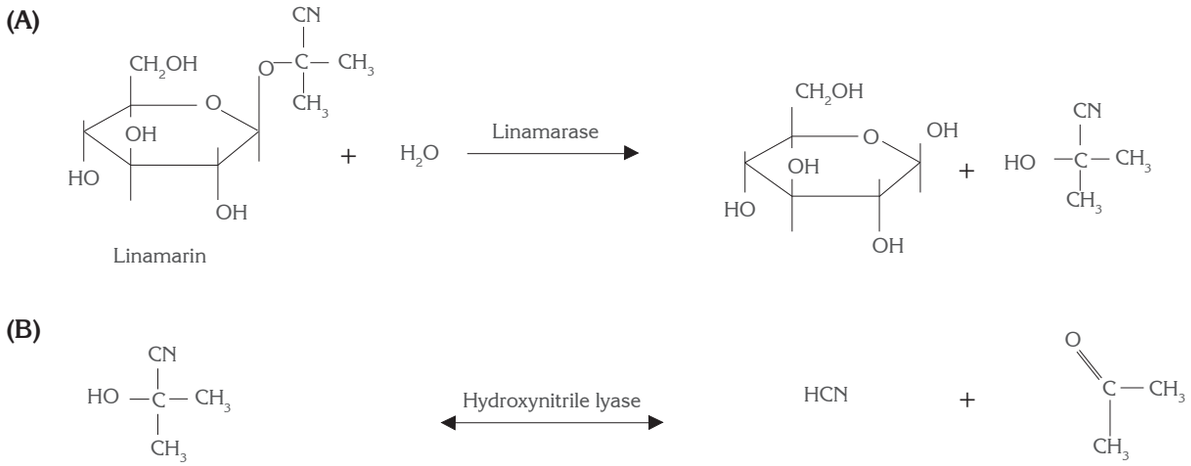


Figure 14-2. The chemical formula for linamarin, and cyanogenesis flow chart illustrates the release of HCN through the actions of linamarase **(A)** and hydroxynitrile lyase **(B)** (Calatayud and Múnera 2000).

wounding (Calatayud et al. 1994a), suggests that cassava–mealybug interactions are unlikely to initiate cyanogenesis.

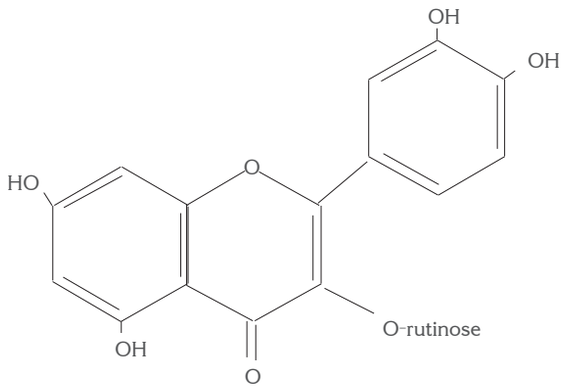
Although no alkaloids were evident in cassava, some glycosylated flavonoids were detected (Calatayud et al. 1994b), including rutin (Figure 14-3), the absence of which, in plants, is more significant than its presence (Harborne and Williams 1975). They were demonstrated as affecting *P. manihoti* growth and development (Calatayud et al. 1994b; Calatayud 2000).

One defensive response that cassava displays against *P. manihoti* appears to be an increase in rutin levels. Such an increase varies with season and is less pronounced during dry times. This partly explains increases in natural populations of *P. manihoti* in the field during drought (Calatayud et al. 1994c). However, the negative effect of rutin on *P. manihoti* growth and development does not seem to result from a toxic action on the insect but more from being phagorepellent in nature (Calatayud 2000).

Conclusions

In *M. esculenta*, the natural defenses against arthropod pests described in the literature seem to affect in particular the establishment or sustained feeding (through phagorepellence) of the pest in the plant. The mechanisms used are physical (pilosity and callus formation) or chemical (HCN and rutin).

No example from the literature has clearly shown a cassava variety having a toxic effect on pests or as possessing a toxic molecule that works against the pests' development and growth. This is partly evidenced by the almost total lack of development of varietal resistance to control the several arthropod pests of cassava (Bellotti and Schoonhoven 1978; Bellotti et al. 1999).



Rutin = quercetin (3,3', 4', 5,7-pentahydroxyflavone) + rutinose
Rutinose = rhamnose + glucose

Figure 14-3. Chemical formula for rutin (Calatayud and Múnera 2000).

However, a variety of cassava (M Ecu 72) and a wild *Manihot* species (*M. flabellifolia* Pohl [Euphorbiaceae]) demonstrated resistance, and may therefore be promising for isolating genes for resistance to whitefly, *Aleurotrachelus socialis* Bondar (Hemiptera: Aleyrodidae) (Bellotti et al. 1999; Carabalí et al. 2010). The mechanisms of resistance to this whitefly are yet to be described, although physical factors appear probable.

Acknowledgments

The authors express their gratitude to Ana Milena Caicedo for her critical reading and suggestions for the manuscript.

References

Beck SD; Reese JC. 1976. Insect-plant interactions: nutrition and metabolism. Recent Adv Phytochem 10:41–92.

Bellotti AC; Riis L. 1994. Cassava cyanogenic potential and resistance to pests and diseases. In: Proc International Workshop on Cassava Safety, held in Ibadan, Nigeria, March 1994. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. WOCAS, ISHS, and ISTRC, Wageningen, Netherlands. p 141–152.

Bellotti AC; Schoonhoven A van. 1978. Mite and insect pests of cassava. Annu Rev Entomol 23(1):39–67.

Bellotti AC; Smith L; Lapointe SL. 1999. Recent advances in cassava pest management. Annu Rev Entomol 44:343–370.

Butler GW; Bailey RW; Kennedy LD. 1965. Studies on the glucosidase "linamarase". Phytochemistry 4(3): 369–381.

Calatayud P-A. 2000. Influence of linamarin and rutin on biological performances of *Phenacoccus manihoti* in artificial diets. Entomol Exp Appl 26(1):81–86.

Calatayud P-A; Le Rü B. 1995. Potential biochemical mechanisms used by Congolese cassava to resist mealybug. In: Proc Second International Scientific Meeting of the Cassava Biotechnology Network, held in Bogor, Indonesia, Aug 1994, vol 2. Working Document No. 150. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. p 485–500.

Calatayud P-A; Le Rü B. 2006. Cassava-mealybug interactions. IRD Éditions, Montpellier, France. 110 p.

Calatayud P-A; Múnera DF. 2000. Las defensas naturales en la yuca a las plagas artrópodas. In: Proc XXVIII Congress of SOCOLEN, held in Medellín, July 2000. Sociedad Colombiana de Entomología (SOCOLEN), Bogotá, DC, Colombia. p 265–271.

Calatayud P-A; Rahbé Y; Tjallingii WF; Tertuliano M; Le Rü B. 1994a. Electrically recorded feeding behaviour of cassava mealybug on host and non-host plants. Entomol Exp Appl 72(3):219–232.

Calatayud P-A; Rahbé Y; Delobel B; Khuong-Huu F; Tertuliano M; Le Rü B. 1994b. Influence of secondary compounds in the phloem sap of cassava on expression of antibiosis towards the mealybug, *Phenacoccus manihoti*. Entomol Exp Appl 72(1): 47–57.

Calatayud P-A; Tertuliano M; Le Rü B. 1994c. Seasonal changes in secondary compounds in the phloem sap of cassava in relation to plant genotype and infestation by *Phenacoccus manihoti* (Homoptera: Pseudococcidae). Bull Entomol Res 84:453–459.

Calatayud P-A; Rouland C; Le Rü B. 1995. Influence of linamarin in cassava-mealybug interactions. Acta Bot Gall 144(4):427–432.

Calatayud P-A; Boher B; Nicole M; Geiger JP. 1996. Interactions between cassava mealybug and cassava: cytochemical aspects of plant cell wall modifications. Entomol Exp Appl 80:242–245.

Carabalí A; Bellotti AC; Montoya-Lerma J; Fregene M. 2010. *Manihot flabellifolia* Pohl, wild source of resistance to the whitefly *Aleurotrachelus socialis* Bondar (Hemiptera: Aleyrodidae). Crop Prot 29(1): 34–38.

Castaño O; Bellotti AC; Vargas O. 1985. Efecto del HCN y de cultivos intercalados sobre daño causado por la chinche de la viruela *Cyrtomenus bergi* Froeschner al cultivo de la yuca. Rev Colomb Entomol 11(2):24–26.

Conn EE. 1980. Cyanogenic compounds. Annu Rev Plant Physiol 31:433–451.

Cortés ML; Sánchez T; Riis L; Bellotti AC; Calatayud P-A. 2003. A bioassay to test HCN toxicity to the burrowing bug, *Cyrtomenus bergi*. Entomol Exp Appl 109:235–239.

Fraenkel G. 1969. Evaluation of our thoughts on secondary plant substances. Entomol Exp Appl 12:473–486.

Harborne JB; Williams CA. 1975. Flavone and flavonol glycosides. In: Harborne JB; Mabry TL; Mabry H, eds. The flavonoids. Academic Press, New York. p 377–441.

Hruska AJ. 1988. Cyanogenic glucosides as reference compounds: a review of the evidence. J Chem Ecol 14:2213–2217.

Pancoro A; Hughes MA. 1992. *In situ* localization of cyanogenic ß-glucosidase (linamarase) gene expression in leaves of cassava (*Manihot esculenta* Crantz) using non-isotopic riboprobes. Plant J 2(5): 821–827.

Riis L. 1997. Behaviour and population growth of the burrower bug, *Cyrtomenus bergi* Froeschner: effects of host plants and abiotic factors. Dissertation. Department of Ecology and Molecular Biology, Royal Veterinary and Agricultural University, Copenhagen, Denmark. 167 p.

Robinson T. 1974. Metabolism and function of alkaloids in plants. Science 184:430–435.

Schoonhoven A van 1974. Resistance to thrips damage in cassava. J Econ Entomol 67(6):728–730.

Whittaker RH. 1970. The biochemical ecology of higher plants. In: Sondheimer E; Simeone JB, eds. Chemical ecology. Academic Press, New York. p 43–70.

CHAPTER 15

Biotechnology for Cassava Improvement: Genetic Modification and Clean-Seed Production

Paul Chavarriaga[1]*, Roosevelt H. Escobar*[2]*, Danilo López*[3]*, Jesús Beltrán*[4]*, William Roca*[5]*, and Joe Tohme*[6]

In Memoriam

*Carlos Julio Herrera (r.i.p.) was co-author of this chapter for the first edition of this book, which was published in the Spanish language. The chapter was entitled "Biotecnología para el manejo de plagas en la producción de semilla limpia" [*Biotechnology for pest control in clean-seed production*]. Carlos was widely respected as an expert and teacher on insect pests of cassava. We therefore dedicate this English-language chapter to his memory.*

Carlos Julio Herrera leads a training session with a group from the Women Farmers' Association of Santa Ana (ASOPROSA)[7], Department of Cauca, Colombia. Themes were the production of planting materials and control of cassava pests and diseases. (Photo by R. Escobar.)

1. Research Associate, Genetic Transformation Platform, CIAT, Cali, Colombia. E-mail: p.chavarriaga@cgiar.org
2. Research Assistant, Biotechnology Unit, CIAT. E-mail: r.escobar@cgiar.org
3. Research Assistant, Genetic Transformation Platform, CIAT. E-mail: d.lopez@cgiar.org
4. Doctoral Candidate, The City University of New York, USA. E-mail: jabz81@gmail.com
5. formerly Plant Physiologist and Leader, Project on the Biodiversity and Genetic Resources of Andean Roots and Tubers, CIP, Lima, Peru. E-mail: w.roca@cgiar.org
6. Molecular Plant Breeder and Agrobiodiversity, Director, Research Area, CIAT. E-mail: j.tohme2@cgiar.org
7. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, and Abbreviations, and Technical Terminology,* this volume.

Introduction

Genetic transformation technology, using *Agrobacterium*, has made possible the acquisition of transgenic varieties of the world's most important food crops. The varieties from first-generation transgenic plants are today cultivated on 134 million hectares. They contain genes that mostly confer resistance to herbicides and insect pests. The list of genetically modified crops includes soybean, maize, cotton, colza, alfalfa, sugar beet, tomato, and red pepper, among others. They are cultivated in 29 countries, including the EU countries of Czech Republic, Germany, Poland, Portugal, Romania, Slovakia, Spain, and Sweden; and the Central American countries of Costa Rica and Mexico (James 2011).

Genetic modification technology to improve world agriculture was also adopted for cassava in the 1980s. Somatic embryos of genetically modified cassava plants were first produced between 1993 and 1996 (Sarria et al. 1993, 1995; Schopke et al. 1996). Since then, innovative traits have been introduced, ranging from resistance to herbicides (Sarria et al. 2000), through reduced cyanide content in the plant (Siritunga and Sayre 2003; Siritunga et al. 2004), to modifications of the amount (Ihemere et al. 2006) and quality (Raemakers et al. 2005) of starch accumulated in roots. Jørgensen et al. (2005) recently demonstrated that silencing of specific genes for biosynthetic routes in cassava is possible. For example, the quantity of cyanogenic glycosides (cyanide) that the plant produces can be reduced, using RNA interference (RNAi) technology. We can now talk of a fast-approaching second generation of transgenic cassava by the introduction and expression of genes to improve the nutritional value of the roots, i.e., increasing carotene content (Welsch et al. 2011) and protein (Abhary et al. 2011), or by introducing into cassava genes that will help control the devastating disease caused by the African Cassava Mosaic Virus (Vanderschuren et al. 2007).

New genetic information has been introduced into cassava plants, essentially using *Agrobacterium tumefaciens* as a natural vector of the genes of interest. Commonly, two types of tissues are used to generate *de novo* plants: totipotent cells (able to differentiate and regenerate a complete organism) derived from somatic embryos, and also known as friable embryogenic calluses (FECs; Taylor et al. 1996); and the cotyledons of somatic embryos (Taylor et al. 1996). Transgenic plant regeneration is usually achieved by inducing or germinating embryos and/or inducing organs (organogenesis) directly from totipotent cells. Common agents for selecting transgenic cells include antibiotics, herbicides, fluorescence, and sugars such as mannose.

Cassava is conventionally propagated in the field by planting pieces of stems, known as stakes, obtained from plants of the previous crop. This system presents relative advantages, particularly the main one of lower production costs. However, under certain circumstances, the system incurs problems of transmission of pests and diseases (usually viral and/or bacterial in nature). Such problems hinder the exchange of germplasm between countries, create seed shortages during the year's production peaks in certain regions, delay distribution systems, and slow down the adaptation and/or adoption of new clones. These and other problems can be resolved by applying *in vitro* techniques.

Implementing multiplication systems that use *in vitro* tissue culture of planting materials enables the distribution of disease-free clones of interest to small farmers or industries. CIAT has defined the basic system for *in vitro* propagation and germplasm cleaning, thus facilitating the consolidation of the *in vitro* bank held at CIAT and the exchange of genetic materials among countries.

This chapter provides an overview of the advances made in (1) cassava transformation achieved recently, focusing on the use of genetically modified cassava to study genes and promoters, improve the nutritional quality of roots, study leaf retention, and alter starch content and quality to produce biocombustibles; and (2) multiplication systems for planting materials at small-farmer and industrial levels.

Cassava as a Model for Testing the Expression of Genes and Promoters

A major constraint to incorporating new traits into cassava through genetic modification comprises the proven availability of promoters—regulatory sequences for gene expression—in this plant's storage roots. Based on previous reports on the specific expression in cassava roots of a glutamic acid-rich protein (also known as Pt2L4; de Souza et al. 2009), the promoter region (CP2) of this gene was cloned in front of the *GUSPlus* reporter gene and expressed in genetically modified plants grown in the field (Beltrán et al. 2010).

The expression of the reporter gene led to an intense coloration of storage roots and stem vascular

tissues. Leaves showed a less intense expression, and the pith an absence of expression. Fluorometric analyses revealed that the promoter CP2 was equally active in root pulp and stems, although 3.5 times less active in leaves. These findings were corroborated by quantitative analyses of messenger RNA (mRNA) levels, using real-time PCR developed for transgenes in cassava (Beltrán et al. 2009).

A second, larger version of promoter CP2—promoter CP1—was also cloned in front of the *GUSPlus* gene and found expression in transgenic carrot plants, which also have roots that store carbohydrates. The transformation and regeneration system in carrot is much more expeditious than that of cassava. Promoter CP1 seems to preferentially express in secondary phloem and root vascular cambium, although, again, expression in vascular leaf tissue was less, by six times.

The results of these studies demonstrated that genetically modified cassava plants grown in the field provide a good model for testing genes and promoters of interest. They also enabled the isolation and characterization of regulatory sequences of cassava genes for use in directing preferential expression to the root, the most economically valuable plant organ.

Provitamin A Deficiency in Cassava and Prospects of Improving this Trait through Biotechnology

The cassava plant originates in South America, where, since ancestral times, it has been consumed as a food staple providing dietary energy. The roots contain large quantities of carbohydrates, hence its importance in nutrition. However, they contain little protein and few micronutrients (OECD 2009), compared with sweet potato, potato, bean, maize, or wheat. Nevertheless, it is widely consumed because of its ability to accumulate carbohydrates and to tolerate drought and acid soils (Kawano 2003). It is the principal dietary energy source for more than 600 million people, especially low-income populations in less developed countries, who often face food shortages (Thro et al. 1999a, 1999b). Cassava is therefore an appropriate crop for which to use biotechnology to produce varieties with higher levels of nutrients such as ß-carotene.

Beta-carotene is the fundamental source of vitamin A, essential for human and animal health, and best known as critical in the maintenance of ocular epithelia in, for example, the retina and cornea. Not so well known, but nevertheless equally important, is the role vitamin A plays in enabling T-lymphocytes to produce antibodies during infections, so that these natural killer cells carry out phagocytosis. Vitamin A is also attributed as having the roles of a hormone for cell development and gene expression, and of an anticarcinogen. Cell differentiation and growth are regulated by vitamin A. Today, we know that vitamins and minerals, together with other food components, significantly reduce chronic diseases such as cancer, cardiovascular problems, and degenerative diseases related to aging (Álvarez et al. 2004).

When consumed in a conventional diet (i.e., at 100 g of cassava per day), ß-carotene levels in cassava are insufficient to fulfill Required Daily Allowance (RDA) standards. Conventional improvement would help raise these levels, but procedures are complicated because of cassava's polyploidy, heterozygous nature, and slow multiplication. Furthermore, the accumulation of ß-carotene in cassava roots involves several genes, as to be expected of a multigene synthesis route. Hence, in the attempt to introduce all the "good" alleles of the relevant genes into a single variety, strategies for conventional improvement become even more complicated.

The international initiative HarvestPlus (www.harvestplus.org) involves interdisciplinary and interinstitutional research to reduce micronutrient malnutrition in humans. Within this initiative, CIAT collaborated with the University of Freiburg (Germany) to develop, through conventional improvement and/or biotechnology, cassava genotypes more able to produce and store ß-carotene in roots. This effort's first results demonstrated that cassava genotypes vary in accumulating carotenes in roots. Values ranged from 0.102 to 1.040 mg of total carotene per 100 g of fresh weight (Chávez et al. 2005).

In at least four examples of crops—rice, potato, tomato, and canola—ß-carotene content has been increased substantially by inserting genes of the carotene synthesis route, and which are directed by promoters to express in specific organs, or constitutively. The genetic transformation of rice, using genes of the carotene route (Ye et al. 2000; Paine et al. 2005), was successful in increasing total carotene content in the grain by as much as 27 times to a maximum 37 μg/g. More than 80% (>30 μg/g) corresponded to ß-carotene. In canola, ß-carotene was increased by 50 times (Shewmaker et al. 1999). More recently, in potato, Diretto et al. (2007) demonstrated that ß-carotene in the tuber can be increased by 3600 times, reaching 47 μg/g of dry weight. Hence, on a diet of 250 g of potato per day, half of the RDA

requirements would be supplied. Both in rice grains and potato tubers, the carotene synthesis route was sufficiently complemented to suggest that a similar strategy can be attempted for cassava.

The first significant result that HarvestPlus obtained from its biotechnological approach was the knowledge that the carotene synthesis route does operate in cassava roots. That is, the genes find expression in this organ (Arango-Mejía 2005), indicating that the necessary substrata for the activity of the route's enzymes are present. Without this background, designing an unconventional improvement strategy (i.e., genetic modification) to increase ß-carotene content in cassava roots, by inserting new gene combinations, would be more difficult.

The second significant result is that transgenic cassava plants were produced. They combined one or more genes from the carotene synthesis route with promoters that preferentially directed the expression of these to roots. These plants have already been field-tested (Welsch et al. 2010). The results of overexpression of a gene for phytoene synthetase of bacterial origin (*crt*B) in the root demonstrated that increasing total carotene content is possible. A white-root cassava (genotype 60444; transgenic event pCAS-Phyt-12) that normally carries ≤0.6 µg/g (dry weight) of carotenes contained about 21 µg/g (dry weight), that is, about 35 times as much. The ß-carotene content in this same, non-transgenic genotype increased proportionately from 0.4 to 6.7 µg/g (dry weight).

Thus, these results demonstrated that increasing carotene content in cassava roots is feasible. It can be done by inserting heterologous (foreign) genes under the control of promoters that preferentially express in storage-root tissues. Research is continuing with the genetic modification or transfer of transgenes to yellow-rooted genotypes that have higher carotene content. These genotypes include advanced breeding lines like GM905-21 and GM905-57.

Increasing ß-carotene content in cassava roots would bring additional advantages to the farmer, for example, higher "resistance" to postharvest physiological deterioration (PPD). Chávez et al. (2005) detected a trend in roots with higher carotene contents to delay the beginning of PPD. Possibly, in this type of "resistance", molecules of the type ß-ionone, derived from the catabolism of ß-carotene, are involved, as they play a role in the response to biotic stresses such as fungal infections that are characteristic of PPD (Bouvier et al. 2005). However, PPD is a highly variable characteristic. It is difficult to measure visually; it is influenced by the environment, and depends heavily on the storage conditions of harvested roots.

Leaf Retention

One way of increasing yields of crops such as cassava is to delay leaf senescence by increasing cytokinin levels in the leaves. Cytokinins are plant growth factors implicated in plant development, including leaf longevity. The phenomenon of holding back leaf senescence is known as "stay green" (Thomas and Howarth 2000). Millions of people use cassava as their principal source of carbohydrates, which is why the possibility of using genetic modification to increase root yield (i.e., starch) by increasing leaf longevity is being explored. The trait of "stay green" in cassava is of great commercial interest. Plants improved conventionally for foliage retention have already shown increases of dry matter content as high as 33% more (Lenis et al. 2006). Moreover, delayed senescence enables the plant to have more leaves at harvest, which then can be used as forage of excellent nutritional quality (Buitrago 1990).

Thus, Zhang and Gruissem (2004) introduced the bacterial gene *ipt* into cassava. This gene codes for the enzyme isopentenyltransferase (Akiyoshi et al. 1984; Barry et al. 1984). It is active during leaf senescence, once it is activated by its promoter SAG12, itself derived from *Arabidopsis thaliana* (Lohman et al. 1994; Weaver et al. 1998). The transgenic cassava line 60444-529-28 was selected for field evaluation at CIAT in collaboration with the Institute of Plant Science (now the Institute of Agricultural Sciences) at ETH–Zurich, Switzerland) and the Department of Crop and Soil Sciences of Cornell University (Ithaca, NY, USA). Agromorphological traits were measured, together with levels of cytokinins, abscisic acid (ABA), glucose, sucrose, and starch, all indicators of gene *ipt* expression (López 2008).

Results showed that, effectively, cytokinin levels significantly increased in basal leaves, in tandem with an increase of ABA in apical leaves. Glucose and sucrose levels also increased in apical leaves, stems, and abscission areas. No positive impact on dry matter content was apparent in this particular trial, probably because of unexpected dry periods. Precipitation was also more abundant and erratic than normal, which probably also had an effect on root dry matter content. An alternative explanation is suggested through

experiments by Medford et al. (1989), who determined that increased cytokinin levels can generate changes in the root systems of tobacco and *Arabidopsis*. Changes related to these phenomena are not ruled out for cassava storage roots, despite the difficulty of observing them. They may well have contributed to the reduced dry matter in the transgenic line 60444-529-28.

Another explanation, which also requires experimental verification, is that dry matter was affected by changes related to sugar translocation. Basal leaves may have made higher demands as their longevity increased. However, the transgenic storage roots did not differ morphologically from those of the control.

Measuring sugars in the plant is important, as these usually increase during senescence (Wingler et al. 1998; Stessman et al. 2002). Increase can trigger symptoms associated with senescence such as the yellowing of leaves. Statistically, glucose and sucrose levels were clearly higher in the apical leaves, abscission areas, and stems of transgenic cassava plants. This suggests a pattern of free-sugar remobilization from the youngest leaves towards other plant organs, or the activation of sugar synthesis in younger leaves.

The relationships between altered cytokinin levels and source-sink proportions have been studied in tobacco and lettuce (McCabe et al. 2001; Cowan et al. 2005). Some nutrient deficiencies in young leaves relate to changes in cytokinin and sugar levels (Jordi et al. 2000). Indeed, Cowan et al. (2005) showed that the SAG12-*ipt* transgenic tobacco plants were slower than wild plants to increase the root-to-shoot ratio and the specific leaf area (SLA) after drought. This was interpreted as delayed capacity to remobilize nutrients from source organs (leaves) towards the sink (roots).

The protocol developed to characterize the performance of the transgenic cassava line 6044452928 under field conditions was sufficiently satisfactory and comprehensive for use as a model for future transgenic evaluations. This work also demonstrated that transgenesis is a viable alternative for modifying traits of agronomic importance in cassava such as leaf longevity. Observations made in our field experiments showed that the SAG12-*ipt* system did not obviously affect cassava yield, at least, not under our evaluation conditions in Colombia. Our findings were supported by the results of Zhang et al. (2010) who tested the same genotype in open fields in China discovering that transgenic cassava plants expressing SAG12-ipt did not improve root number, nor root weight when tested in the field. On the contrary, the non-transgenic wild types produced more and heavier roots (Tables 1 in Zhang's paper).

However, as was expected, the SAG12-*ipt* system increased cytokinin levels exclusively in mature leaves. The resulting delayed senescence led to extended leaf life. The retarded senescence of the mature leaves caused changes in source–sink relationships, as reflected by the physiological symptoms associated with senescence (increases in sugars and ABA in apical leaves). However, these changes did not seem to be reflected in the phenotype of young leaves. Larger lobes and petioles in mature leaves could be related to the increase in cytokinins because of their participation in processes of growth and cellular division. Evaluation of the ability of the transgenic cassava line 60444-529-28 to tolerate drought, while minimally affecting yield, may reveal the true potential of taking advantage of the SAG12-*ipt* system in cassava.

Rapid Propagation of Certified Seed

The lack of technology for producing planting materials in sufficient quantities, and in optimal health conditions, becomes an obstacle for the commercial development of cassava. Conventional plant propagation—use of stakes—favors, among other things, the spread of diseases, thus affecting the quality and quantity of "seed" for planting and, hence, the expected yield per production cycle.

CIAT, in collaboration with various actors and agents in development, has implemented and adjusted several multiplication systems at different scales. Thus, with assistance from the DGIS (Netherlands), the Center implemented mass propagation, using bioreactors of the type RITA® (French acronym; Temporary Immersion System for Plant Tissue Culture; Teisson and Alvard 1995). This efficient multiplication system reduces unit costs and propagation time by about 50%, compared with the conventional stake systems and *in vitro* multiplication in solid media.

In the RITA® system, during the immersion cycles, tissues are bathed in a liquid medium that contains nutrients and hormonal regulators (mainly of the cytokinin type). The cycles alternate with dry rest periods and no aeration. The growth of roots, stems (new explants), and leaves is accelerated, and a large quantity of buds is produced. The propagation rate, using this system, is thus increased considerably and can be used for the next micropropagation cycles.

With this methodology, multiplication rates of more than 1:10 can be reached, depending on the variety (Escobar et al. 2001). RITA® has also been successfully used for the proliferation of somatic embryos of coffee (Berthouly and Etienne 1999), banana (Alvard et al. 1993), rubber (Etienne et al. 1997), sugarcane (Lorenzo et al. 1998), and other crops.

The successful use of bioreactors for mass propagation depends on the response of the variety to management under *in vitro* conditions in liquid media. At CIAT, this system was tested successfully for multiplying industrial cassava clones. Experimentally, it was also successful with yam, lulo, sugarcane, potato, tree tomato, sweet potato, and other crops. It was also successful for embryogenesis in cassava, rice, and *Brachiaria*.

The Cassava Biotechnology Network (CBN) conducted a survey of small farmers in different countries (Thro et al. 1997). It found that, in every region, the principal limitation for farmers is access to good-quality planting materials of local and/or improved clones in sufficient quantities at planting times. Thus, CIAT, with support from the CBN and the Participatory Research and Gender Analysis (PRGA) Program, established a low-cost *in vitro* multiplication system at farm level (Thro et al. 1999a; Escobar et al. 2006), to enable rural associations to directly access planting materials through biotechnological techniques. This system permitted the establishment of rural laboratories in the Department of Cauca (CIAT 1999), and the Atlantic Coast (CIAT 2008), Colombia. The associations had been selected for their interest and capacity to manage and implement participatory laboratory processes to benefit their communities and production systems.

The strategy on which the rural laboratories were based was the adaptation to local conditions, using infrastructure and low-cost inputs that are easily obtained from local markets. Examples of successful rural laboratories are those of the associations ASOPROSA, Department of Cauca; the San Jacinto Small Farmers' Municipal Association for Sustainable Development (ASOMUDEPAS), Department of Bolívar; and the Empresa Comunitaria San Rafael in Ovejas, Department of Sucre, all in Colombia.

Alternative systems of producing planting materials can therefore by developed by combining low-cost systems with mass-propagation systems and/or conventional, solid-phase, *in vitro* systems. Such systems would benefit countries that have problems accessing planting materials, but possess potential for development and have end users interested in creating "local banks" of pathogen-free, planting materials (Escobar 2009).

Acknowledgements

We extend our gratitude to:

Willy Gruissem and Peng Zhang (ETH–Zurich) for contributing cassava plants, genetically modified for leaf retention, to test in the field at CIAT; and to Luis Duque and Tim Setter (Cornell University) for their help in analyzing cassava metabolites;

ASOPROSA, the Empresa Comunitaria San Rafael, and ASOMUDEPAS, with whom we developed and set up the low-cost systems for cassava; and

FIDAR, CBN, PRGA, DGIS (Netherlands), and MADR (Colombia) for their financial support towards this research-and-technological adjustment project.

References

To save space, the acronym "CIAT" is used instead of "Centro Internacional de Agricultura Tropical".

Abhary M; Siritunga D; Stevens G; Taylor NJ; Fauquet CM. 2011. Transgenic biofortification of the starchy staple cassava (*Manihot esculenta*) generates a novel sink for protein. PLoS ONE 6(1):e16256. DOI:10.1371/journal.pone.0016256

Akiyoshi DE; Klee H; Amasino RM; Nester EW; Gordon MP. 1984. T-DNA of *Agrobacterium tumefaciens* encodes an enzyme of cytokinin biosynthesis. Proc Natl Acad Sci USA 81:5994–5998.

Alvard D; Côte F; Teisson C. 1993. Comparison of methods of liquid medium culture for banana micropropagation. Effects of temporary immersion on explants. Plant Cell Tissue Organ Cult 32:55–60.

Álvarez MC; Uscátegui RM; López C; Baracaldo CM; Castro L; Noy V. 2004. Plasma retinol concentration according to pubertal maturation in school children and adolescents of Medellín, Colombia. Eur J Clin Nutr 58:456.

Arango-Mejía J. 2005. Análisis de la expresión de los genes *ggps*, *psy*, *pds*, *zds*, *crt*iso y *lcy-ß* de la ruta biosintética de carotenos mediante PCR en tiempo real, y cuantificación de carotenos usando HPLC, en hojas y raíces de plantas de yuca de diferentes edades. BSc thesis. Faculty of Sciences [of the] Pontificia Universidad Javeriana, Bogotá, Colombia.

Barry GF; Rogers SG; Fraley RT; Brand L. 1984. Identification of a cloned cytokinin biosynthetic gene. Proc Natl Acad Sci USA 81:4776–4780.

Beltrán JA; Jaimes H; Echeverri M; Ladino YJ; López D; Duque MC; Chavarriaga P; Tohme J. 2009. Quantitative analysis of transgenes in cassava plants using real-time PCR technology. In Vitro Cell Dev Biol-Plant 45(1):48–56.

Beltrán JA; Prías M; Al-Babili S; Ladino YJ; López D; Beyer P; Chavarriaga P; Tohme J. 2010. Expression pattern conferred by a glutamic acid-rich protein gene promoter in field-grown transgenic cassava (*Manihot esculenta* Crantz). Planta 231(6):1413–1424.

Berthouly M. Etienne H. 1999. Somatic embryogenesis of coffee. In: Jain SM; Gupta PK; Newton RJ, eds. Somatic embryogenesis in woody plants. Kluwer Academic Publishers, London. Vol 5, p 259–288.

Berthouly M; Dufour M; Alvard D; Carasco C; Alemano L; Teisson C. 1995. Coffee micropropagation in a liquid medium using the temporary immersion technique. In: Proc 16th ASIC Colloquium, Kyoto, Japan. International Coffee Science Association (ASIC), Vevey, Switzerland. p 514–519.

Bouvier F; Isner JC; Dogbo O; Camara B. 2005. Oxidative tailoring of carotenoids: a prospect towards novel functions in plants. TRENDS Plant Sci 10(4):187–194

Buitrago A, JA. 1990. La yuca en la alimentación animal. CIAT, Cali, Colombia. 446 p.

Chávez AL; Sánchez T; Jaramillo G; Bedoya JM; Echeverri J; Bolaños EA; Ceballos H; Iglesias CA. 2005. Variation of quality traits in cassava roots evaluated in landraces and improved clones Euphytica 143:125–133.

CIAT. 1999. Annual Report 1999 [of] Project SB-02: Assessing and utilizing agrobiodiversity through biotechnology. Cali, Colombia. p 34–36; 84–88.

CIAT. 2008. Annual Report 2008 [of] Project SB-02: Assessing and utilizing agrobiodiversity through biotechnology. Cali, Colombia. p 197–200.

Cowan AK; Freeman M; Björkman P-O; Nicander B; Sitbon F; Tillberg E. 2005. Effects of senescence-induced alteration in cytokinin metabolism on source–sink relationships and ontogenic stress-induced transitions in tobacco. Planta 221(6):801–814.

de Souza CR; Aragão FJ, Moreira EC; Costa CN; Nascimento SB; Carvalho LJ. 2009. Isolation and characterization of the promoter sequence of a cassava gene coding for Pt2L4, a glutamic acid-rich protein deferentially expressed in storage roots. Genet Mol Res 8(1):334–344

Diretto G; Al-Babili S; Tavazza R; Papacchioli V; Beyer P; Giuliano G. 2007. Metabolic engineering of potato carotenoid content through tuber-specific overexpression of a bacterial mini-pathway. PLoS ONE 2(4):e350. DOI:10.1371/journal.pone.0000350

Escobar RH. 2009. Use of cassava tissue culture at farmers' and industrial level: the Colombian experiences. Paper presented at the ISTRC Meeting, held at the International Potato Center (CIP), Peru, November 2009. (Available at www.cipotato.info/docs/abstracts/SessionVI/OP-40_R_Escobar.pdf)

Escobar RH; Muñoz L; Tohme J; Roca WM. 2001. Estado actual de la micropropagación de la yuca. Paper presented at the Seminario Internacional del Programa Colombiano de Biotecnología Agrícola (PBA), held in Cartagena, Colombia, February 2001.

Escobar RH; Hernández CM; Larrahondo N; Ospina G; Restrepo J; Muñoz L; Tohme J; Roca WM. 2006. Tissue culture for farmers: participatory adaptation of low-input cassava propagation in Colombia. J Exp Agric 42:103–120.

Etienne H; Lartaud M; Michaux-Ferriere N; Carron MP; Berthouly M; Teisson C. 1997. Improvement of somatic embryogenesis in *Hevea brasiliensis* (Müll. Arg) using the temporary immersion technique. In Vitro Cell Dev Biol–Plant 33:81–87.

Ihemere U; Arias-Garzón D; Lawrence S; Sayre R. 2006. Genetic modification of cassava for enhanced starch production. Plant Biotechnol J 4:453–465.

James C. 2011. Global status of commercialized biotech/GM crops: 2011. ISAAA Brief No. 43. International Service for the Acquisition of Agri-biotech Applications, Ithaca, NY, USA.

Jordi W; Schapendonk A; Davelaar E; Stoopen GM; Pot CS; De Visser R; Van Rhijn JA; Gan S; Amasino RM. 2000. Increased cytokinin levels in transgenic P-SAG12:IPT tobacco plants have large direct and indirect effects on leaf senescence, photosynthesis and N partitioning. Plant Cell Environ 23:279–289.

Jørgensen K; Bak S; Busk PK; Sørensen C; Olsen CE; Puonti-Kaerlas J; Møller BL. 2005. Cassava plants with a depleted cyanogenic glucoside content in leaves and tubers. Distribution of cyanogenic glucosides, their site of synthesis and transport, and blockage of the biosynthesis by RNA Interference technology. Plant Physiol 139:363–374.

Kawano K. 2003. Thirty years of cassava breeding for productivity: biological and social factors for success. Crop Sci 43:1325–1335.

Lenis JI; Calle F; Jaramillo G; Pérez JC; Ceballos H; Cock JH. 2006. Leaf retention and cassava productivity. Field Crops Res 95(2–3):126–134.

Lohman KN; Gan S; John MC; Amasino RM. 1994. Molecular analysis of natural leaf senescence in *Arabidopsis thaliana*. Physiol Planta 92(2):322–328.

López V, D. 2008. Establecimiento de una metodología para la evaluación agromorfológica, bioquímica y molecular de clones transgénicos de yuca (*Manihot esculenta*, Crantz) sembrados en campo: El caso de plantas que expresan el gen *ipt* de *Agrobacterium tumefaciens* para retención foliar. MSc thesis. Universidad Nacional de Colombia, Palmira–Colombia. (Also available at www.bdigital.unal.edu.co/714/)

Lorenzo JC; González BL; Escalona M; Teisson C; Espinosa P; Borroto C. 1998. Sugarcane shoots formation in an improved temporary immersion system. Plant Cell Tissue Organ Cult 54(3):97–200.

McCabe MS; Garratt LC; Schepers F; Jordi WJRM; Stoopen GM; Davelaart E; A van Rhijn JH; Power JB; Davey MR. 2001. Effects of pSAG12:ipt gene expression on development and senescence in transgenic lettuce. Plant Physiol 127:505–516.

Medford J; Horgan R; El-Sawi Z; Klee HJ. 1989. Alterations of endogenous cytokinins in transgenic plants using a chimeric isopentenyl transferase gene. Plant Cell 1:403–413.

OECD (Organisation for Economic Co-operation and Development). 2009. Consensus document on compositional considerations for new varieties of cassava [*Manihot esculenta* Crantz]: key food and feed nutrients, anti-nutrients, toxicants and allergens. ENV/JM/MONO(2009)44. Environment Directorate [of the] OECD, Paris, France.

Paine JA; Shipton CA; Chaggar S; Howells RM; Kennedy MJ; Vernon G; Wright SY; Hinchliffe E; Adams JL; Silverstone AL; Drake R. 2005. Improving the nutritional value of Golden Rice through increased pro-vitamin A content. Nat Biotechnol 23(4):482–487.

Raemakers K; Schreuder M; Suurs L; Furrer-Verhorst H; Vincken JP; De Vetten N; Jacobsen E; Visser RGF. 2005. Improved cassava starch by antisense inhibition of granule-bound starch synthase I. Mol Breed 16:163–172.

Roca WM. 1984. Cassava. In: Handbook of plant cell culture. Vol 2. Crop species. Sharp WR; Evans DA; Ammirato P; Yamada Y, eds. MacMillan Publishing Co., New York. p 269–301.

Sarria R; Torres E; Balcázar N; Destéfano L; Roca WM. 1993. Towards the development of *Agrobacterium tumefaciens* and particle bombardment-mediated cassava transformation. In: Roca WM; Thro AM, eds. Proc First International Scientific Meeting of the Cassava Biotechnology Network. CIAT, Cali, Colombia. p 216–221.

Sarria R; Torres E; Balcázar N; Destéfano-Beltrán L; Roca WM. 1995. Progress in *Agrobacterium*-mediated transformation of cassava (*Manihot esculenta* Crantz). In: Proc Second International Scientific Meeting Cassava Biotechnology Network held in Bogor, Indonesia, 22–26 August 1994. Working document no. 150. CIAT, Cali, Colombia. p 241–244.

Sarria R; Torres E; Angel F; Chavarriaga P; Roca WM. 2000. Transgenic plants of cassava (*Manihot esculenta*) with resistance to Basta obtained by *Agrobacterium*-mediated transformation. Plant Cell Rep 19(4):339–344.

Schopke C; Taylor NJ; Carcamo R; Konan NK; Marmey P; Henshaw GG; Beachy RN; Fauquet CM. 1996. Regeneration of cassava plants (*Manihot esculenta* Crantz) from microbombarded embryogenic suspension cultures. Nat Biotechnol 14:731–735.

Shewmaker CK; Sheehy JA; Daley M; Colburn S; Dang YK. 1999. Seed-specific overexpression of phytoene synthase: increase in carotenoids and other metabolic effects. The Plant J 20(4):401–412.

Siritunga D; Sayre RT. 2003. Generation of cyanogen-free transgenic cassava. Planta 217:367–373.

Siritunga D; Arias-Garzón D; White W; Sayre R. 2004. Over-expression of hydroxynitrile lyase in transgenic cassava roots accelerates cyanogenesis and food detoxification. Plant Biotechnol J 2:37–43.

Stessman D; Miller A; Spalding M; Rodermel S. 2002. Regulation of photosynthesis during *Arabidopsis* leaf development in continuous light. Photosynth Res 72:27–37.

Taylor NJ; Edwards M; Kiernan RJ; Davey CDM; Blakesley D; Henshaw GG. 1996. Development of friable embryogenic callus and embryogenic suspension culture systems in cassava (*Manihot esculenta* Crantz). Nat Biotechnol 14:726–730.

Teisson C; Alvard D. 1995. A new concept of plant *in vitro* cultivation in liquid medium: temporary immersion. In: Terzi M; Celal R; Falavigna A, eds. Current issues in plant molecular and cellular biology. Kluwer Academic Publisher, Dordrecht, Netherlands. p 105–110.

Thomas H; Howarth CJ. 2000. Five ways to stay green. J Exp Bot 51(Suppl 1):329–337. DOI:10.1093/jexbot/51.suppl_1.329.

Thro AM; Herazo LE; Lenis JI. 1997. Flor de yuca: Que florece un región: Qué puede hacer la biotecnología para ayudar el pequeño productor de yuca en la Costa Norte de Colombia? CBN Report. CIAT Working document no. 164. p 15.

Thro AM; Roca WM; Restrepo J; Caballero H; Poats S; Escobar R; Mafla G; Hernández C. 1999a. *in vitro* biology have farm-level impact for small-scale cassava farmers in Latin America? In Vitro Cell Dev Biol 35:382–387.

Thro AM; Fregene M; Taylor N; Raemakers CJJM; Puonti-Kaerlas J; Schopke C; Visser R; Potrykus I; Fauquet C; Roca W; Hershey C. 1999b. Genetic biotechnologies and cassava-based development of marginal rural areas. In: Hohn T; Leisinger K, eds. Biotechnology of food crops in developing Countries. Springer Verlag, Vienna. p 142–186.

Vanderschuren H; Akbergenov R; Pooggin MM; Hohn T; Gruissem W; Zhang P. 2007. Transgenic cassava resistance to African cassava mosaic virus is enhanced by viral DNA-A bidirectional promoter-derived siRNAs. Plant Mol Biol 64(5):549-557. DOI:10.1007/s11103-007-9175-6

Weaver LM; Gan S; Quirino B; Amasino RM. 1998. A comparison of the expression patterns of several senescence associated genes in response to stress and hormone treatment. Plant Mol Biol 37:455–469.

Welsch R; Arango J; Bär C; Salazar B; Al-Babili S; Beltrán J; Chavarriaga P; Ceballos H; Tohme J; Beyer P. 2010. Provitamin A accumulation in cassava (*Manihot esculenta*) roots driven by a single nucleotide polymorphism in a phytoene synthase gene. Plant Cell 22:3348–3356.

Wingler A; von Schaewen A; Leegood RC; Lea PJ; Quick WP. 1998. Regulation of leaf senescence by cytokinin, sugars, and light: effects on NADH-dependent hydroxypyruvate reductase. Plant Physiol 116:329–33.

Ye X; Al-Babili S; Klöti A; Zhang J; Lucca P; Beyer P; Potrykus I. 2000. Engineering the provitamin A (beta-carotene) biosynthesis pathway into (carotenoid-free) rice endosperm. Science 287:303–305.

Zhang P; Gruissem W. 2004. Extension of cassava leaf life by autoregulatory inhibition of senescence. In: Abstracts [of the] Sixth International Scientific Meeting of the Cassava Biotechnology Network, "Adding value to a small-farmer crop", held in Cali, Colombia, 8–14 March 2004. CBN–VI; CIAT; and eight others, Cali, Colombia. PS4, p 99.

Zhang P; Wang WQ; Zhang GL; Kaminek M; Dobrev P; Xu J; Gruissem W. 2010. Senescence-inducible expression of isopentenyl transferase extends leaf life, increases drought stress resistance and alters cytokinin metabolism in cassava. J Integr Plant Biol 52(7):653–669.

CHAPTER 16

Cassava Viral Diseases of South America

Lee Calvert[1], *Maritza Cuervo*[2], *and Iván Lozano*[3]

Vegetatively propagated cassava is particularly prone to damage by viruses as infection tends to build up in successive cycles of propagation. At least 16 different viruses have been isolated so far from cassava, but there are probably others that have yet to be described (Calvert and Thresh 2002).

Because the center of origin of cassava is in the Neotropics and its introduction into other regions has been relatively recent, only one of the viruses attacking this crop in Central and South America has been found elsewhere. In addition, several Neotropical viral diseases are asymptomatic and do not damage plants, reflecting long periods of coevolution between host and pathogens.

The main cassava viruses causing diseases of economic importance that deserve special attention in plant quarantine controls are the African cassava mosaic virus (ACMV), East African cassava mosaic virus (EACMV)[4], South African cassava mosaic virus (SACMV), cassava brown streak virus (CBSV), Indian cassava mosaic virus (ICMV), cassava common mosaic virus (CsCMV), cassava vein mosaic virus (CVMV), and cassava frogskin virus (CFSV). In South and Central America, particular attention should be paid to the latter three.

Cassava Common Mosaic Disease

Background and distribution

Cassava common mosaic disease (CsCMD) was first reported in southern Brazil (Silberschmid 1938; Costa 1940). It has since been found in several countries of South America, and in Africa and Asia.

Usually, the disease is not important in Latin America and the Caribbean. No detailed studies exist of affected areas in Colombia (Nolt et al. 1992). The disease is most prevalent in southern Brazil and Paraguay. In these regions, the disease is important and phytosanitary control measures are recommended to reduce losses.

The disease has no known vector and its dissemination throughout a crop is attributed to mechanical transmission.

Description

Plants infected by CsCMD develop symptoms of mosaic and chlorosis in leaves. Sometimes, infected leaves present clear, dark green spots, bordered by veins. Symptoms are more severe during prolonged and relatively cold periods—a frequent situation in the South American subtropics. Under these conditions, infected plants are usually dwarfed and yield losses may be as high as 60% (Costa and Kitajima 1972) (Figure 16-1).

Etiology and epidemiology

Cassava common mosaic disease is caused by the virus of the same name (CsCMV) which can infect species belonging to several families of dicotyledonous plants. This virus was originally classified in the potexvirus group, that is now referred to as the genus Potexvirus. The virions of CsCMD are elongated, semi-flexuose particles that measure 15 × 495 nanometers (Kitajima et al. 1965) and contain RNA.

In cassava, the virus presents the nuclear inclusions typical of potexviruses, as found in another

1. Virologist, formerly of CIAT, Cali, Colombia.
2. Research Associate, Germplasm Health Laboratory, Genetic Resources Program, CIAT. E-mail: m.cuervo@cgiar.org
3. Research Associate, Virology Laboratory, CIAT. E-mail: i.lozano@cgiar.org
4. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Figure 16-1. Symptoms caused by CsCMD.

host *Nicotiana benthamiana*. The virus is known to also systemically infect *Euphorbia* spp., *Cnidoscolus conitifolius*, and other species of the Euphorbiaceae family (Costa and Kitajima 1972).

The CsCMV viral particles contain a simple protein cover with a molecular weight of 26,000 Da (Nolt et al. 1991). The genome consists of single-stranded RNA, of which the complete sequence is known (Calvert et al. 1996). The organizational structure, proteins, and molecular weights are usually similar to those of other potexviruses.

The principal source of inoculum is infected plant material. Because the virus spreads systemically through the plant, stakes from diseased plants are also infected. The virus is highly stable and may spread through mechanical transmission on machetes or other implements used in agricultural tasks. Although this mode of transmission is inefficient, it is the only known means of dissemination from plant to plant.

Management and control

Eliminating plants that express CsCMV symptoms provides adequate control. The symptoms are evident in primary leaves. If this is not done early in the cropping cycle, the plants must then be marked and the stems burned after the roots are harvested. To minimize the risk of mechanical transmission, cutting tools should be periodically disinfected (Lozano and Nolt 1989). Care in selecting healthy planting materials can eradicate CsCMV or at least mitigate, to a minimum, the economic damage it causes.

Cassava Vein Mosaic Disease

Background and distribution

The first report on cassava vein mosaic disease (CVMD) was in 1940 (Costa 1940). The areas where the disease is prevalent are still inhabited by mainly rural communities where the lack of economic resources contributes to ignorance on this disease. Because symptoms are sporadic and usually not readily visible, the disease is unlikely to receive adequate attention at the end of the crop's growing cycle (Figure 16-2).

The disease is very common in the semiarid areas of Northeast Brazil. However, its presence in other regions of the country has also been reported, that is, in the States of Ceará, Pernambuco, Alagoas, Piauí, and Bahia (Calvert et al. 1995), and in some neighboring regions.

Description

The first four or five leaves of infected stakes present chlorotic veins. The chlorosis starts forming a pattern

Figure 16-2. Symptoms caused by CVMV.

of rings that, as they join, create a circular spot. Leaves with severe symptoms commonly have deformed blades and show epinasty. Sometimes, symptoms disappear and their expression is influenced by climatic conditions. Leaves of infected plants become prematurely old and fall, reducing leaf area. Frequently, in mature plants, observing leaves with symptoms of mosaic is difficult, as these are more pronounced in the semiarid areas than in the humid coastal regions of Northeast Brazil. The disease does not seem to affect plant vigor.

Etiology and epidemiology

Cassava vein mosaic disease is caused by a virus of the same name (CVMV), which presents isometric particles, 50 nm in diameter (Kitajima and Costa 1966). The genome consists of double-stranded DNA, which has a length of 8200 base pairs.

The CVMV virus was at first tentatively classified as a member of the caulimovirus group. The complete sequence of CVMV has been determined and the genomic organization differs from that of either the caulimoviruses or badnaviruses (Calvert et al. 1995). The virus will probably be classified as a unique genus of the plant pararetroviruses.

Very little is known about the epidemiology and control of CVMV. The only known host is cassava and the primary mode of dissemination is by infected planting materials. Commercial varieties are rarely found totally infected. Dissemination occurring within the field suggests the existence of a vector as yet unidentified. However, few studies exist on the virus's dissemination and more research is needed to establish the effectiveness of using virus-free material. The virus can remain in a latent state in plants, especially during the rainy seasons of the Brazilian coastal regions.

Management and control

The disease can be effectively controlled by removing infected plant materials immediately the symptoms appear. Many infected plants seem to tolerate CVMV and produce stems of normal appearance that could be used as good planting material. Although the economic importance of CVMD has not been fully quantified, it can cause losses, especially if it appears at the beginning of the cropping cycle.

In Brief: Viral Diseases in South America

- In South America, different viral diseases attack cassava. Some are asymptomatic and are not economically important to the crop.
- Common mosaic has been reported in Brazil and other South American countries. This disease develops symptoms of mosaic and chlorosis in infected plants and is transmitted mechanically.
- The vein mosaic virus is found mainly in Northeast Brazil. Infected plants present chlorosis of the veins and, when symptoms are severe, the leaves become deformed and present epinasty. These phenomena are influenced by climatic conditions. The virus can spread from plant to plant and, although its economic importance has not been fully quantified, it can cause losses.

Cassava Frogskin Disease

Background and distribution

Cassava frogskin disease (CFSD) was first reported in 1971, in the Department of Cauca, southern Colombia (Pineda et al. 1983). Its place of origin seems to be the Amazon Region of Brazil or Colombia, where it infects the different cassava varieties cultivated by indigenous communities. However, the farmers assumed that the disease was a physiological disorder associated with the varieties and, therefore, did not report it earlier.

In the Amazon, the disease is known as *lagarto-jacaré* because the symptoms expressed by roots resemble that lizard's skin. Along the North Coast, Colombia, in 1981, an allegedly new disease called "Caribbean mosaic" was reported as presenting symptoms of mosaic in the leaves of cassava variety Secundina (Calvert 1994). Research demonstrated that *lagarto-jacaré*, caiman-lizard disease, and Caribbean mosaic are all the one and same CFSD.

Of the cassava diseases, frogskin is considered to be one of the most damaging to the crop (Lozano and Nolt 1989), as it directly affects root production, causing yield losses of 90% or more (Figure 16-3).

By the 1980s, the disease had appeared in most cassava-producing regions of Colombia and was

Figure 16-3. General appearance of roots infected by cassava frogskin disease.

steadily spreading. It has now been reported from Brazil, Costa Rica, Panama, Peru, and Venezuela. In Panama's case, this disease was first detected in 1999, in cassava plots planted with materials that came from Costa Rica, a country that had already reported the disease.

Description

Symptom expression is variable according to temperature and genotype. In most varieties, infected plants do not present visible signs in their aerial parts, which sometimes appear healthy and vigorous. Stems of these plants are thicker, especially at the base of the plant, as the increased thickness of stems is related to the lack of starch accumulation in roots. However, because these stems are thick, farmers tend to select them as planting materials.

In the roots, symptoms range from very mild to severe, depending on the plant's age and climatic factors (Figure 16-4). Dry or hot conditions tend to inhibit the development of symptoms, whereas cooler conditions favor expression. Even in mildly infected plants, economic losses occur because of the lack of starch accumulation.

Symptoms consist of small longitudinal fissures located near the callus where the roots originate. They then continue appearing along the roots' length. As the young roots increase in diameter, the fissures tend to scar, giving the lesions a lip-like form. As the roots mature, the lesions increase in size and number, and join to create the appearance of a net or honeycomb. The root peel or epidermis appears cork-like and easily comes off. According to the severity of symptoms, the lesions' depth and number increase until the roots become deformed. All these symptoms may occur throughout the root's length or may be restricted to one part, mostly towards the middle.

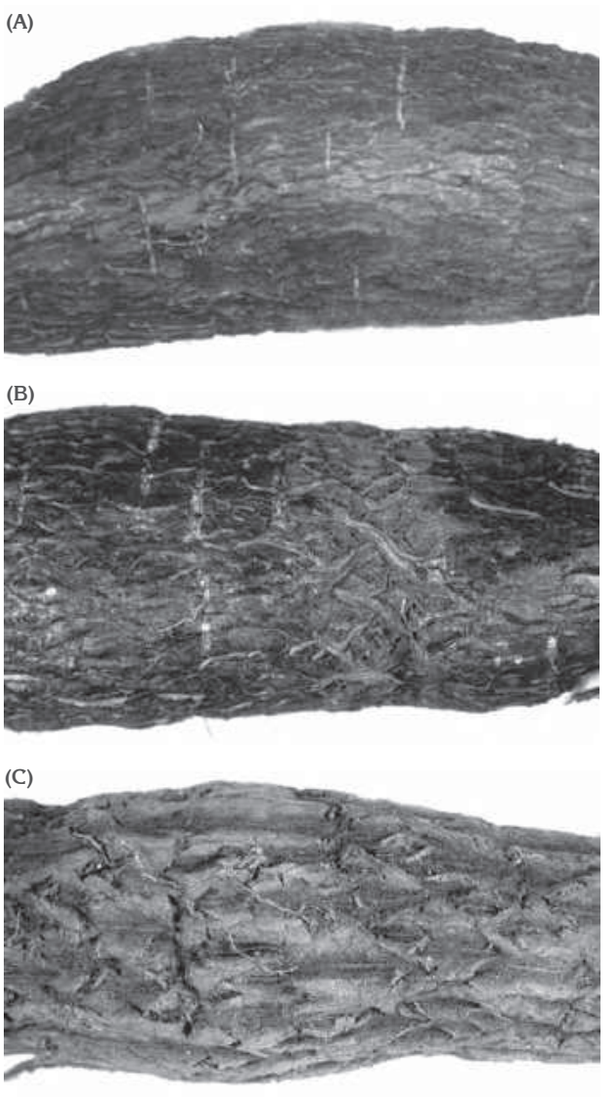


Figure 16-4. Symptoms of frogskin disease in cassava roots: **(A)** healthy root; **(B)** root with mild symptoms; and **(C)** root with severe symptoms.

The root system of infected plants usually does not develop in the same way as healthy plants. The roots remain thin and woody, with a thick, cork-like peel. Their starch content is very low. Sometimes, within one plant, some roots bulk normally, although they may be more fibrous, while others are severely affected.

Diagnosis

The disease can be detected by carefully examining the roots for the characteristic symptoms, whether these are mild or severe.

This disease is easily transmitted through grafts. Hence, grafting can be used as another diagnostic method. The test consists of grafting an indicator variety (such as 'Secundina', accession CIAT M Col 2063) that has been duly certified as virus-free onto the plants being evaluated (Figure 16-5).

To increase the germination rate of the grafts, buds are best removed from the stocks. After 3 or 4 weeks, the plants should be checked to confirm the presence of symptoms such as mosaic in the foliage of shoots, thus indicating the disease's presence. To ensure effective appearance of symptoms, grafts must be kept at an average temperature of 28 °C. Where they are grown in a greenhouse or screenhouse, they may be placed under tables.

The disease may be eliminated through thermotherapy and *in vitro* meristem culture (Mafla et al. 1984). Once treated, grafts must be made with variety Secundina to confirm the planting materials' health.

Figure 16-5. Detecting cassava frogskin disease through grafting test.

Notable progress in the characterization and detection of the virus associated with this disease has led to the development of a molecular diagnostic method, using RT-PCR (Reverse Transcriptase-PCR). Comparative studies of the two methodologies available for detecting this virus have shown that new molecular technology of detection is more effective and reliable than the symptomatology and the use of warning plants.

Etiology and epidemiology

Identifying the causal agent of CFSD has been a challenge since the disease was first discovered. However, based on 30 years of experimental data and advances made in the development and implementation of molecular techniques, the disease has been associated with a reovirus—the CFSV (Cuervo 1990; Calvert et al., 2008).

The presence of virus-like isometric particles of about 70 nm in diameter was observed through the electron microscope in tissue sections from cassava leaves, petioles, stems, and roots.

So far, nine species of viral double-stranded (ds) RNA are associated with this disease, and complementary DNA (cDNA) clones to six genomic segments have been synthesized from purified viral dsRNAs. The putative proteins predicted from the sequence of the cassava viral cDNA clones obtained show similarities to the P1, P2, P3, P4, P5, and P10 proteins of rice ragged stunt (reo)virus (RRSV). Phylogenic analyses confirm that CFSV is a member of the family Reoviridae and that it is most closely related to RRSV (Calvert et al. 2008).

This virus has been detected in samples collected in different regions of Colombia and has never been detected in healthy plants.

To date, 30% of the reovirus's genome has been sequenced and the existence of genetic variability in this virus was verified by examining infected plants collected from different regions of Colombia. Molecular analysis of the samples revealed at least three different strains of the virus (Calvert et al. 2008; Cuervo 2006).

Field studies on transmission indicate that frogskin disease spreads from plant to plant. Although the transmission rate is relatively low, compared with many plant viruses transmitted through a vector, dissemination patterns suggest that the disease is transmitted by an aerial vector.

The whitefly *Bemisia tuberculata* has frequently been associated with the disease (Angel et al. 1990), but the insect's efficiency in transmitting it is low. Although more than 100 experiments on transmission through *B. tuberculata* were conducted, no correlations were found between the number of insects and the percentage of transmission. This indicates that the vector of this disease has not yet been clearly identified.

When the percentage of plants infected by CFSD is low, dissemination of the disease is very slow. Even so, if due precautions are not taken in each cycle, the incidence of CFSD increases. The higher the number of infected plants in the field, the faster the rate of dissemination becomes. Use of vegetative seed (stakes) from infected cassava fields therefore becomes the disease's main mode of dissemination.

Parallel research at CIAT has also associated CFSD with a phytoplasm (see Chapter 8). PCR techniques allowed the detection of a phytoplasm in leaves infected with frogskin disease. (Álvarez et al. 2009)

Resistance

Field studies have demonstrated that different levels of resistance exist among cassava varieties. The number of lines presenting significant levels of resistance after several years of evaluation indicates that the use of resistant materials would be the most useful measure for controlling this disease. Resistant lines lose less starch and suffer fewer yield losses, compared with susceptible lines.

Management and control

The following recommendations are aimed at preventing the introduction and dissemination of frogskin disease in cassava-producing areas:

1. As the disease spreads mainly through the use of contaminated stakes, the most important control measure is to obtain planting materials (stakes) from healthy plantings that have been technically managed, with excellent plant health control.

2. At harvest, the stakes selected for future planting should be placed beside their respective roots. Later evaluation will confirm the absence of symptoms.

3. As a method of integrated pest management, tools should be disinfected with detergent or chlorine solution.

4. Heavily infected cassava plantings (i.e., at more than 10%) must be burned, including both roots and aerial parts. Harvest residues, particularly stems, should also be eliminated because they can re-sprout.

5. Systems of plant health surveillance and quarantine must be strengthened to prevent the introduction of infected planting materials to national territory, or their mobilization within that territory.

Cassava frogskin disease in brief

- Frogskin disease is a serious disease for the cassava crop because it directly affects root production and can cause yield losses of more than 90%.

- The disease has been continually spreading and already affects other regions of Colombia and other countries.

- Symptom expression varies with temperature and cassava genotype.

- The root system of infected plants usually does not develop to the same extent as healthy roots. Instead, they become thin and woody, with very low starch content.

- Although the causal agent has not yet been fully identified, research to date suggests that it is probably of viral origin. However, its association with a phytoplasm, or a combination of both types of organisms, has not been ruled out.

- The disease spreads mainly by planting contaminated vegetative seed (stakes). It also appears to be transmitted, albeit slowly, by an aerial vector.

- Different levels of resistance exist among cassava varieties. Hence, with the use of tolerant varieties, healthy planting materials, and good plant health control, CFSD is one disease that can be controlled.

Viral diseases in Africa

In terms of economic and social importance, perhaps the most relevant cassava diseases that are propagated by infected planting materials are: cassava mosaic disease (CMD) and cassava brown streak disease (CBSD), two viral diseases only present in Africa and, in the case of CMD, India and Sri Lanka as well (Monger et al. 2001; Calvert and Thresh 2002; Thresh et al. 1994). Because these diseases are not present in the Neotropics, CIAT has not carried out much research on them. Major research achievements on these diseases have been made at the International Institute of Tropical Agriculture (IITA) based at Ibadan, Nigeria, and other collaborating institutions.

Cassava mosaic disease has attracted the attention since long time ago and considerable knowledge on the disease and its vector (the whitefly *Bemisia tabaci*) is available (Legg and Fauquet 2004; Legg and Thresh 2000; Thresh and Cooter 2005; Patil and Fauquet 2009). Symptoms in the leaves are characteristic and easy to identify (Figure 16-6) although variable from a green mosaic to a yellow mosaic, distortion of leaflets, rupturing of tissue, and premature leaf abscission. Resistance to CMD has been identified and analyzed (Fargette et al. 1996; Hahn et al. 1980; Thresh et al. 1998) or developed through genetic transformation (Zhang et al. 2005). Molecular markers associated with resistance to CMD have been identified and successfully used (Akano et al. 2002; Okogbenin et al. 2007). More recently there have been reports on the association of at least two different satellite DNAs with CMD (Ndunguru et al. 2008; Patil and Fauquet 2010).

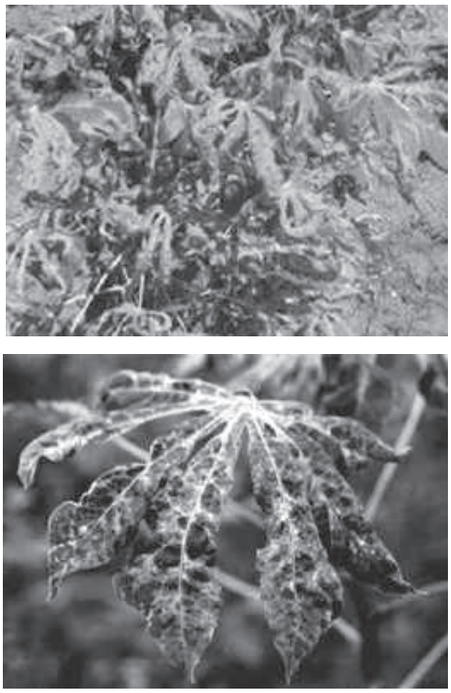


Figure 16-6. Cassava mosaic disease (CMD) in cassava. (Photos: Legg, Owor, and Okao-Okuja; G. Mkamilo.)

Cassava brown streak disease, on the other hand, remained a minor disease problem restricted to the coastal areas of East Africa. Recently, however, it started to spread westbound and is now a major concern in many regions of Africa (Hillocks et al. 2002; Hillocks and Jennings 2003). The disease is also transmitted by *B. tabaci* (Maruthi et al. 2005) and has been characterized from the molecular point of view (Mbanzibwa et al. 2009a, 2009b; Monger et al. 2001; Monger et al. 2010). CBSD is named after the brown elongated necrotic lesions that often develop on young stem tissue as well as in roots (Figure 16-7). Necrosis

(A)

(B)

Figure 16-7. Symptoms of cassava brown streak disease (CBSD) on **(A)** leaves in Tanzania and **(B)** roots in Uganda. (Photos: R. Howeler.)

in the roots greatly reduces their economic value. The degree of root necrosis and the characteristic constrictions associated is variable with some varieties only expressing these symptoms late in crop growth (Calvert and Thresh 2002). Symptoms can only be observed in the leaves but are highly variable ("featherly" chlorosis to yellow blotches associated to leaf veins) and often inconspicuous.

In response to the expanding relevance of CBSD, efforts to develop tolerant/resistance cultivars have increased in recent years. New sources of resistance seem to have been found in a backcross population involving *M. esculenta* subsp. *flabellifolia* (M Fregene 2012, pers. comm.).

References

Akano A; Dixon A; Mba C; Barrera E; Fregene M. 2002. Genetic mapping of a dominant gene conferring resistance to cassava mosaic disease. Theor Appl Genet 105(4):521–525.

Álvarez E; Mejía JF; Llano G; Loke JB; Calari A; Dubuk B; Bertaccini A. 2009. Characterization of a phytoplasma associated with frogskin disease in cassava. Plant Dis 93:1139–1145.

Angel JC; Pineda BL; Nolt B, Velasco AC. 1990. Mosca blanca (Homoptera: Aleyrodidae) asociada a transmisión de virus en yuca. Fitopatol Colomb 13:65–71.

Calvert LA. 1994. The safe movement of cassava germplasm. In: Report of the First Meeting of the International Network for Cassava Genetic Resources, organized by CIAT, IITA, and IBPGR, and held at CIAT, Cali, Colombia, August 1992. International Plant Genetic Resources Institute (IPGRI), Rome. p 163–165.

Calvert LA; Thresh JM. 2002. The viruses and virus diseases in cassava. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 237–260.

Calvert LA; Ospina MD; Shepherd RJ. 1995. Characterization of cassava vein mosaic virus: a distinct plant pararetrovirus. J Gen Virol 76(5): 1271–1278.

Calvert LA; Cuervo M; Ospina MD; Fauquet C; Ramírez BC. 1996. Characterization of cassava common mosaic virus and a defective RNA species. J Gen Virol 77(3):525–530.

Calvert LA; Cuervo M; Lozano I; Villareal N; Arroyave J. 2008. Identification of three strains of a virus associated with cassava plants affected by frogskin disease. J Phytopathol 156:647–653.

Costa AS. 1940. Observações sôbre o mosaico comum e o mosaico das nervuras da mandioca (*Manihot utilissima* Pohl.). J Agron (Piracicaba) 3:239–248.

Costa AS; Kitajima EW. 1972. Studies on virus and mycoplasma diseases of the cassava plant in Brazil. In: Proc Cassava Mosaic Workshop, Ibadan, Nigeria. International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. p 18–36.

Cuervo M. 1990. Caracterización de los ácidos ribonucleicos de doble cadena (dsRNA) asociados con algunas enfermedades virales en yuca. (*Manihot esculenta* Crantz). Fitopat Colomb 14(1):10–17.

Cuervo M. 2006. Caracterización molecular de algunos aislamientos del virus del cuero de sapo recolectados en diferentes zonas de Colombia. MSc thesis. Universidad Nacional de Colombia, Palmira, Colombia.

Cuervo M; Ospina MD; Fauquet C; Ramírez Angel JC; Pineda B; Nolt BL; Velasco AC. 1990. Mosca blanca (Homoptera: Aleyrodidae) asociada a transmisión de virus en yuca. Fitopatol Colomb 13:65–71.

Fargette D; Colon LT; Bouveau R; Fauquet C. 1996. Components of resistance of cassava to African cassava mosaic virus. Eur J Plant Pathol 102(7): 645–654.

Hahn SK; Terry ER; Leuschner K. 1980. Breeding cassava for resistance to cassava mosaic disease. Euphytica 29(3):673–683.

Hillocks RJ; Jennings DL. 2003. Cassava brown streak disease: A review of present knowledge and research needs. Int J Pest Manage 49(3):225–234.

Hillocks RJ; Thresh JM; Tomas J; Botao M; Macia R; Zavier R. 2002. Cassava brown streak disease in northern Mozambique. Int J Pest Manage 48(3): 178–181.

Kitajima EW; Costa AS. 1966. Particulas esferoidais associadas ao virus do mosaico das nervuras da mandioca. Bragantia 25(18):211–221.

Kitajima EW; Wetter C; Oliveira AR; Silva DM; Costa AS. 1965. Morfologia do virus do mosaico comun da mandioca. Bragantia 24(21):247–260.

Legg J; Fauquet C. 2004. Cassava mosaic geminiviruses in Africa. Plant Mol Biol. 56:585–599.

Legg J; Thresh J. 2000. Cassava mosaic virus disease in East Africa: a dynamic disease in a changing environment. Virus Res. 71:135–149.

Lozano JC; Nolt BL. 1989. Pests and pathogens of cassava. In: Kahn RP, ed. Plant protection and quarantine, 2: Selected pests and pathogens of quarantine significance, vol 2. CRC Press, Inc., Boca Raton, FL, USA. p 174–175.

Mafla G; Roa JC; Roca WM. 1984. Erradicación de la enfermedad cuero de sapo de la yuca (*Manihot esculenta*) por medio del cultivo de meristemos: Efecto de la termoterapia y del tamaño del explante en la tasa de saneamiento. In: Perea D; Angarita ZA, eds. Proc Congreso Nacional de Cultivo de Tejidos Vegetales, held in Bogotá, DC, Colombia. Universidad Nacional de Colombia, Bogotá, DC, Colombia. p 171–175.

Maruthi MN; Hillocks RJ; Mtunda K; Raya MD; Muhanna M; Kiozia H; Rekha AR; Colvin J; Thresh JM. 2005. Transmission of *Cassava brown streak virus* by *Bemisia tabaci* (Gennadius). J Phytopathol 153(5):307–312.

Mbanzibwa DR; Tian YP; Tugume AK; Mukasa SB; Tairo F; Kyamanywa S; Kullaya A; Valkonen JPT. 2009a. Genetically distinct strains of *Cassava brown streak virus* in the Lake Victoria basin and the Indian Ocean coastal area of East Africa. Arch Virol 154:353–359.

Mbanzibwa DR; Tian YP; Mukasa SB; Valkonen JPT. 2009b. *Cassava brown streak virus (Potyviridae*) encodes a putative Maf/HAM1 pyrophosphatase implicated in reduction of mutations and a P1 proteinase that suppresses RNA silencing but contains no HC-Pro. J Virol 83(13):6934–6940.

Monger WA; Seal S; Isaac AM; Foster GD. 2001. Molecular characterization of the *Cassava brown streak virus* coat protein. Plant Pathol 50(4): 527–534.

Monger WAT; Alicai T; Ndunguru J; Kinyua ZM; Potts M; Reeder RH; Miano DW; Adams IP; Boonham N; Glover RH; Smith J. 2010. The complete genome sequence of the Tanzanian strain of *Cassava brown streak virus* and comparison with the Ugandan strain sequence. Arch Virol 155:429–433.

Ndunguru J; Fofana B; Legg JP; Chellappan P; Taylor N; Aveling T; Thompson G; Fauquet C. 2008. Two novel satellite DNAs associated with bipartite cassava mosaic begomoviruses enhancing symptoms and capable of breaking high virus resistance in a cassava landrace. Global Cassava Partnership – First Scientific Meeting. Ghent, Belgium. p 141.

Nolt BL; Velasco AC; Pineda B. 1991. Improved purification procedure and some serological and physical properties of cassava common mosaic virus from South America. Ann Appl Biol 118(1):105–113.

Nolt BL; Pineda B; Velasco AC. 1992. Surveys of cassava plantations in Colombia for virus and virus-like diseases. Plant Pathol 41(3):348–354.

Okogbenin E; Porto MCM; Egesi C; Mba C; Espinosa E; Santos LG; Ospina C; Marín J; Barrera E; Gutiérrez J; Ekanayake I; Iglesias C; Fregene MA. 2007. Marker-assisted introgression of resistance to cassava mosaic disease into Latin American germplasm for the genetic improvement of cassava in Africa. Crop Sci 47:1895–1904.

Patil B; Fauquet C. 2009. Cassava mosaic geminiviruses: actual knowledge and perspectives. Mol Plant Pathol 10:685–701.

Patil B; Fauquet C. 2010. Differential interaction between cassava mosaic geminiviruses and geminivirus satellites. J Gen Virol 91:1871–1882.

Pineda B; Jayasinghe U; Lozano JC. 1983. La enfermedad "cuero de sapo" en yuca (*Manihot esculenta* Crantz). ASIAVA (Colombia) 4:10–12.

Silberschmid KO. 1938. O mosaico da mandioca. Biológico 4(6):177–181.

Thresh JM; Fargette D; Otim-Nape GW. 1994. The viruses and virus diseases of cassava in Africa. Afr Crop Sci J 2(4):459–478

Thresh JM; Otim-Nape GW; Fargette D. 1998. The components and deployment of resistance to cassava mosaic virus disease. Integrated Pest Management Reviews 3(4):209–224.

Thresh JM; Cooter TJ. 2005. Strategies for controlling cassava mosaic disease in Africa. Plant Pathol. 54:587–614.

Zhang P; Vanderschuren H; Fütterer J; Gruissem. 2005. Resistance to cassava mosaic disease in transgenic cassava expressing antisense RNAs targeting virus replication genes. Plant Biotechnol J 3(4):3853–97.

Part D

Improvement and Technification

CHAPTER 17

Manihot Genetic Resources at CIAT (Centro Internacional de Agricultura Tropical)

Gustavo Jaramillo O.[1]

Introduction

Among the dozens of *Manihot* species, cassava (*M. esculenta* Crantz) is unique in being cultivated. Its allogamous reproductive mode and its highly heterozygous genetic constitution are the main reasons for propagating the crop by cuttings (or stakes) instead of by sexual seed. To preserve the visible phenotypic characters, the species has been cultivated and maintained over the years by continuous vegetative propagation.

The primary center of origin and diversity is the western Amazon Region. In pre-Columbian times, cassava migrated westwards to Peru, and then northwards to Colombia, and from there entered Central America. It also migrated southwards to Paraguay and Argentina, although when this migration occurred is not precisely known (D Debouck 2001, pers. comm.). In the 1500s, cassava was taken by the Spanish and Portuguese to Africa and Asia, which then became secondary centers of diversity (Hershey and Amaya 1979).

Within the system of the Consultative Group on International Agricultural Research (CGIAR)[2], CIAT has the global responsibility to conserve the genetic resources of *M. esculenta*. Currently, the collections held at the CGIAR centers are under the auspices of the Food and Agriculture Organization of the United Nations (FAO), as patrimony for humanity. As with other crops, the conservation of cassava germplasm is justified by the following points:

1. To prevent the loss of wild and cultivated species to *genetic erosion*, caused by pressure factors such as the adoption of modern varieties, land clearing for urbanization, and alteration of natural habitats.

2. To maintain a high degree of *genetic variation* for use in crop improvement programs.

Although cryopreservation techniques are currently being enhanced, conservation in the germplasm bank at CIAT is based mainly on two systems: field and *in vitro*. These two modalities of *ex situ* conservation successfully maintain the status of gene combinations, that is, without change, as verified by the clones' genetic stability. They also contribute important elements for the conservation, characterization, and use of germplasm (Debouck and Guevara 1995).

This chapter compiles information from several scientific articles and discusses collection, conservation, characterization, documentation, and distribution—all activities for managing a cassava germplasm bank.

Clone Codification and Nomenclature

According to Jaramillo (1993), the germplasm bank held at CIAT uses the following scheme:

Manihot esculenta varieties

For landraces collected inside and outside Colombia, CIAT assigns a three-part code:

M + country + consecutive number

- The letter "M" corresponds to the first letter of the genus name (*Manihot*).

1. Agronomist, formerly of Cassava Program, CIAT, Cali, Colombia. E-mail: gjo97@hotmail.com
2. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

- "Country" refers to the country of origin, and is expressed as the first two or three letters of the country's name, following the FAO code.

- The consecutive number is in Arabic numerals, and indicates the material's order of entry at CIAT.

For example, M Bra 383 indicates a cassava clone of Brazilian origin that had entered the collection at CIAT as number 383.

Improved hybrids

The original identification of hybrids from the CIAT Cassava Improvement Project is conserved by assigning a four-part code:

> Type of cross + record of the cross + hyphen + selected genotype

For example, CM 340-55 indicates a hybrid of controlled pollination (CM). The parents crossed were M Col 22 and M Col 645, with the cross being recorded as 340. The plant selected was number 55. We point out that a clone's code never changes. Even in the event that one disappears or dies, its code is never assigned to another clone.

Vulgar, regional, or common names for cassava clones are also important. Usually, farmers give varieties simple names that relate to some characteristic of the plant or to its place of origin, for example:

Algodonas:	Varieties that are easy to cook
Rojitas:	Varieties with red petioles
Llaneras:	Varieties from the *Llanos* (i.e., Eastern Plains of Colombia)
Negritas:	Varieties with dark stems or crown

The use of common names has many limitations and can be confusing, particularly as a common name may be used for two or more very different or contrasting genotypes.

Released materials are also given common names, usually by the institutes or agencies who do the releasing. These names relate to details specific to the clone or release site such as Catumare, Costeña, Caribeña, and Rojita. Table 17-1 details the most common regional cassava varieties in Colombia and the materials released in the country to date.

Wild *Manihot* species

The species collected are introduced into CIAT. Seeds are used to obtain varieties, for which the following five-part code is proposed:

> M + abbreviation + seed population + hyphen + selected genotype

Examples include M alt 003-004, and M fmt 001-001, where:

- The letter "M" corresponds to the first letter of the genus name (*Manihot*).

- The "abbreviation" consists of three letters that refer to the species, as according to the list proposed by Chávez et al. (1987; Table 17-2).

- "Seed population" refers to a consecutive number given in the order in which the wild species was introduced into CIAT.

- "Selected genotype" refers to the code number of the selected plant. This number is then used consecutively.

Cultivated cassava × wild relative hybrids

A four-part code has been proposed, as follows:

> Type of cross + record of cross + hyphen + selected genotype

- Type of cross:
  Open pollination = OW (open wild)
  Polycross = SW
  Self-pollination = AW
  Controlled pollination = CW

- Record of cross:
  This consecutive number refers to the parents used in the cross. A fictitious example would be:

Type	Record, which refers to cross:	Mother	×	Father
CW	1	M Col 1505		M aes 001-002

- Selected genotype:
  This selection number is assigned consecutively, starting at 1. Using the previous example, this would be CW 1–001, CW 1–002, and so forth.

Table 17-1. Examples of important cassava clones, their assigned codes, regional names, year of release in Colombia, and planting site.

CIAT code	Regional name	Other codes assigned by ICA or CIAT	Year of release in Colombia	Planting site: country or locality in Colombia
M Bra 356	Ornamental	M Col 2264		Brazil
M Col 113	Valluna			Hillsides of Valle and Cauca
M Col 1438	Llanera	CMC 9		Eastern Plains
M Col 1468	Mantiqueira	Manihot ICA P-11; CMC 40	1984	Inter-Andean valleys
M Col 1505	Verdecita	Manihot ICA P-12; CMC 76	1984	Inter-Andean valleys
M Col 1522	Algodona			Caucan hillsides
M Col 1684	Matasuegra			Quilichao
M Col 2058	Popayán			Caucan hillsides
M Col 2059	Sata Dovio			Caucan hillsides
M Col 2060	Regional Amarilla			Caucan hillsides
M Col 2061	Regional Morada			Caucan hillsides
M Col 2063	Secundina			North Coast
M Col 2066	Chiroza Gallinaza			Quindío
M Col 2215	Venezolana 1; Coñito			North Coast
M Col 2216	Venezolana 2; Ven. Negra			North Coast
M Col 2253	Blanca Mona			North Coast
M Col 2257	Americana			Mondomo
M Col 2258	Batata			Mondomo
M Col 2259	Selección 40			Mondomo
M Col 2260	Negrita			Mondomo
M Col 2261	Panameña			La Cumbre/Cajibío
M Col 2478	Chiroza Llanera			San Martín, Meta
M Col 2479	Vajuna Negra			Caucan hillsides
M Col 2625	Vivas			Cajibío
M Col 2627	Chiroza Morada			La Libertad, Meta
M Col 2628	Chiroza Blanca			La Libertad, Meta
M Col 2733	Chiroza Falsa			Mondomo
M Col 2737	Brasilera			Meta
M Col 2740	Sata			Caucan hillsides
M Col 2752	Cogolliroja			Flandes, Tolima
M Col 2753	Aroma			Flandes, Tolima
M Col 2756	Costeña			Supatá, Cundinamarca
M Col 2758	Parrita			Quilichao/Jamundí
M Col 2759	Chiroza Manzana			Alcalá, Valle
M Cub 74	Señorita Falsa			Cuba
M Pan 139	Dayana			Panama
M Tai 1	Rayong 1			Thailand
HMC 1	ICA Armenia	Manihotica P-13	1986	Inter-Andean valleys
CG 1141-1	ICA Costeña		1991	North Coast
CM 523-7	ICA Catumare (Raya 7)		1990	Eastern Plains
CM 2177-2	ICA Cebucán		1990	Eastern Plains
CM 3306-4	ICA Negrita		1993	North Coast
CM 3306-19	CORPOICA Colombia		2000-B	North Coast
CM 3555-6	CORPOICA Sucreña		2000-B	North Coast
SGB 765-2	CORPOICA Caribeña		2000-B	North Coast
SGB 765-4	CORPOICA Rojita		2000-B	North Coast
CM 6740-7	Reina		2000-B	Eastern Plains
CM 6438-14	Juan V			Eastern Plains

Table 17-2. Manihot species, in alphabetical order and with their respective abbreviations.

No. in series	Species	Abbr.	No. in series	Species	Abbr.
1	*M. acuminatissima* Müller von Argau	acu	51	*M. michaelis* McVaugh	mic
2	*M. aesculifolia* (Kunth) Pohl	aes	52	*M. mirabilis* Pax	mbl
3	*M. affinis* Pax & K. Hoffmann	alf	53	*M. mossamedensis* Taubert	mos
4	*M. alutacea* Rogers & Appan	alt	54	*M. nana* Müller von Argau	nan
5	*M. angustiloba* Müller von Argau	ang	55	*M. neusana* Nassar	neu
6	*M. anisophylla* Müller von Argau	aph	56	*M. oaxacana* Rogers & Appan	oax
7	*M. anomala* Pohl	anm	57	*M. oligantha* Pax & K. Hoffmann	oli
8	*M. attenuata* Müller von Argau	att	58	*M. orbicularis* Pohl	orb
9	*M. auriculata* McVaugh	aur	59	*M. paviifolia* Pohl	pav
10	*M. brachyandra* Pax & K. Hoffmann	bnd	60	*M. peltata* Pohl	pel
11	*M. brachyloba* Müller von Argau	blo	61	*M. pentaphylla* Pohl	pnt
12	*M. caerulescens* Pohl	cae	62	*M. peruviana* Müller von Argau	per
13	*M. carthaginensis* (Jacq.) Müller von Argau	cth	63	*M. pilosa* Pohl	pil
14	*M. catingae* Ule	cng	64	*M. pohlii* Wawra	poh
15	*M. caudata* Greenman	cdt	65	*M. populifolia* Pax	plf
16	*M. cecropiifolia* Pohl	cec	66	*M. pringlei* S. Watson	pri
17	*M. chlorosticta* Standley & Goldman	chl	67	*M. procumbens* Müller von Argau	pcb
18	*M. condensata* Rogers & Appan	con	68	*M. pruinosa* Pohl	pru
19	*M. corymbiflora* Pax	cmf	69	*M. pseudoglaziovii* Pax & K. Hoffmann	pse
20	*M. crassisepala* Pax & K. Hoffmann	cra	70	*M. purpureocostata* Pohl	pur
21	*M. crotalariiformis* Pohl	ctl	71	*M. pusilla* Pohl	psa
22	*M. davisiae* Croizat	dav	72	*M. quinquefolia* Pohl	qfl
23	*M. dichotoma* Ule	dch	73	*M. quinqueloba* Pohl	qba
24	*M. divergens* Pohl	dve	74	*M. quinquepartita* Huber ex Rogers & Appan	qpt
25	*M. epruinosa* Pax & K. Hoffmann	epr	75	*M. reniformis* Pohl	ren
26	*M. esculenta* Crantz	esc	76	*M. reptans* Pax	rpt
27	*M. falcata* Rogers & Appan	fal	77	*M. rhomboidea* Müller von Argau	rho
28	*M. filamentosa* Pittier	fmt	78	*M. rubricaulis* I.M. Johnston	rub
29	*M. flemingiana* Rogers & Appan	fgn	79	*M. sagittatopartita* Pohl	sag
30	*M. foetida* (Kunth) Pohl	foe	80	*M. salicifolia* Pohl	slc
31	*M. fruticulosa* (Pax) Rogers & Appan	fru	81	*M. sparsifolia* Pohl	spr
32	*M. glaziovii* Müller von Argau	gla	82	*M. stipularis* Pax	sti
33	*M. gracilis* Pohl	gcl	83	*M. stricta* Baillon	str
34	*M. grahamii* Hooker	grh	84	*M. subspicata* Rogers & Appan	sub
35	*M. guaranitica* Chodat & Hassler	gut	85	*M. surinamensis* Rogers & Appan	sur
36	*M. handroana* Cruz	han	86	*M. tenella* Müller von Argau	ten
37	*M. hassleriana* Chodat	hsl	87	*M. tomatophylla* Standley	tll
38	*M. heptaphylla* Ule	hph	88	*M. tomentosa* Pohl	tsa
39	*M. hunzikeriana* Martinez-Crovetto	huk	89	*M. tripartita* (Sprengel) Müller von Argau	tpa
40	*M. irwinii* Rogers & Appan	irw	90	*M. triphylla* Pohl	tph
41	*M. inflata* Müller von Argau	inf	91	*M. tristis* Müller von Argau	tst
42	*M. jacobinensis* Müller von Argau	jac	92	*M. variifolia* Pax & K. Hoffmann	var
43	*M. janiphoides* Müller von Argau	jnp	93	*M. violacea* Pohl	vio
44	*M. jolyana* Cruz	jol	94	*M. walkerae* Croizat	wlk
45	*M. leptophylla* Pax & K. Hoffmann	lph	95	*M. warmingii* Müller von Argau	wrm
46	*M. leptopoda* (Müll. Arg.) Rogers & Appan	da	96	*M. websteri* Rogers & Appan	web
47	*M. longipetiolata* Pohl	lon	97	*M. weddelliana* Baillon	wdd
48	*M. maguireana* Rogers & Appan	mag	98	*M. xavantinensis* Rogers & Appan	xav
49	*M. maracasensis* Ule	mcn	99	*M. zehntneri* Ule	zeh
50	*M. marajoara* Huber	mjr			

SOURCE: Chávez et al. (1987).

Collection or Acquisition

Accessions of germplasm banks are usually landraces or traditional varieties selected by farmers over the years. Many germplasm banks also hold modern varieties, including those in disuse, and wild species. For JG Hawkes, University of Birmingham (pers. comm.), collection is the first and fundamental stage on which to develop an appropriate set of holdings. With it, the following can be guaranteed:

a. An optimal collection size that is reasonable in terms of costs and management, and possessing broad genetic diversity.

b. The exploration of high-priority areas.

c. The exploration of areas at high risk of genetic erosion.

d. The introduction of the smallest possible number of duplicates.

e. Reduced risk of introducing pests and diseases. To achieve this, full knowledge of the species to be cultivated should be available.

To attain these objectives, as much scientific preparation is needed as for logistics.

Passport data

This basic information is taken from both the sample and collection site. Hence, for each sample collected or introduced, the respective passport information must be completed. For this purpose, the standard form (Appendix 1, page 340), established by Gulick et al. (1983), should be used. The minimum data for morphological descriptors should also be recorded on this format.

Passport information is of vital importance. It not only identifies each sample, but it also reduces the risk of collecting or introducing duplicates, and permits the recovery of materials missing in the collection. Indeed, a sample with no passport data has no value.

Status of the collection at CIAT

Table 17-3 presents the *Manihot* accessions that CIAT conserves in the *in vitro* germplasm bank. This bank represents the world's largest *Manihot* collection. To date, it holds 6739 accessions. Of these, 5301 (i.e., about 87%) are *M. esculenta* clones and the other 883 accessions (13%) correspond to 33 wild species. Of the cassava clones themselves, about 91% are landraces, while the rest comprise advanced (improved) cultivars, hybrids, and genetic stock (K family for genetic mapping).

Table 17-3. Number of *Manihot* accessions conserved in the *in vitro* germplasm bank held at CIAT.

Source of accession	ISO code	Number of *in vitro* accessions
Argentina	ARG	122
Bolivia	BOL	7
Brazil	BRA	1281
Colombia	COL	2000
China	CHN	2
Costa Rica	CR	102
Cuba	CUB	84
Dominican Republic	DOM	5
Ecuador	ECU	116
Fiji	FJI	6
Guatemala	GUA	92
Honduras	HND	36
Indonesia	IND	253
Jamaica	JAM	22
Malaysia	MAL	61
Mexico	MEX	106
Nigeria	NGA	19
Nicaragua	NIC	4
Panama	PAN	51
Paraguay	PAR	208
Peru	PER	421
Philippines	PHI	6
Puerto Rico	PTR	17
Salvador	SLV	11
Thailand	TAI	37
USA	USA	10
Venezuela	VEN	253
Vietnam	VTM	9
ICA-CIAT hybrids	CG; CM[a]	
	SG; SM[b]	408
Subtotal		**5749**
Genetic stock[c]		**146**
Wild species	33 species *in vitro*	**883**
Total		**6778**

a. CG and CM = hybrids obtained through controlled pollination.
b. SG and SM = hybrids obtained through open pollination.
C. Genetic stock = K family for the study of genetic mapping.

SOURCE: www.ciat.cgiar.org/urg

According to Debouck and Guevara (1995), 94% of the cultivated cassava germplasm collection at CIAT consists of Latin American accessions, that is, from the region recognized as the primary center of diversity. The introduction of about 800 accessions from the National Cassava & Fruits Research Center (CNPMF, its Portuguese acronym), Brazil, has broadened the holdings at CIAT with a highly representative sample of genetic diversity, especially from Northeast Brazil.

Of the 61 countries where *M. esculenta* is important, 24 (39%) have contributed to the collection. High-priority areas for acquiring germplasm are Central America (Nicaragua, Honduras, and El Salvador); Amazon Region (central and western Brazil); Chaco Region (Paraguay and Bolivia); Venezuela and eastern Colombia; the Guianas and the Ecuadorian mountains; and, lastly, the Caribbean Region (Dominican Republic and Haiti, which are regarded as of moderate priority for collection).

With respect to Asia, important elite genotypes were introduced into CIAT from national improvement programs, especially that of Thailand. This country, together with China, Vietnam, and the Philippines, has recently become a priority area for acquiring germplasm that would effectively represent this secondary center of diversity.

The absence of a centralized collection of African germplasm has restricted representation of this continent. However, this situation will improve in the near future because the International Institute of Tropical Agriculture (IITA) is compiling information on national collections and consolidating regional collections of African germplasm. Advances in virus indexing techniques will also help.

More important than country representation is that of existing diversity, for which strategies of acquisition and collection have been established.

Germplasm Conservation Methods

CIAT conserves the international germplasm collection by using two systems: active conservation in the field, and active conservation *in vitro*. Replication of germplasm through these two systems guarantees its safety against unforeseen contingencies or natural disasters. Future plans are directed towards enhancing cryogenic conservation techniques to thereby guarantee long-term conservation that is safe and economic.

In-Field Active Genebank

For the CIAT Cassava Improvement Project, this traditional form of conservation has advantages and disadvantages. The advantage is one of immediate and almost permanent availability of stakes and leaves to make evaluations, either locally or at the experiment station, on, for example, morphology, physiology, resistance to pests and diseases, and nutrient contents.

The disadvantages include the heavy need for space; higher risk of losing materials to problems such as pests, diseases, poor soils, and lack of adaptation; and higher costs of maintenance and conservation.

Planting methods

Showcase collection of existing variability. A showcase collection, highly visible to visitors from the road, is planted at the beginning of the genebank. One or two furrows of five plants each are planted at 1 × 1 m, leaving 2 to 3 m between plots. Each plot receives a placard with the clone's name and a description of its main characteristics. The clones and their characteristics are studied before being chosen for this planting.

The genebank proper. All the bank's accessions are planted in plots, with the number of plants depending on the size of the plot and maintenance costs. A plot may be planted like a trial, with rows, or like an observation field, with rows planted at 5 to 6 plants each and separated by a row in between to prevent competition between genotypes. They may also be planted on plots of two furrows, with 5 to 10 plants per plot, leaving a space of at least 2 or 3 m between plots. To reduce the risk of losing materials, the planting should be replicated.

Furthermore, major collections such as that at CIAT, where the entire collection would occupy more than 6 hectares, the accessions are best classified according to vigor or architecture. The scale used ranges from 1 to 3, where 1 refers to non-branching, 2 to medium branching, and 3 to highly branching. Planting distances are therefore set according to vigor, thus saving area and costs.

Planting for the field genebank is carried out in alphabetical order of the accessions, according to countries of origin (e.g., M Arg, M Bol, M Bra, and M Cub) and then by number of accession within each country (e.g., M Arg 1, M Arg 2, M Arg 3, and so forth).

Hybrids are best planted by group, starting with vigor, and following the order: CG, CM, SG, and SM.

Renewal period

To reduce the risk of losing materials to biotic and abiotic factors, the field bank should be renewed every year at the beginning of the rainy season. Once renewal is accomplished, the old bank must be kept for at least another 6 to 8 months; it should not be immediately eliminated from the field. This way, stakes for replanting the new bank are guaranteed and always available. Thus, every field bank remains standing for 16 to 18 months.

Maintenance

A germplasm collection in the field is more complicated to maintain than cassava trials or other types of plots, because of, for example, wide variability in plant size and adaptation to soil conditions, and the different degrees of resistance and susceptibility to pests and diseases. Hence, to be on top of any problem that may occur, the bank should be monitored every 2 or 3 weeks. Pests and diseases must be controlled by applying integrated pest-and-disease management (IPDM), as follows:

Weed control. Weeds constitute the factor that most increases field management costs. Consequently, herbicide use is recommended.

Timely replanting. For a field bank, the minimum number of plants per plot must be determined. If a plot has fewer plants than this number, then a replanting must be planned. The replanting must be done no later than 2 months after the original planting, using stakes 40 cm long.

Controlling thrips and other pests. Pests that delay growth such as thrips must be controlled until the plants are at least 6 months old to ensure that these produce seed (stakes) that guarantee renewal. Thrips can be controlled with Sistemin® (a dimethoate) at a dosage of 2 cc/L (commercial product).

Controlling bacterial blight and superelongation disease. Bacterial blight (*Xanthomonas axonopodis*) is a disease that must not exist in a cassava field bank. If, for whatever reason, this disease appears, commercial formalin at 5% must be applied to both the infected plants and their neighbors. The diseased plants are then immediately eradicated.

Control measures for superelongation disease (*Sphaceloma manihoticola*) include the eradication of infected plants and later fumigation with cupric fungicides such as Kocide® and copper oxychloride.

Soil problems. The field bank occupies a large area. Some plots are therefore often affected by soil problems such as waterlogging and salinity. In such cases, planting may take place elsewhere in the field or the plants may be moved to bags that are provisionally placed in an appropriate screenhouse or greenhouse.

Excessive branching. The most vigorous clones may close alleys with their branches and foliage, hampering personnel movement and data collection. Unfortunately, cutting the foliage increases the possibility of attack from stemborers. Thus, pruning the foliage of highly vigorous clones must be as minimal as possible.

Quarantine measures

The use of quarantine measures in the field bank aims to prevent the introduction or dissemination of diseases and pests. Recommendations include:

- Whenever seed (stakes) or foliage must be cut, workers should each carry a recipient containing soap or commercial formalin to disinfect the machetes.
- Workers who come from other plots must shake out and clean their work clothes before entering the bank.
- All tools and machinery to be used in the bank must be disinfected.
- New clones entering the bank, even if they are from the same region, state, or country, should never be directly introduced. Instead, they should be first planted within a greenhouse or screenhouse. Later, they may be planted in an isolated plot and then, once their health is verified, they may enter the bank.

Morphological and agronomic descriptors. "Morphological descriptor" is understood as that set of characteristics that easily identify and differentiate a genotype, including heritability and stability before environmental changes. Descriptors are mainly used to characterize the accessions of any given collection.

For the morphological characterization of *M. esculenta*, an up-to-date list of the morphological and

agronomic descriptors is used. This list was standardized for cassava by the International Plant Genetic Resources Institute (IPGRI, now Bioversity International) at a 1995 meeting held in Cruz das Almas (Bahia), Brazil (Gonçalvez et al. 1996).

As Gonçalves and Guevara noted (1998), the list comprises 13 minimal descriptors that are necessarily included in passport data, another 13 principal and 11 secondary descriptors, a further 21 for preliminary agronomic evaluation, and 17 for complementary evaluation (e.g., flowers, fruits, and seeds), totaling 75 descriptors. Wild *Manihot* species require a second table with different descriptors.

To manage a given collection, all accessions must be duly characterized morphologically. As Iglesias et al. (1995) point out, the integration of morphological with biochemical and molecular descriptors, and accompanied by passport data, form a valuable tool for identifying duplicate accessions in that collection.

Biochemical descriptors, using isoenzymes. Ocampo et al. (1993) indicated that, because of the limitations presented by morphological markers for evaluating a collection's materials, techniques for the electrophoresis of total seed protein must be used. However, these are limited to differentiating among genetically close materials. The later development of isoenzyme electrophoresis techniques largely resolved this limitation. These techniques use an electrical field to separate enzymes present in a raw extract of a tissue. Because of their electrical charges and sizes, the enzymes migrate to different positions within a gel matrix of either starch or polyacrylamide.

Because enzymes catalyze specific biochemical reactions, an enzyme's location in the gel can be seen. Through adding a substratum and appropriate cofactors, reaction products can be detected through color reactions. Thus, a visible band is formed at the site where a given enzyme is located. When different molecular forms of an enzyme have affinity for a single substratum, these forms make up an isoenzyme family.

The pattern of isoenzyme bands is analyzed quantitatively, using a laser densitometer. It is also qualitatively codified according to the presence or absence of each of the 22 bands (Figure 17-1).

Molecular characterization. According to Ocampo et al. (1995), given the limitations of morphological and biochemical descriptors, materials should be evaluated directly from their genomes. This

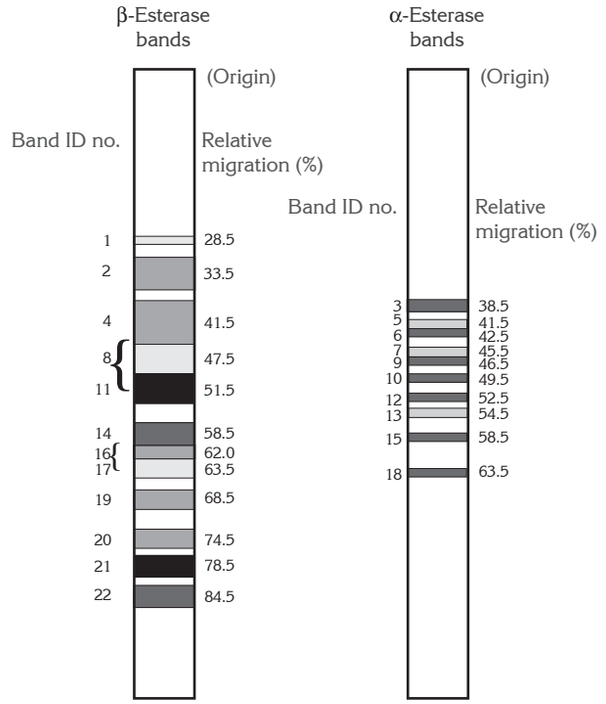


Figure 17-1. Zymogram showing patterns of isoenzyme bands of α- and β-esterases obtained from cassava tissues.

was initially done, using the "restriction fragment length polymorphism" (RFLP) but several markers are now available such as amplified fragment length polymorphism" (AFLP), microsatellites, simple sequence repeats (SSR), or single nucleotide polymorphism (SNP).

The evaluation of major germplasm collections, using only different types of molecular markers or isoenzymes, would be laborious and expensive, although the costs and the efficiency has improved astonishingly fast in recent years. The importance of morphological and agronomic characterization should not be ignored, but used to complete the first stages of characterization. Thus, a large collection would be reduced to small groups, which can then be more efficiently and economically evaluated, using the isoenzyme or different molecular markers techniques.

Duplicate identification and elimination. In a germplasm collection that is maintained vegetatively, accessions are often duplicated. Preliminary observations of the collection at CIAT estimated that the level of duplication is between 20% and 25%. Hershey, cited by Iglesias et al. (1995), noted that the presence of a large number of duplicates in a germplasm collection has negative implications for their management and use in improvement programs, such as:

- Significant increase in the costs of conservation and evaluation
- Skewing of genetic variability
- Narrowing of the genetic base
- Undesirable homozygosis in crosses

Iglesias et al. (1995) pointed out that, over the years, the *Manihot* collection at CIAT has been classified by basic morphological descriptors, which had first been defined by the International Board for Plant Genetic Resources (IBPGR, now Bioversity International). In themselves, they do not reliably identify duplicates. However, if biochemical characterization is included, based on codifying the presence or absence of 22 isoenzyme bands of α- and ß-esterases in STET gels, confidence levels increase greatly.

Given the above considerations and to eliminate duplicates from the international cassava collection, CIAT developed and applied a model based on the following criteria:

- *Preliminary grouping of clones.* Grouping is based on within-group identification, the selection of four primary morphological characteristics, and 12 electrophoretic bands of high-level confidence:
  - Morphological characteristics: Stem colenchyma, stem epidermis, stem growth habit, and root external color
  - Presence or absence of electrophoretic bands coded 3, 4, 9, 10, 12, 13, 14, 15, 19, 20, 21, and 22

- *Secondary grouping of clones.* In groups larger than 10 clones, a second level of grouping is made by cluster analysis, using the following group of morphological characteristics and electrophoretic bands of secondary level of confidence:
  - Morphological characteristics: Height of first branching, color of apical leaf, pubescence, vein color, lobe shape, lobe width, petiole color, cortex color, and root pulp color
  - Presence or absence of electrophoretic bands coded 1, 6, 8, 18, 2, 5, 7, and 17

- *Confirmation in the field.* Clones grouped with possible duplicates are planted in the field and the morphological descriptors are reevaluated. Clones with identical descriptors are checked for their passport data. If these are the same, the duplicates are eliminated from the field collection, but they remain in the *in vitro* collection for later confirmation with RFLP molecular markers.

Preliminary agronomic evaluation

The CIAT Cassava Improvement Project uses the following strategy for the preliminary agronomic evaluation of the cassava germplasm bank:

a. Define and select edaphoclimatic areas that contrast and represent cassava-producing areas.

b. Select the group of accessions to be evaluated.

c. Plant according to the system "bank's observation field", which consists of a row of six plants per accession, separated by one furrow in between.

d. Select the best materials and later evaluate these in a preliminary yield trial, followed by conventional yield trials.

e. Select the materials that best show integration of adaptation, yield potential, resistance to pests and diseases, and root quality.

f. After several cycles, followed by advanced stages, classify the selected materials as "elite" and recommend them to national programs or use them as parental materials in hybridization schemes.

Documentation and exchange

According to Debouck and Guevara (1995), this stage encompasses the following genebank activities to provide information for entering institutional documentation system (Oracle):

- Passport data
- Morphological and isoenzymatic characterization
- Preliminary agronomic evaluation
- Conservation methods and techniques
- Indexing tests
- Germplasm exchange

The mandate assigned to CIAT by the CGIAR includes not only germplasm conservation, but also its *distribution or exchange*. Given these goals, the following protocol (Figure 17-2) was established for field conservation to minimize the distribution of pests and diseases:

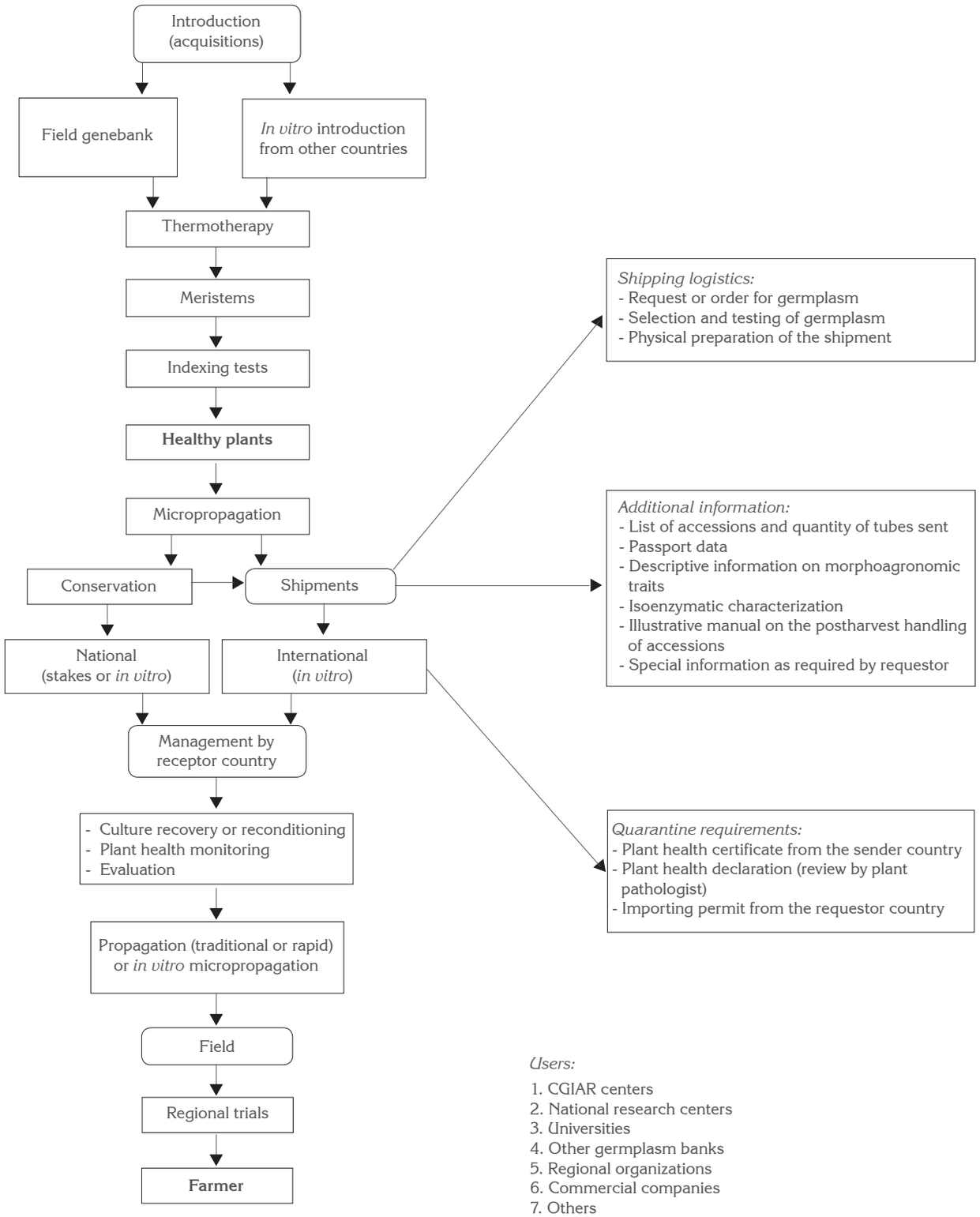


Figure 17-2. Exchange of *Manihot* germplasm (from Debouck and Guevara 1995).

- Prohibit shipments to the exterior of all materials in the form of stakes.

- Only indexed stakes may be sent when the materials are for purely experimental or very specific purposes, and will be planted in the greenhouses of non-cassava-producing countries of temperate areas. Furthermore, the stakes must be accompanied by the exporting country's plant health certificate and the importing country's previously obtained importing permit.

- Cassava plant materials may be distributed to other countries only as meristem culture from plants that underwent thermotherapy and indexing. Sexual seed may also be distributed, provided that plant health certificates and importing permits have been issued.

In Vitro Active Genebank

Debouck and Guevara (1995) noted that the cassava *in vitro* active genebank (IVAG) consists of maintaining the plants under slow-growth conditions by providing physical and chemical conditions that extend, as far as possible, the interval before transfer to fresh media is needed. In *in vitro* conservation, the growth rate of cultures can be controlled by managing the following factors:

- Temperature
- Inorganic and organic substances
- Growth regulators
- Osmotic regulators
- Ethylene inhibitors and capturers

Conditions for conservation and renewal

The findings of several years of research by CIAT scientists indicated the following growth conditions for *in vitro* cassava conservation:

- A constant temperature between 23 and 24 °C
- A photoperiod of 12 h of light
- Light intensity at 1000 lux
- Modified culture media (MS) (Table 17-4)
- Test tubes of 25 × 150 mm, covered with aluminum foil and sealed with plastic
- Conservation of five tubes per clone

Under these conditions, the *in vitro* collection presents an average period of conservation of 12.8 months, ranging from 10.3 to 18.5 months, according to country of origin.

Procedures for *in vitro* conservation

Debouck and Guevara (1995) suggest the following procedures:

- Enter the materials
- Establish the *in vitro* culture
- Evaluate and monitor the cultures' aseptic state
- Maintain and renew the materials
- Monitor viability and genetic stability
- Document and systematize the bank

Table 17-4. Culture media used for the operations of introduction, conservation, transfer to greenhouse, and exchange of *in vitro* cassava clones.

Constituents of the medium	Concentration in medium:		
	4E (for meristem initiation, micropropagation, and exchange)	8S (for conservation)	17N (for transfer to greenhouse)
Inorganic salts	MS	MS	1/3 MS
m-Inositol	100 mg/L	100 mg/L	100 mg/L
Thiamine HCl	1 mg/L	1 mg/L	1 mg/L
Sucrose	2%	2%	2%
BAP	0.04 mg/L	0.02 mg/L	—
GA	0.05 mg/L	0.10 mg/L	0.01 mg/L
ANA	0.02 mg/L	0.01 mg/L	0.01 mg/L
Agar	0.7 g	0.7 g	0.7 g
pH	5.7–5.8	5.7–5.8	5.7–5.8

SOURCE: Debouck and Guevara (1995).

With regard to "entering the materials", Colombian materials may be introduced as plant materials (or stakes), whereas introductions from other countries are made only *in vitro*. The cultures are then multiplied or micropropagated. After micropropagation, the cultures are planted in 8S culture medium to conserve them and then placed under conditions specific to their establishment.

Under these conditions, the cultures are left for more than 2 weeks and then evaluated for plant development and health, taking into account the following basic aspects: state of the medium, state of the tube's cover and seal, seedling development, plant health, and each tube's nomenclature and identification. Once the evaluation is completed, each material is registered in the database, identified by its varietal name, date of entry, culture medium, and location in the conservation room.

The materials are stored within this room at five tubes per variety. These are located on shelving and are ordered according to code. Arrangement by stand, row, shelf, and test-tube rack facilitates searching.

Maintenance and renewal

In vitro conservation requires that conditions in the conservation room be maintained constant, using equipment for regulating temperatures, relative humidity, and light. Tasks for renewing materials are also carried out here.

The materials coming from conservation are micropropagated and then placed in 4E growth medium for recovery and strengthening. When these materials are established, they are propagated again and moved to 8S medium for conservation. The following information is recorded in the database: date of exit for subculturing and cause of exit, whether contamination, subculturing, elimination, or exchange. Finally, genetic stability is monitored, using morphoagronomic and biochemical criteria.

Cleaning clones

According to Guevara and Valderrama (1995), the literature reports more than 50 cassava diseases produced by viruses, bacteria, fungi, and phytoplasmas. Among the most important viral diseases are:

- African mosaic virus (ACMV), caused by viruses from the Geminivirus group
- Vein mosaic virus (CVMV), caused by the Caulimovirus group
- Common mosaic virus (CsCMV), belonging to the Potexvirus group
- Frogskin disease (CFSD) complex, including Caribbean mosaic (CMD)
- Colombian symptomless virus (CCSpV), belonging to the Potexvirus group

All these viruses can be eliminated by using thermotherapy techniques associated with meristem culture. Figure 17-3 illustrates the general scheme for eliminating viruses from cassava. The steps are:

- Applying thermotherapy to meristem culture (i.e., to *in vitro* seedlings) or to shoots that have germinated from stakes originating in the field
- Thermally treated materials undergo indexing tests
- Micropropagation of healthy clones, using *in vitro* culture techniques
- Virus detection

Indexing tests

Indexing tests for cassava viruses can be applied to both *in vitro* seedlings and greenhouse plants. The general methodology used to eliminate cassava viruses includes the following techniques:

- *Grafting with the highly susceptible clone M Col 2063 or 'Secundina'*. This test is used mainly to detect frogskin disease. To graft, the material being evaluated is the main plant (stock), while Secundina is the graft (i.e., grafted onto the main plant). Should the stock be infected, symptoms will be expressed in the graft (Figure 17-4). With this hypersensitive material, readings are normally made at 30 days. The graft must be absolutely clean to prevent the reading of false positives.
- *The ELISA test* is used for the following viruses: African mosaic virus (ACMV), vein mosaic virus (CVMV), Colombian symptomless virus (CCSpV), and Caribbean mosaic (CMD).
- *Double-stranded RNA* (dsRNA) is used to test for the RNA of the following cassava viruses: frogskin disease (CFSD); common mosaic virus (CsCMV); and latent viruses.

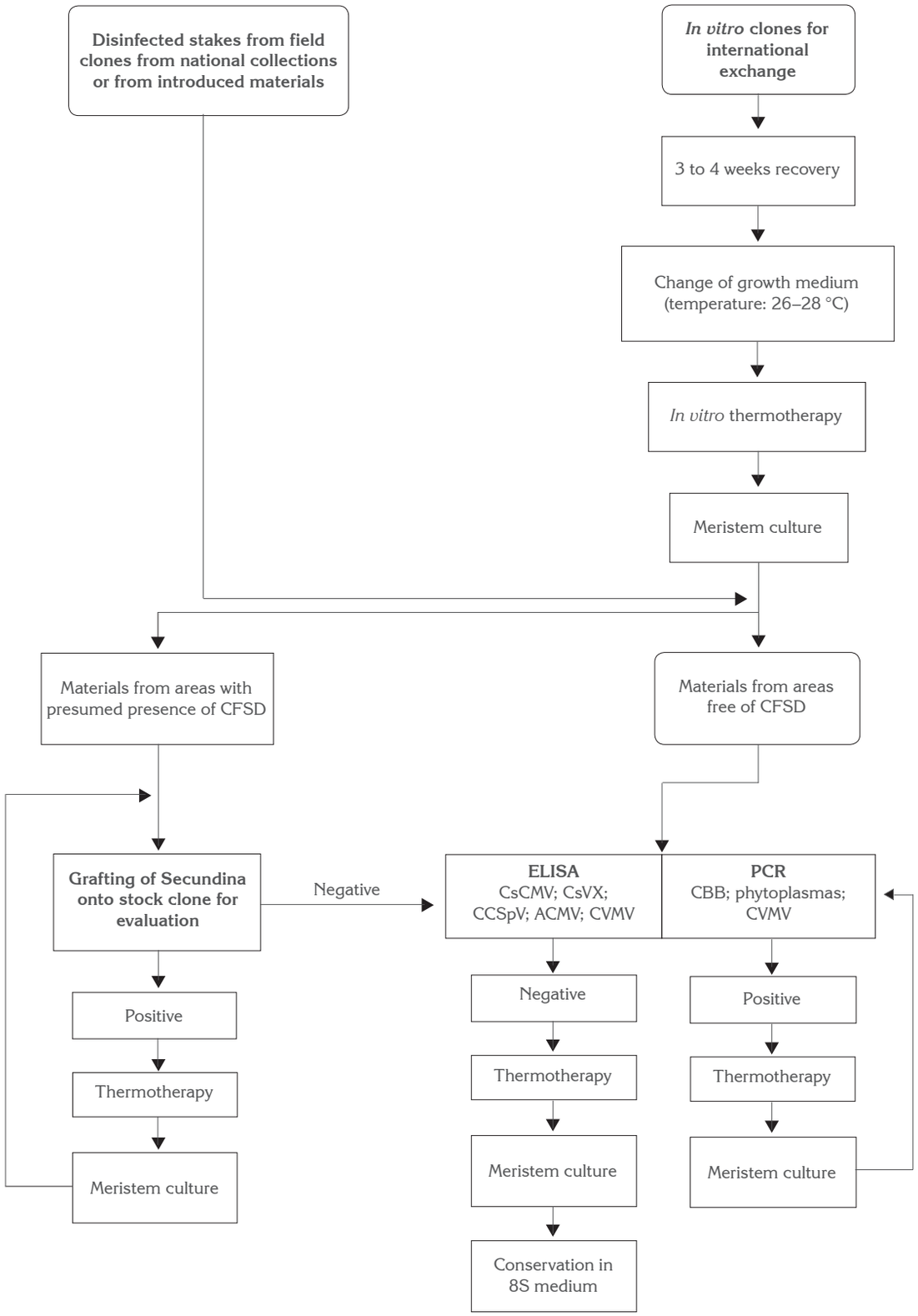


Figure 17-3. Procedures for detecting and eliminating cassava pathogens (from Debouck and Guevara 1995). For an explanation of abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Figure 17-4. The highly susceptible cassava variety Secundina (with leaves) is grafted onto the stock (stake of the clone being evaluated). (Photo by Norma Flor, Genetic Resources Unit, CIAT.)

- *Polymerase chain reaction* (PCR) is used to detect bacterial blight (CBB), phytoplasmas, and vein mosaic virus (CVMV).

Cryogenic Conservation

According to Escobar et al. (1998), the *in vitro* base genebank (IVBG) is founded on the cryoconservation of clones, that is, on the total suppression of their growth, metabolism, and other biological processes by applying very low temperatures. Mutations are also prevented. Conservation thus becomes indefinite.

The method consists of isolating precultured meristems by using a cryoprotectant agent, completing a stage of controlled cooling, and transferring to liquid nitrogen at 196 °C. The protocol established for cassava cryopreservation at CIAT is as follows:

- Isolation of meristems that measure 2 to 3 mm long and had been taken from a 3 to 4-month-old *in vitro* culture
- Pretreatment in 4E medium for 3 days
- Preculture on solid C4 medium for 3 days, in the dark, and at temperatures between 26 and 28 °C
- Cryoprotection in liquid medium for 2 h on ice
- Dehydration or drying for 1 h, using filter paper, at room temperature
- Programmed slow cooling, using a CryoMed freezer at -40 °C
- Immersion and storage in liquid nitrogen for at least 3 h
- Heating to 37 °C for 45 s
- Re-culturing:
  - R1 and R2 balance media for 2 days each
  - Transfer to CIAT 4E semisolid medium
- Evaluation:
  - Tissue survival or viability
  - Shoot formation after 1 month

Studies on cryogenic conservation currently conducted at CIAT have led to the development of two main methodologies:

- For *botanical seed*, working with *M. esculenta* and *M. carthaginensis*. This method permits total recovery of viable plants.
- For *planting materials*, which itself has two methodologies:
  - Classical, where the varietal response is modified.
  - New, which has a practical sense in that active work is done, especially on the "core'" collection. The technique is called encapsulation/dehydration.

The IVBG constitutes a basic working, but inactive collection that is conserved for the long term. Once the technique is completely developed, this bank will be able to totally maintain the germplasm's genetic stability. This collection is expected to become an efficient and economic alternative for conserving cassava clones. Thus, cryopreservation would be a safe method for long-term storage in a reduced space. It would also be free of changes and relatively low-cost.

Debouck pointed out that cryoconservation is not envisioned as a distribution method, for which the

in vitro active genebank is more suitable. The main activities involved in cassava germplasm exchange by the CIAT *in vitro* bank are presented in Figure 17-2.

Nucleus or Core Collection

The concept

The concept of a "nucleus" or "core" collection was proposed by Frankel in 1984 (cited in Iglesias et al. 1992) to define a set of accessions that, with a minimum of repetition, would represent the genetic diversity of a given species. The accessions that become part of a core collection are selected for their representativeness and ecological or genetic differences. Iglesias et al. (1992) also discuss the following points:

- A core collection must be constituted in such a way that its genetic diversity is maximized. This means that duplicated or closely related accessions must be excluded. Normally, core collections for cultivated species are separated from those of their wild relatives.

- For a given species, other groups of accessions may exist for specific purposes. These can also be core collections. An example is the group of elite clones within the germplasm collection held at CIAT.

Advantages of a core collection

As a representative sample, a core collection has the following advantages:

- It increases efficiency in the use of genetic resources by facilitating evaluation and access to existing genetic variability.

- It enables the use of methodologies that can later be extended to the entire collection.

- Facilitates the possibility of duplicating accessions for other institutions.

Requisites

Ideally, a core collection for a cultivated species has the following characteristics:

- It covers the total range of genetic variability existing in that species

- It consists mainly of landraces, for which the passport data are complete.

- It does not include duplicated accessions.

- It has been well characterized, using morphological and molecular descriptors.

- Traits such as agronomic and physiological characteristics, root quality, and resistance to diseases and pests have been evaluated.

- Information on the crop's evolution and different centers of genetic diversity is adequate.

Collection size

Brown (cited in Iglesias et al. 1992) recommends selecting 5% of all accessions in large collections such as for maize, and 10% for small collections such as for cassava. Also taken into account are factors for conservation and the limits imposed by sample size on the evaluation of certain characteristics. Hence, a core collection of 600 to 650 accessions was first proposed as an objective for the cassava collection at CIAT.

Parameters for definition

The general criteria for defining the cassava core collection were classified into four groups:

- Geographic origin
- Diversity of morphological characteristics
- Diversity in the band patterns of α- and ß-esterases
- A priori selection of accessions based on the following requisites:
  - Clones included in studies by the Cassava Biotechnology Network (CBN)
  - The most frequently planted local varieties
  - Elite clones from the cassava improvement program; these genotypes represent, with high frequency, those genes that favor a large number of characteristics

To sample the main collection's genetic diversity, emphasis was given to geographic origin. About two-thirds of accessions in the core collection were selected this way (Table 17-5).

Table 17-5. Parameters, including country of origin, for determining the number of accessions to be selected for the cassava core collection held at CIAT[a].

Origin	No. of access.	Local cultivars (%)	Level of duplic. (%)	Base number of local cultivars	Importance as diversity center		Total diversity of country in collection at CIAT		Diversity of ecosystems		Factor of correction by size[b]	Sum of weights[c]	Geographic origin[d]	Morphological diversity[e]	Divers. of esterase	A priori selection[f]	Final no. of access.[g]
					Score	Weight 1	Score	Weight 2	Score	Weight 3							
Argentina	16	40	10	6	1	1.00	25	0.75	2	0.40	1.00	2.15	2	4	0	3	8
Bolivia	3	100	0	3	1	1.00	5	0.95	2	0.40	1.00	2.35	1	2	0	3	3
Brazil[h]	1637	95	20	1244	1	1.00	40	0.60	5	1.00	0.20	0.52	110[i]	13	15	20	101
China	2	100	0	2	3	0.50	25	0.75	3	0.60	1.00	1.85	1	0	0	2	2
Colombia	1907	95	20	1449	1	1.00	75	0.25	5	1.00	0.20	0.45	111	15	13	14	146
Costa Rica	147	40	20	47	2	0.75	80	0.20	2	0.40	0.80	1.08	9	7	5	4	23
Cuba	74	90	20	53	2	0.75	80	0.20	2	0.40	0.80	1.08	10	5	1	2	18
Domin. Rep.	5	100	10	5	2	0.75	10	0.90	3	0.60	1.00	2.25	2	2	0	4	5
Ecuador	117	100	25	88	1	1.00	50	0.50	3	0.60	0.80	1.68	25	6	0	4	32
Fiji	6	100	10	5	3	0.50	50	0.50	1	0.20	1.00	1.20	1	0	0	2	2
Guatemala	91	100	50	46	2	0.75	80	0.20	2	0.40	0.80	1.08	8	6	0	2	15
Indonesia	51	10	15	4	3	0.50	10	0.90	3	0.60	0.80	1.60	1	0	2	5	7
Malaysia	68	70	15	40	3	0.50	50	0.50	2	0.40	0.80	1.12	8	0	1	6	15
Mexico	100	95	30	67	2	0.75	75	0.25	3	0.60	0.80	1.28	14	6	0	2	20
Panama	42	100	20	34	2	0.75	75	0.25	2	0.40	0.80	1.12	6	2	0	2	9
Paraguay	192	100	20	154	1	1.00	80	0.20	2	0.40	0.60	0.96	25	8	3	7	40
Peru	405	95	20	308	1	1.00	60	0.40	2	0.60	0.60	1.20	63	10	3	2	76
Philippines	6	30	0	2	3	0.50	5	0.95	2	0.40	1.00	1.85	1	0	0	2	2
Puerto Rico	15	40	15	5	2	0.75	60	0.40	2	0.40	1.00	1.55	1	2	0	4	7
Thailand	8	10	0	1	3	0.50	75	0.25	2	0.40	1.00	1.15	0	0	0	4	4
USA	9	0	0	0	3	0.50	100	0	1	0.20	1.00	0.70	0	0	0	4	4
Venezuela	240	95	20	182	1	1.00	60	0.40	4	0.80	0.60	1.32	41	9	3	3	55
CIAT clones	317	0	0	0									0	3	5	27	33
IITA clones	19	0	0	0									0	0	0	3	1
Total	**5477**			**3744**									**440**	**100**	**51**	**121**	**630[j]**

a. Access. = accessions; duplic. = duplication; Score of a scale; divers. = diversity.
b. Factor of correction according to the size of the collection, where >1000 = 0.2; 400–1000 = 0.4; 100–400 = 0.6; 20–100 = 0.8; 1–20 = 1.0.
c. Sum of weights (1, 2, and 3) × factor of correction according to size of collection.
d. Number of accessions for core collection = (sum of weights × base number of local cultivars × constant), where the constant = 0.17.
e. Clones included in the pilot *in vitro* active genebank (IVAG) at CIAT/IBPGR (now Bioversity International).
f. Selected by three criteria:
   • Included in studies conducted by the Cassava Biotechnology Network (CBN), based on the diversity of geographic origin and agronomic value
   • Most widespread cultivars
   • Elite clones held at CIAT and the International Institute of Tropical Agriculture (IITA)
g. The final number may be less than the sum of the columns, given that the same clone may have been selected for different parameters.
h. Includes 800 accessions introduced in 1991/92.
i. Sixty accessions will be introduced, followed by another 800 new accessions, totaling 970 in all.
j. The final number may be smaller after detecting and eliminating duplicates.

SOURCE: Iglesias et al. (1992).

Clones included in the core collection

The application of all the parameters mentioned above enabled the definition of a first list of clones to include in the core collection at CIAT (Table 17-6).

Iglesias et al. (1992) also noted that, when defining a core collection, the question arises of how flexible its structure should be in accepting changes. Presumably, excessive dynamism would not be good if what is desired is a reference sample for the systematic evaluation of different characteristics. However, such a structure should allow the incorporation of new accessions that will increase even more the selected sample's representativeness of the genetic diversity existing in the field.

In practical terms, 70% to 80% of the core collection, as initially defined, could reasonably be expected to remain unmodifiable. The remainder may be subjected to change, in accordance with new information obtained over the short and medium term.

Wild *Manihot* Species

Few crops have such a high number of related or wild species as *M. esculenta*. According to Chávez (1990), wild *Manihot* species constitute a valuable resource for improvement programs, because of their:

- High potential as sources of genes for resistance to pests and diseases

Table 17-6. Clones included in the core collection at CIAT, using different parameters.

Origin	Number of clones included according to parameter:				Final number in core
	Geographic origin	Morphological diversity	Diversity of esterases	A priori selection	
Argentina	2	4	0	3	8
Bolivia	1	2	0	3	3
Brazil	110	13	15	20	101
China	1	0	0	2	2
Colombia	111	15	13	14	146
Costa Rica	9	7	5	4	23
Cuba	10	5	1	2	18
Dominican Republic	2	2	0	4	5
Ecuador	25	6	0	4	32
Fiji	1	0	0	2	2
Guatemala	8	6	0	2	15
Indonesia	1	0	2	5	7
Malaysia	8	0	1	6	15
Mexico	14	6	0	2	20
Nigeria	0	0	0	3	3
Panama	6	2	0	2	9
Paraguay	25	8	3	7	40
Peru	63	10	3	2	76
Philippines	1	0	0	2	2
Puerto Rico	1	2	0	4	7
Thailand	0	0	0	4	4
USA	0	0	0	4	4
Venezuela	41	9	3	3	15
Hybrids	0	3	5	27	33
Total	**440**	**100**	**51**	**131**	**590**

SOURCE: Iglesias et al. (1992).

- Tolerance of most of the common abiotic stresses
- Broad genetic variability for important agronomic and biochemical characteristics such as low hydrocyanic acid content and high protein content
- Highly desirable C4 photosynthetic route

Because of the importance of these species and the considerable genetic erosion they suffer, one conservation option is to establish an *ex situ* germplasm bank with these valuable materials.

Coding and abbreviations

Within the *Manihot* genus, all species studied have the same number of chromosomes: 2n = 36. To date, 98 wild species plus cassava have been recognized, with five more being described. Taxonomically, the *Manihot* genus is separated into 18 sections.

Chávez et al. (1987) indicated that, for coding, CIAT has developed and set up a standardized system of nomenclature for *Manihot* species and sections. Tables 17-2 and 17-7 list the abbreviations of all 99 species and 18 sections. In this system, an abbreviation is made up of three lowercase letters to represent the species, with the first letter being taken from the first letter of the species's name. No abbreviation is repeated. For the sections, the abbreviations used each consists of three uppercase letters, thus differing from the lowercase abbreviations for species.

Table 17-7. *Manihot* sections in alphabetical order, with their respective abbreviations.

Serial number	Section	Abbreviation
1	Anisophyllae Rogers & Appan	ANY
2	Brevipetiolatae Pax	BRE
3	Caerulescentes Rogers & Appan	CAE
4	Carthaginenses Rogers & Appan	CAR
5	Crotalariaeformes Rogers & Appan	CRO
6	Foetidae Rogers and Appan	FOE
7	Glaziovianae Pax	GLA
8	Graciles Rogers & Appan	GCL
9	Grandibracteatae Pax	GND
10	Heterophyllae Pax	HET
11	Manihot P. Miller	MAN
12	Parvibracteatae Pax	PAR
13	Peltatae Pax	PEL
14	Peruvianae Rogers & Appan	PER
15	Quinquelobae Pax	QUI
16	Sinuatae Pax	SIN
17	Tripartitae Rogers & Appan	TRI
18	Variifoliae Rogers & Appan	VAR

The list contains all the taxonomically critical wild species of the *Manihot* genus as published by Rogers and Appan (1973). It also includes the new species recently described by Nassar (2000). Synonyms are excluded. Allem (2002) provided an update of the origins and taxonomy of cassava.

Possible contributions

For Chávez (1990), current studies have demonstrated that many of the wild species have potential in improvement programs as sources of genes for beneficial characteristics, including resistance to pests and diseases, adaptation, and tolerance of abiotic stresses. Table 17-8 details the possible contributions that some wild species may make.

Table 17-8. Outstanding characteristics and possible benefits from wild *Manihot* species.

Species	Characteristic and/or benefit
M. pringlei	Low cyanide content
M. glaziovii	Resistance to African mosaic virus
M. pseudoglaziovii	Resistance to bacterial blight; resistance to drought; tolerance of cold
M. reptans	Resistance to bacterial blight
M. tristis	High starch content
M. angustiloba	High starch content
M. neusana	Resistance to stemborer
M. pohlii	Resistance to stemborer
M. grahamii	Resistance to stemborer; tolerance of cold
M. chlorosticta	Adaptation to saline soils
M. carthaginensis	Resistance to drought
M. dichotoma	Resistance to drought
M. irwinii	Excellent adaptation to lateritic acid soils
M. tripartita	Excellent adaptation to lateritic acid soils
M. orbicularis	Excellent adaptation to lateritic acid soils
M. peltata	Tolerance of acid soils
M. attenuata	Tolerance of cold
M. rubricaulis	Tolerance of cold
M. gracilis	Dwarf type

SOURCE: Chávez (1990).

References

To save space, the acronym "CIAT" is used instead of "Centro Internacional de Agricultura Tropical".

Allem AC. 2002. The origins and taxonomy of cassava. In: Hillocks RJ; Thresh JM; Bellotti AC, eds. Cassava: biology, production and utilization. CABI Publishing, Wallingford, UK. p 1–16

Chávez R; Roca W; Hershey C. 1987. Abreviatura para los nombres de las especies silvestres de *Manihot*. Yuca Bol Inf 11(2):5–6.

Chávez R. 1990. Especies silvestres de *Manihot*: Un recurso valioso. Yuca Bol Inf 14(1):2–5.

Debouck D; Guevara C. 1995. Unidad de Recursos Genéticos: Laboratorio de cultivo de tejidos. CIAT, Cali, Colombia. 16 p. (Multicopied.)

Escobar R; Mafla G; Roca W. 1998. Cassava cryopreservation, I. In: Engelmann F; Takagi H, eds. Cryopreservation of tropical plant germplasm: current research progress and aplication. Japan International Research Center for Agricultural Sciences (JIRCAS); International Plant Genetic Resources Institute (IPGRI), Rome, Italy. p 404–406.

Gonçalvez WMG; Costa IRS; Vilarinhos AD; Oliveira RP. 1996. Banco de Germoplasma de Mandioca: Manejo, conservação e caracterização. Documentos CNPMF No. 68. Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Cruz das Almas, Brazil. 103 p.

Gonçalves WM; Guevara C. 1998. Descritores morfológicos e agronômicos para a caracterização de mandioca (*Manihot esculenta* Crantz). In: Proc Latin American workshop on Recursos Genéticos de Mandioca, held at Cruz das Almas (Bahia), Brazil, in October 1995. Centro Nacional de Pesquisa de Mandioca e Fruticultura Tropical (CNPMF) [of the] Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Cruz das Almas, Brazil. p 78–83.

Guevara C; Valderrama A. 1995. Esquema de indexación para un banco de germoplasma de *Manihot esculenta*. Unidad de Recursos Genéticos [of] CIAT, Cali, Colombia. 13 p. (Multicopied.)

Gulick P; Hershey C; Esquinas J. 1983. Genetic resources of cassava and wild relatives. International Board for Plant Genetic Resources (IBPGR), Rome, Italy. 56 p.

Hershey C; Amaya A. 1979. Germoplasma de yuca: Evolución, distribución y colección. In: Manual de producción de yuca. CIAT, Cali, Colombia. p E15–E26.

Iglesias C; Hershey C; Iwanaga M. 1992. Importancia de las colecciones núcleo para la conservación y utilización de los recursos genéticos. In: Proc Taller Internacional sobre Recursos Genéticos de la Yuca, held at CIAT, Cali, Colombia, August 1992. CIAT, Cali, Colombia. p 17–22.

Iglesias C; Guevara C; Ocampo C; Jiménez A. 1995. Identificación de duplicados genéticos en la colección de germoplasma de yuca conservada en el Centro Internacional de Agricultura Tropical (CIAT). CIAT, Cali, Colombia. 12 p. (Multicopied.)

Jaramillo G. 1993. Terminología, codificación y disponibilidad de germoplasma en mejoramiento de yuca. CIAT, Cali, Colombia. 16 p. (Multicopied.)

Nassar NMA. 2000. Cytogenetics and evolution of cassava (*Manihot esculenta* Crantz). Genet Mol Biol 23:1003–1014.

Ocampo C; Hershey C; Iglesias C; Iwanaga M. 1993. Esterase isozyme fingerprinting of the cassava germplasm collection held at CIAT. In: Roca W; Thro AM, eds. International Scientific Meeting of the Cassava Biotechnology Network (CBN), held in Cartagena, Colombia, August 1992. CIAT, Cali, Colombia. p 81–89.

Ocampo C; Angel F; Jiménez A; Jaramillo G; Hershey C; Granados E; Iglesias C. 1995. DNA fingerprinting to confirm possible genetic duplicates in cassava germplasm. In: Proc Second International Scientific Meeting of the Cassava Biotechnology Network (CBN), held in Bogor, Indonesia, August 1994. CIAT, Cali, Colombia. Vol 1, p 145–151.

Roca W; Chávez R; Marín ML; Arias D; Mafla G; Reyes R. 1989. *In vitro* methods of germoplasm conservation. Genome 31(2):813–817.

Rogers DJ; Appan SG. 1973. Manihot and manihotoides (Euphorbiaceae). A computer-assisted study. Flora Neotropica. Monograph No. 13. Hafner Press, New York. 272 p.

Appendix 1:

Form for Collecting Cassava Materials

Note: The section on descriptors must be answered

Genus: _____ Species: _____ Subspecies: _____

Name of collectors (initials): _____ Provisional code (collected sample) _____

Institution responsible: _____

Collection date (year/month/day): _____ International code (collected sample) _____

Country of collection: _____ Province/State: _____

Site: Closest municipality or town: _____

Distance (km): _____ Address: _____

Latitude: degrees: _____ minutes: _____ North _____ South _____

Longitude: degrees: _____ minutes: _____ East _____ West _____

Altitude: meters above sea level: _____

Sample's immediate origin (encircle):

Wild	1	Local market	5
Farm field	2	Commercial market	6
Local store	3	Institute	7
Household plot or garden	4	Other: _____	8

Sample's status (encircle):

Wild	1	Landrace	4
Weedy	2	Improved cultivar	5
Improved line	3	Other: _____	6

Local name: _____

Photo (encircle): Yes No Photo code: _____

Sample type (encircle): Plant 1 Seed 2 Both 3

Herbarium sample from the site (encircle): Yes No

Amount of material (number of seeds or stakes): _____

Primary morphological **descriptors** (encircle):

Color of apical leaf		3	5	7	9				
Color of adult leaf		3	5	7	9				
Color of petiole		1	2	3	4	5	7	9	
Lobe shape	1	2	3	4	5	6	7	8	9
External stem color	3	4	5	6	7	8	9		
External root color		1	2	3	4				
Color of root cortex	1	2	3	4					
Color of root pulp		1	2	3					

Growth habit (encircle):

Tree 1 Shrub 2 Creeper 3 Other 4 _____

Part of plant used (encircle): Roots 1 Foliage 2

Principal use (encircle):

Human consumption (fresh)	1	Animal consumption (dried or processed)	4
Human consumption (dry or processed)	2	Starch extraction	5
Animal consumption (fresh)	3	Other: _____	6

Special qualities according to farmers (encircle):

Yield	1	Resistance to diseases	5
Starch content	2	Resistance to pests	6
Culinary quality	3	Edaphic adaptation	7
Roots tolerant of PPD	4	Other: _____	8

Notable defects according to the farmer: _____

Diseases or pests and their severity:

(Scale of severity, where 1 = little damage; 2 = moderate damage; 3 = severe damage)

Disease or pest	Severity	Disease or pest	Severity

Crops in association: Yes 1 None 2 Details: _____

Information on wild species sample: _____

Natural vegetation (encircle):

Wet rainforest	1	Spiny forest	6
Humid rainforest	2	Desert thicket	7
Semi-humid rainforest	3	Desert	8
Dry forest	4	Other: _____	9
Very dry forest	5		

Topography (encircle):

Swampy	1	Undulating	5
Flood-prone plains	2	Hills	6
Vega	3	Mountainous	7
Plains	4	Other: _____	8

Soil texture (encircle):

Sandy	1	Clayey	5
Loamy-sandy	2	Stony	6
Loam	3	Organic	7
Loamy-clayey	4	Other: _____	8

Drainage (encircle):

Poor 1 Moderate 2 Good 3 Excessive 4

Slope (encircle):

Flat or almost flat (<4°) 1 Moderate slope (4°–14°) 2 Steep slope (>14°) 3

Brightness (encircle):

With sun 1 With shade 2

Comments: _____

CHAPTER 18

Cassava Genetic Improvement

Hernán Ceballos[1], *Nelson Morante*[1], *Fernando Calle*[1], *Jorge Iván Lenis*[1], *Gustavo Jaramillo O.*[2], *and Juan Carlos Pérez*[2]

Introduction

A highly profitable investment in agricultural research in terms of return to research is crop genetic improvement. Increases in productivity of principal grains and oil-bearing crops observed during the 20th century have been demonstrated to be due mostly to their genetic improvement (Fehr 1987).

Cassava has also benefited from technological contributions, particularly from genetics (Kawano et al. 1998; Kawano 2003), which has enabled the development of new varieties that more adequately meet the needs of farmers and consumers. Colombia possesses one of the few cassava genetic improvement programs found in the world, thus greatly favoring cassava growers in this country. This chapter describes the methodologies used by this program and its most relevant achievements.

Advantages and Disadvantages of Vegetative Reproduction

Genotype refers to all the genetic characteristics of an individual. To a great extent, plant breeding consists of identifying genetically desirable individuals, that is, those that have a superior genotype.

Cassava is reproduced vegetatively. Each and every propagule obtained through vegetative reproduction is genetically identical, and constitutes what is known as a *clone*. This implies that when a desirable genotype is identified, the latter can be multiplied and perpetuated, generation after generation, without *genetic segregation* occurring. In this regard, cassava and other crops with vegetative reproduction such as sweet potato, potato, yam, and fruit trees offer a great advantage over those that multiply only through botanical or sexual seed.

From the genetic viewpoint, cassava varieties are, in fact, hybrids between two selected parents. Cassava improvement starts with thousands of crosses and continues with an elaborate and expensive evaluation process (described in more detail below) to finally identify a few individuals that are genetically superior. Outstanding hybrids result from a cross that produces a unique and specific combination of genes that confers on them the *hybrid vigor* that characterizes them.

An optimal combination will give good hybrid vigor and result in a successful variety (i.e., a cultivar that farmers will plant). Very few combinations of progenitors stand out, which means that thousands of crosses must be evaluated every year. Once a genetically superior cassava plant is identified, it can be multiplied vegetatively to deliver that genetic superiority to farmers.

For many other crops, where reproduction is not vegetative, farmers may also plant hybrid materials (e.g., maize, sorghum, and carrot). These hybrids result from combinations of 2 to 4 progenitors that have been specifically identified because when they are crossed, they produce outstanding material, similar to what occurs with cassava. The seed resulting from such crosses is what farmers plant.

These hybrids are identified genetically by the term *F1* (i.e., first filial generation). Thus, the vigor observed in F1 of a commercial hybrid cannot be transmitted adequately to later generations. If farmers plant seed

1. Breeder, Biologist, Agronomist, and Agronomist, respectively, Cassava Program, CIAT, Cali, Colombia. E-mails: h.ceballos@cgiar.org; n.morante@cgiar.org; f.calle@cgiar.org, and j.lenis@cgiar.org
2. Agronomist and Breeder, respectively, formerly of Cassava Program, CIAT. E-mails: gjo97@hotmail.com and juanchoperezv@hotmail.com

harvested from F1 (technically identified as *F2* or second filial generation), "degeneration" can be observed. In other words, the high yield, uniformity, and other desirable characteristics that farmers receive from the purchased hybrid seed are gradually lost in subsequent filial generations. Hence, farmers must purchase hybrid seed year after year. The scientific basis of this "degeneration" is genetic segregation, mentioned above.

Technically, what occurs with genetic segregation is that the genes present in an F1 hybrid are shuffled, in the same way as a pack of cards are before being dealt. When an individual of any species undergoes sexual reproduction, the genes present in the individual are reorganized. From the evolutionary viewpoint, this is critical because it enables the creation of new genetic forms or recombinations that constitute the foundation of evolution. From the agricultural viewpoint, however, this is sometimes inconvenient, as the shuffling of genes, which creates new genetic forms, destroys that specific, difficult-to-obtain, yet desirable combination of genes once a successful hybrid produces F1 seed. Once a superior hybrid is identified in crops such as maize, the problem of how to perpetuate it then has to be solved, because the option of vegetative reproduction is not available. Hence, cloning would provide great advantage for such commercial hybrids.

To multiply a hybrid and produce seed for sale to farmers, the parental lines must be "fixed" by producing highly endogamous lines and later crossing them. This procedure complicates farmers' access to hybrid materials and makes them much more costly. In contrast, with cassava, once the genetically superior plant is identified, it can be reproduced vegetatively in such a way that farmers do not need to purchase hybrid seed year after year. However, as described later, the use of inbred parents allows for much more refined processes of improvement. Non-additive genetic effects (dominance and epistasis), responsible for heterosis, can be exploited more efficiently. It also enables the implementation of improvement methods such as backcrossing, which has been, and still is, widely used (Allard 1960; Blair et al. 2007).

Vegetative reproduction nevertheless presents some drawbacks: the rate of vegetative multiplication in cassava is very low—one plant produces only 6 to 10 cuttings or stakes—whereas, in sexual reproduction, the rate is usually much higher. For example, a maize cob normally produces about 400 seeds, so that the multiplication rate would be 1:400.

Another disadvantage of vegetative multiplication is the frequent accumulation of diseases, especially viral, in planting materials. Once the plant acquires a pathogen (particularly a virus), it is highly unlikely that it can free itself of that pathogen. Hence, all the stakes extracted from that plant will contain the pathogen. Good plant health management of cassava seed is therefore essential, and farmers must be encouraged to make minimal efforts to maintain the health of their planting materials. In contrast, botanical seed, resulting from sexual reproduction, is usually free of viral pathogens.

Another adverse aspect of vegetative multiplication is that stakes or trimmed stems require much more care than botanical seed. The conditions under which planting materials are stored will affect plantlets vigor and thus influence the crop's general performance.

For the above reasons, this paper gives special attention to the management of cassava vegetative seed to achieve an optimal physiological and sanitary state that maximizes returns to farmers.

A final drawback of vegetative multiplication is the volume that planting materials occupy. A 10-ton truck can load enough cassava seed for about 10 ha. The same truck could transport enough maize seed for about 400 ha.

Factors for a Successful Plant Breeding Program

The success of a genetic improvement program for a crop depends mainly on:

1. Continuity over time
2. Appropriate definition of objectives
3. Implementation of a good improvement scheme
4. Availability of representative environments for evaluations

Continuity over time

This is particularly important for cassava because of its prolonged selection cycle, which typically requires more than 5 years. The rest of the chapter describes this issue in detail, as do other publications such as Ceballos et al. (2004, 2007a) and Morante et al. (2005). In contrast, a selection cycle for grains or legumes can be completed in less than one year. Crop genetic improvement is a continuous and gradual process that requires several cycles to achieve its objectives. As a result, a fundamental need is to ensure that resources

will guarantee the continuous execution of the activity. Objectives for the process should be more or less stable, and changes introduced gradually and only when their need has been convincingly confirmed.

Adequate definition of objectives

Plant breeders should adequately define the objectives of their programs. Usually, for most crops and, in this regard, cassava is no exception, the goal is to increase yield per unit area; also to (1) maximize stability of production so that farmers will have adequate food security from their harvest, and (2) maintain or improve product quality so that this better meets the needs of end consumers. Stability of production is important and is achieved when the developed material is genetically tolerant or resistant to the main biotic and abiotic production constraints.

Because cassava is usually grown in marginal environments, it is highly susceptible to natural disasters such as drought or prolonged winters. A successful variety must necessarily have qualities that enable it to bear these and other stresses. Each environment where cassava is grown has its own list of factors that limit production. In the North Coast of Colombia, for example, the absence of rains and availability of water form the principal abiotic constraints to productivity. With regard to pests and diseases, mites (*Mononychellus tanajoa*, *M. caribbeana*, *Tetranychus urticae, T. cinnabarinus, Oligonychus peruvianus*), thrips (*Frankliniella williamsi*), and the stemborer (*Chilomima clarkei*) pose the most common problems.

In Valle del Cauca, in contrast, the availability of water is not such a major problem, which means that, instead of mites, the principal pest are whiteflies (*Aleurotrachelus socialis* and, to a lesser extent, *Bemisia tuberculata*). (In other regions of the world, *B. tabaci* is the main disease vector, including diseases such as the African cassava mosaic disease or cassava brown streak). In some areas of Colombia, cassava bacterial blight (*Xanthomonas axonopodis* pv. *manihotis*) and superelongation (*Sphaceloma manihoticola*) are also economically significant constraints.

All these observations are integrated into the process of genetic improvement for each ecoregion, so that resulting materials will have good levels of tolerance or resistance to these stresses. This activity is fundamental, both to maximize production and guarantee its stability, the latter of which is essential for the farmer's economic survival.

Any genetic material produced should also adequately meet the needs of users or end consumers. These can be described as four major destinations for cassava in Colombia (as with the rest of the world), each of which defines specific requirements from the crop. Aspects of quality are becoming extremely important and are described in more detail in the next section.

Developing a good improvement scheme

Once defined, the improvement program's specific objectives should be implemented. For this, a good improvement scheme is necessary. Because this issue is complex, it is treated in more detail as this chapter develops.

Representative environments

Finally, to identify superior cassava varieties that adapt to the environments for which they are directed, evaluations in representative sites of the targeted environments must be conducted. Here, a compromise must be made on the number of environments that can be handled with the objective of maintaining the widest diversity of situations in which, in practice, this crop is found.

For Colombia, six relevant and distinctive environments can be determined for cassava: (1) subhumid Caribbean (Department of Atlántico), (2) humid Caribbean (Córdoba), (3) Orinoquía (Meta), (4) inter-Andean valleys (Valle del Cauca), (5) high-altitude areas of about 1800 m above sea level (Cauca), and (6) humid lowlands (Putumayo). In these six environments, most of the conditions under which cassava is cultivated in the country are represented. They are also representative of most cassava-growing environments around the world.

Specific Requirements for Cassava as Demanded by Different Industrial Uses

As already mentioned, several industries base their activity on processing cassava roots. These industries need raw material at competitive prices, in constant supplies, and typically possessing good levels of dry matter. These requirements are constant for all industries. However, specific requirements for certain qualitative characteristics exist for different industrial uses (Table 18-1).

Table 18-1. Differences in some of the specific requirements for cassava according to its final use. Values in parentheses indicate the relative significance of each characteristic on a scale of 1 to 3, where 1 = very important; 3 = not so important.

Parameter	Final use		
	Starches, bioethanol, and animal feed	Fresh-root consumption	Food processing
Yield	(1)	(2)	(1)
Cyanogenic glucosides	(3) Bitter cassavas are preferred as they do not require so much surveillance	(1) Only "sweet" cassavas are acceptable	(1) Only "sweet" cassavas are acceptable
Parenchyma color	(3) For starches, it must be white; for balanced feeds, an orange color (indicating high carotene content) is suitable	(1) Usually white is preferred, although in some regions yellow roots are acceptable	(2) Currently, only white roots are processed; yellow roots, however, offer advantages
External appearance of roots	(3) An undesirable presentation implies that less surveillance is needed	(1) The more a root looks like variety 'Chiroza' (dark coffee-colored peel and pink cortex), the better its price will be	(3) Industry does not need "markers" to recognize good cassava, as it works through contract
Tolerance of root diseases and pests	(2) Only where they affect yield	(1) If presentation is affected, even if it is only a "cosmetic" problem, the price will be greatly affected	(1) Root smallpox disease is only a cosmetic problem, but it affects prices to industry
Dry matter contents	(1) The higher the content, the higher the price	(2) Varieties for fresh consumption usually have intermediate levels of dry matter content	(1) High dry matter content is usually preferred; the proportion of sugars can be significant
Culinary quality	(3) Poor quality material is even preferred as field surveillance will not be needed	(1) The basic criterion for this type of use	(2) Quality of the processed product is more important; hence, cassava of intermediate culinary quality can be excellent

Starch production and energy source for animal feed

For these industries, the principal objective would be to produce varieties with (1) high yield potential to enable the production of raw material at competitive prices, and (2) high dry matter content to facilitate starch extraction or the drying of roots. Yellow roots would be more suitable for animal feeds, while white roots are preferred by the starch industry. *In planta* modification to produce varieties with special starch characteristics offers opportunities and advantages over the chemical and/or physical modification currently carried out to generate starches with special functional properties (Ellis et al. 1998; Davis et al. 2003).

Fresh-root consumption. This is the traditional market for fresh roots, which are sold in both open-air markets and supermarkets. For this end use, cassava should be "sweet" (low contents of cyanogenic glucosides), with usually intermediate dry matter content, and, especially, excellent culinary quality. The root appearance (e.g., form, peel color, and parenchyma or pulp color) is fundamental. Productivity in this case has a smaller relative weight than for cassava destined for either starch or balanced feed industries.

Food-processing industries. This growing sector is represented by pre-cooked and frozen croquettes and fried cassava chips. In these cases, productivity is essential, and root characteristics should be adjusted to industrial requirements. For croquettes, for example, varieties should be "sweet", with little fiber and levels of dry matter that are usually higher than for fresh consumption. Sugar levels in roots affect the quality of fried cassava chips.

Table 18-1 describes the principal selection criteria according to uses given to cassava in Colombia. Other

cassava products for human consumption include *gari* (toasted fermented cassava meal) and *fufu* (boiled cassava pounded into a paste and eaten with stews and soups), which are consumed in Africa; and *farinha* (toasted cassava meal) and *casabe* (a flatbread), which are typical in several South American countries (Cock 1985). Another highly distinctive use of cassava, which is uncommon in Colombia but adopted in countries such as Cuba (García L and Herrera 1998), is the harvest of young foliage. For this use, cassava is planted at high densities and foliage is cut about every 4 months.

Bioethanol. This is a growing industry, thanks to price increases in oil and oil derivatives on the one hand and technology developments on the other. Research on the economic and competitive hydrolysis of maize endosperm (before fermentation is begun and distillation carried out) has directly benefited similar processes conducted on cassava roots.

Adding value to crops

Traditionally, the production chain for the food sector has been fractionated so that little or no interaction exists between its different components. Thus, crop breeders interacted only with farmers who purchased their products. Communication was usually very limited between plant breeders, the sector purchasing and selling agricultural products, processors, and, in the final analysis, end consumers.

Recently, however, recognition is growing of the need for greater integration among the different components of a given production chain. This principle is influencing policies of agricultural research in Colombia (CONPES 2000), including the case of cassava within the poultry and pig-raising chains. Thus, suppliers of genetic resources are interacting more closely with, for example, merchants of grains and other agricultural products, livestock producers, food processors, and food wholesalers and retailers to discover the specific needs of the different actors.

In other words, crop genetic improvement has been reoriented so that its objectives aim more precisely at the needs of end users. Thus, in well-developed markets, cash crops seek to better meet the needs of merchants, processors, and consumers of agricultural products. For less developed markets or household consumption, the end user is usually the farmers themselves. In this case, specific participatory research methodologies have been developed to seek better satisfaction of farmers' needs as they themselves define them (CIAT 1991).

A better comprehension of the needs of different consumers enables breeders to identify the opportunities a given crop offers, and thus make it more competitive or profitable. Such knowledge, in its turn, permits a definition of research objectives not only from the viewpoint of genetically improving crops, but also from other aspects that must accompany and complement the release of new varieties. These principles also are valid, and are being applied, for the cassava crop.

Kleese (2000) suggested several factors for consideration when value is to be added to a given crop. These include:

The needs of end users should be understood. Through such understanding, areas with potential for exploitation can be identified. In some areas of economic activity, barriers may exist to free exchange of information, stemming from aspects of intellectual property, common in many highly competitive markets.

Substituting values versus creating new added values. The most obvious opportunities for adding value to a crop occur when the latter can meet needs covered by other ingredients. For cassava, the use of yellow roots (high carotene content) reduces the need for exogenous supplements of carotenes and/or colorings in poultry feeds. It can also be useful in a basic strategy to reduce the awful effects of vitamin A deficiency in humans (Echeverri 2001).

Another example that stands out is that, sometimes, added value results by removing a given product, as in the case of inositol in maize. This product links with phosphorus in such a way that it cannot be absorbed by monogastric species. Hence, the phosphorus found in chicken and pig manure from major operations is becoming a true ecological problem. A strategic alternative, in this case, would be to improve the crop to reduce inositol content (and, hence, the quantity of phosphorus linked to it), or, instead, add enzymes that will degrade it. The end beneficiary of these potential solutions would be the environment itself.

The need to capture a new added value. Two fundamental aspects of introducing crops with added value are whether the market would pay for the new value, and how the different actors of a given

production chain would share the additional profits. With respect to the latter aspect, it should be remembered that, in each case, an added value to a specific crop would compete with other alternatives available on the market. Policies being implemented should guarantee that any additional profitability is adequately distributed among the different actors of the production chain to prevent monopolization by one or another.

Redefining an added value. For farmers, yield has been the most prevalent way of determining the value of most cash crops. Ideally, the adding of value should be done without it being at the expense of a crop's productivity. For cassava, higher dry matter content and increased carotene content in roots are examples of where value can be added without necessarily reducing productivity. Assuming the simplest case where parity with productivity exists, how and who defines the magnitude of increase in the crop's value? A need must be recognized for which the consumer or processor is willing to pay extra for a product that will be more useful in meeting that need.

If this incentive does not exist, farmers will not necessarily adopt a new variety, as happened in the case of quality-protein maize (QPM)[3]. This maize was improved so that, while obtaining yields and grain quality similar to normal maize, it also offered greater availability of two essential amino acids: lysine and tryptophan (Vasal 2000). However, this maize was not extensively adopted because the food industry was unwilling to pay higher prices for it, even though it better met the industry's needs.

Can the technology function? It is clear that crop genetic improvement can improve a crop's nutritional quality. Maize with its variants of high oil content (Dudley et al. 1974) or high protein quality (Vasal 2000) demonstrates this clearly. Iron and zinc can be added to beans (Beebe et al. 2000) and carotenes to cassava (Chávez et al. 2000). But, would such modifications be sufficiently large to be reflected in changes in the crop's commercial value?

In some specific cases, answers to these questions are even more difficult to obtain. For example, in the marketing of transgenic crops (maize and cotton) that carry the gene from the entomotoxin of *Bacillus thuringiensis* (*Bt*), numerous factors intervene to influence the final commercial value that these crops have. Production by farmers benefits from the reduced need to apply agricultural chemicals to control insects that are controllable by the gene *Bt*. The environment also benefits from fewer indiscriminate interventions by farmers. However, public opinion has been manipulated in such a way that, in many cases, the polemics of transgenic crops move away from the specifically technical and scientific to the more philosophical and political, distorting the true value that these products may have.

Transgenic crops possess enormous potential for the possibilities offered, in different crops, through the addition of value. For example, the quality of oil in a given oleaginous crop could be modified to benefit human health by decreasing the proportion of the saturated fraction. Transgenesis could genetically alter the rice crop to increase carotene and iron contents ("golden rice") (Ye et al. 2000); and reduce amylose content in cassava starch (Munyikwa 1997) to produce waxy cassava that would have enormous potential in the starch industry. But, as well as the undeniable increase in the crop's value from a biological viewpoint, aspects, including psychological, must be considered as they intervene in the definition of the final value that such a crop would have for society.

Preserving the added value. This is also relevant. For those products whose added value is easily detectable (e.g., the yellow color of cassava roots with high carotene content), management is simple. However, some characteristics are difficult to detect, as in the case of beans with high levels of iron and zinc. In such cases, an independent marketing chain may be required to preserve the product's identity as having added value. However, this same need would increase marketing costs.

Freedom to operate. This refers, mainly, to the growing quantity of legal restrictions that stem from intellectual property rights for different products such as genes, procedures, and enzymes. Sometimes, a vacuum exists in the legislation of numerous countries on the use of genetically modified organisms. In other cases (Argentina, Canada, China, and USA), the regulation of its production and use is lax. In yet other cases (mainly Europe), the production, marketing, and use of food derived from genetically modified crops are highly restricted. Ironically, this situation contrasts with the production and use of drugs and medicines that are also obtained through genetic transformation techniques, but which have not generated as much polemic as the case of agricultural products.

3. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Flowering and the Acquisition of Botanical or Sexual Cassava Seed

As described in Chapter 2 on the plant's morphology, cassava is a monoecious species that has staminate (male) and pistillate (female) flowers on the same inflorescence (Figure 2-5, Chapter 2, this volume). Crop genetic improvement requires, as an essential stage, the development of new genotypes that are superior to those already available at the time of development. New genotypes occur through crosses between progenitors that have been selected for the purpose because they present one or more desirable characteristics. Crossing consists of facilitating the deposit of pollen from one progenitor's male flower onto the stigma of a female flower of another progenitor.

In controlled crosses, flowers are handled directly to ensure greater control over pollination. Occasionally, the researcher may decide to carry out self-pollination, whereby pollen from one plant is deposited on the female flowers of the same plant. This, however, is carried out only for research purposes; it very rarely gives rise to a commercial variety.

Flowering in cassava is always associated with stem branching in such a way that those cultivars that do not branch, do not flower either. The plants flower preferably during the short days of the year (Jennings 1970). Flowering in this crop is highly variable, influenced by genetic—some varieties rarely flower, while others flower abundantly—and environmental factors—the same variety may not flower in lowlands but will flower exuberantly in mid-altitudes. As a result, the production of botanical seed in a genetic improvement program is highly variable and depends heavily on the combination of progenitors that are to be crossed, as well as the sites and timing of pollinations.

After pollination and subsequent fertilization, the ovary develops, forming the fruit, which takes about 3 months to achieve maturity. The fruit is a dehiscent capsule and is either trilocular ovoid or globate. It measures 1.5 to 2.0 cm in diameter, and has six narrow longitudinal and prominent edges (Figure 18-1). The capsule is hard and has three loculi, each of which contains a seed. Seeds are elliptical and coffee-colored or gray, with black or coffee-colored guttae (or spots), depending on the mother variety (Figure 2-6, Chapter 2, this volume).

Figure 18-1. Clockwise, fruits at 1, 2, and 3 months after pollination, and cassava seeds.

The production of sexual (or botanical) cassava seed at CIAT involves several stages and options. Understanding the plant's flowering system helps in handling the procedure with maximum efficiency. Seed production includes, in addition to parent selection, hybridization or crossing, seed collection and the seeds' correct coding, storage and treatment, and use of an elaborate planting system.

Hybridization

The relatively large size of flowers ensures that controlled pollination in cassava is easy and relatively simple. The female flowers usually open 10–14 days before the male ones of the same inflorescence do. However, female and male flowers of different racemes on the same plant commonly flower at the same time, enabling self-pollination. Flowers usually open at mid-day.

During free pollination of flowers, both self- and cross-pollinated seeds may be produced, in proportions that depend on genotype, planting design, type of insects present in the area, and timing of pollination. With some practice and judging from the flower's color and form, predicting which female or male flowers will open during the day is possible. A more effective method is to loosen an unopened tepal of the female flower. If a drop of nectar lies near the tepal's base the flower will open that day (Figure 18-2).

When two different progenitors are crossed, the resulting progeny constitutes a family, usually called *F1*. Because of cassava's high heterozygosity (the genetic heterogeneity present in an individual), each seed produced in an F1 cross generates a genetically

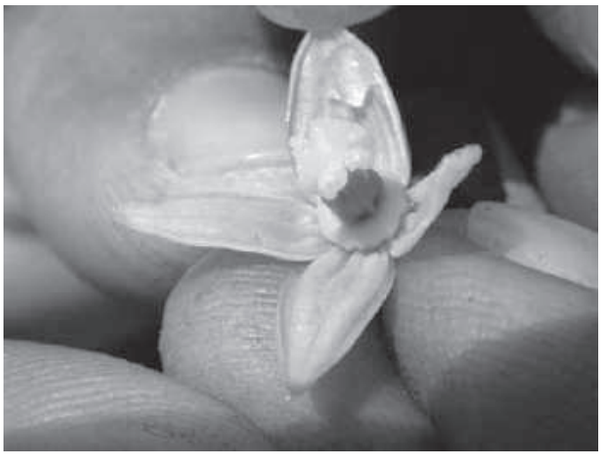


Figure 18-2. A tepal of a female flower carries a drop of nectar, which indicates that the flower is receptive to pollination.

different plant, which then has the potential to produce a new variety. Consequently, great genetic variability can be easily introduced and managed through these crosses, which in their turn, permit the selection and acquisition of genetically superior individuals. However, the production of large quantities of seed is laborious and, usually, expensive. Within CIAT's scheme of cassava improvement, two types of crosses are made for seed acquisition: controlled and open (or *polycrosses*).

Controlled crosses

For controlled crosses, both female and male progenitors are known, so that the progenies produced constitute a family of *full sibs*. Selected parents are organized in separated crossing blocks and pollinations are directed mostly between varieties for a single adaptation area. However, they are also carried out between varieties from different areas to transfer and recombine specific characteristics and increase the *plasticity* of the materials, so that they may adapt more broadly and/or possess better stability in production.

For controlled crosses, 10 to 20 plants per selected genotype are used as parental materials, planted in rows with distances between plants being 1 m and between rows 2 m. The latter distance is to facilitate circulation of the people who observe and select flowers ready for pollination each day.

Pollination is carried out in the morning after female flowers, likely to be receptive that day, are chosen. They are then covered with cloth bags, measuring 20 × 25 cm, to protect them from undesirable pollen after opening. Those male flowers that are close to opening are themselves collected on the same day in the morning and deposited in plastic or glass bottles, identified with the variety's name (Figure 18-3). The flowers will open in their bottles at mid-day.

Pollination is carried out by first finding suitable female flowers and then gently rubbing their stigmas with pollen-bearing anthers (Figure 18-4). As many as three different female flowers can be pollinated by a single male flower. The pollinated flowers are then

Figure 18-3. One of the plastic bottles used to store male flowers after their collection in the morning until their use at mid-day.

Figure 18-4. Procedure used for controlled crosses in cassava.

Figure 18-5. Tags used to identify different pollinations and the bags with which cassava flowers and fruits are covered.

identified, using tags on which the crosses are detailed (thus noting the origin of the pollen, together with the date and number of pollinated flowers) (Figure 18-5). Those of the raceme's female flowers that had not opened by the time of pollination are eliminated to prevent later confusion with those that were pollinated. The information of all crosses within one day is tabulated and later transferred to either a card system or directly to an electronic system. Thus, crosses can be organized first by the female parent and then by the male parent, following an alphanumerical order for each clone that was used as a progenitor.

Pollinated flowers can be covered immediately with either a cloth or paper bag, but they can also be left uncovered, as, apparently, exposed flowers are rarely, if at all, contaminated by pollen from other sources. However, flowers that are covered after pollination frequently have a low percentage of formed fruits, possibly because the temperature inside the bag increases sufficiently to "burn" the flower. After 3 weeks, the formed fruits must be covered with cloth bags to prevent attack from fruit fly (*Anastrepha pickeli*) and to collect seeds when dehiscence occurs (Figure 18-4). Fruits reach maturity at about 3 months after pollination.

Polycrosses

For open pollination, only the female progenitor is known, as the pollen may come from any of the surrounding plants. In this case, the possibility exists that, occasionally, self-pollination will occur. Progeny that results from open pollination of the same female progenitor constitutes a *half-sib* family, as the identification of the male progenitor remains uncertain. Within such a family the plants may have some phenotypic, but fewer, similarities than do full siblings from controlled crosses.

Open-pollinated seed can be collected from any cassava planting, but on the condition of having a mixture of numerous and genetically different materials. Different methods exist for increasing the possibility that the source of pollen is the desired one. The most commonly used is to plant a mixture of selected clones in isolated blocks, where they can cross exclusively with each other, while avoiding undesirable varieties. In this case, seeds from individual plants are collected, and records of female progenitors are kept. Such a system is called *polycrossing*.

CIAT uses a system of constructing blocks of polycrosses in which a spatial arrangement is designed to favor homogeneous pollination among the varieties involved. The field plans of the polycrossing plots follow Wright's methodology (1965). With this design, the same possibilities exist for crosses among selected varieties. Planting distances are 1.5 m between plants and 2 m between rows. To ensure that crosses are carried out among the varieties to be crossed, these blocks are surrounded by 8-m-wide barriers of male-sterile plants, planted at 1 m between plants and between rows. These barriers reduce pollen flow from one block to another and reduce the possibility of pollen from undesirable plants intervening in the pollinations.

Fruits generated by this system are collected when they are sufficiently mature physiologically, at about 2 months after fertilization. At this time, the fruits lose their natural shine, becoming opaque green in color. The peel then loosens readily from the fruit capsule, and dehiscence begins, with the edges separating until they are totally freed. At this moment, the peel takes on a coffee color (Figure 18-1).

Seed collection and coding the crosses

The dried and sectioned fruits in the bags, which were put in place earlier, are collected from the field and

seed is selected after all residues are removed from the peel. The seeds are organized; for controlled crosses, first according to the female progenitor and then to the male progenitor; and, for open-pollinated crosses, to the female progenitor, which is the only one known. The seed is then tested for density in a solution of 2% sodium hypochlorite to eliminate those with low-density or are non-viable and also to disinfect seeds of possible pathogens adhering on their exterior.

To facilitate data management, a code is assigned to each cross according to the progenitors involved. CIAT uses a code of two letters to indicate the type of cross and the progenitors involved. When the cross is controlled, different letters have been used over time such as "CG" or "CM". Currently, the letters "GM" are being used. Following the letters is a code of up to four numbers that represents a consecutive record of the crosses done at CIAT. This number identifies the family of the full sibs that possess progenitors in common. For example, the family CM 6740 identifies all progeny derived from the cross between M Col 1505 and M Pan 51. The same cross can be made over several years. However, if the same progenitors are used, the progeny produced will always have the same code, regardless of the year in which the cross is made.

As each individual of a full-sib family is genetically different from its siblings, the individuals of a single family are distinguished by a hyphen followed by a consecutive number. Thus, CM 6740-7 identifies the clone that was recently released as 'Reina'. In addition to CM 6740-7, numerous individuals within that family were produced, but only the seventh one was superior enough to be released as a new variety. Another interesting example is that of the family CM 3306, which produced excellent progeny that resulted in the release of the variety ICA-Negrita (CM 3306-4). More recently, the Colombian Corporation of Agricultural Research (CORPOICA) released CM 3306-19. In addition, the clone CM 3306-9 showed exceptional performance in Guajira, despite the severe drought conditions that are typical of the region.

For seeds resulting from open pollination, the letters "SG" were first used but are now replaced by the letters "SM". These letters are also followed by four numbers that represent a consecutive index that identifies a given polycrossing plot (i.e., a single group of progenitors), and the mother from which seed was obtained. For example, SM 1219 identifies the whole progeny derived from the mother CG 1450-4 that participated in the polycrossing plots of 1987. The code thus identifies not only the female progenitor from which this half-sibling family is derived, but also the group of individuals among which the male progenitor is to be found.

As in controlled crosses, the code for the half-sibling family is followed by a hyphen and a number that distinguishes the different individuals composing it. Thus, clone SM 1219-19 stands out among its half siblings for its superiority in mid-altitude valley environments. Unlike what happens for controlled crosses, the different individuals of an SM family may have different male progenitors.

Storing and treating botanical seed

Botanical cassava seed, stored at room temperature, maintains high viability for about one year after harvest. For medium-term storage (i.e., several years), they are conserved at 5–10 °C and 60% relative humidity.

Seeds are packed in small envelopes carrying the names of the cross and its parents, the source of seed, date of harvesting the fruits, and the number of seeds in the bag. During storage, seed is treated with fungicides and insecticides. In addition, drying in an oven at 55–60 °C for 10 to 14 days is sometimes recommended to eliminate potential risks of pests and pathogens from the seed. Such treatment also helps break seed dormancy, which normally lasts 2 months after harvesting.

Little information exists as to the optimal storage conditions for seed. Under normal environmental conditions, germination drops drastically 2 years after seed is harvested, becoming non-existent by the third year (Kawano 1978). However, Martín and Ruberte (1976) found that storage under dry (in calcium chloride) laboratory conditions still produces a good germination rate, even after more than 2 years of storage. At the International Institute of Tropical Agriculture (IITA), Nigeria, germination studies (1979) of seeds stored for more than 7 years at 5 °C and 60% relative humidity found that viability in seeds between 0 and 7 years old had not declined in any way.

Sowing sexual seed and transplanting seedlings

As mentioned earlier, the management of sexual seed is not difficult, but requires special care, particularly in the first stages of seedling development. The first consideration for sowing seed is the time at which this is carried out. Normally, sowing in trays should be 6 to

8 weeks before the crop is normally planted in the area, so that transplanting to the field coincides with that time. If several planting times are available, one should be chosen, according to convenience or relative importance of each time.

Seed is sown in trays, plastic bags, or in a bed prepared in the field. The percentage of germination from sowing directly in the field tends to be low and should be avoided if possible. The most preferable method is sowing in trays with individual compartments for each seedling. Ideally, a compartment should be about 3 × 3 cm and 6 cm deep (Figure 18-6). Trays without compartments are acceptable, but great care is needed to maintain the exact identification of each seed.

The planting substrate in the trays may be soil or an artificial mixture. It should be well drained and free of insects, pathogens, or weed seeds. For greater safety, the soil should be sterilized by steaming or fumigation. The substrate should have a good balance of nutrients and, especially, an adequate level of phosphorus. After preparing the trays or bags with soil, the seeds are systematically planted to a depth of about 1.0–1.5 cm. Seed packets should be arranged in ascending order according to the code, and the seeds sown in that order, identifying each family with a plastic or wooden marker that carries the code and faces the first row.

To germinate, cassava seed has highly specific requirements, which, if they are not fulfilled, can lead to a very low germination rate. The two most important requirements are suitable temperature and sufficient moisture in the soil or substrate. The optimal temperature regime fluctuates between 25 and 35 °C in a site where temperatures can be controlled. Otherwise, in a greenhouse or mesh house, temperatures may reach as high as 38 °C during the day. The substrate should be kept moist, but not saturated. Plants grow best under sunlight with normal intensity and no shade.

Figure 18-6. A tray is used for sowing botanical cassava seed, which is left until it germinates and the resulting seedlings transplanted to the field.

Six to 8 weeks after sowing, or when seedling height averages about 20 cm, the plantlets are transplanted to the field. The soil should be well prepared and preferably with ridges. Planting distance depends on the selection system implemented. In each transplant site, a small hole is made. Seedlings should be extracted from the tray with minimal damage to the roots, transplanting in the same order that the seeds were sown, that is, in ascending order of the number of the cross. The easiest way to transplant all the seedlings is in serpentine form, planting down the field and returning in the opposite direction. A free space is left between different crosses where a stake is placed carrying their identification.

If the soil has insufficient moisture at the time of transplanting, each seedling should be irrigated individually. During the first month, until the plants are well established, adequate soil moisture must be maintained. Also, during this establishment period, seedlings are highly susceptible to damage by cutting insects, slugs, and other animals, which means that protection requires continuous treatment and frequent checks. In areas where thrips cause damage, the plants must be protected by insecticide applications for the first months, until they are old enough to form pubescence on leaf buds (the most common form of resistance).

Throughout the cycle, the normal practices of any cassava trial are carried out. Only for the first 2 or 3 months are plants from sexual seed more delicate than those derived from stakes. Once past this period, they achieve an almost normal development.

The Cassava Genetic Improvement Scheme Used in Colombia

Below, we briefly describe the procedures for the genetic improvement of cassava for specific environments in Colombia. In this section, the reader can better understand the complexity of the improvement system and the need for continuity of adequate resources. Additional information can be found in other publications such as those by Ceballos et al. (2004, 2007a) anSd Morante et al. (2005).

Selecting parents for new groups of crosses

A major decision to make in crop genetic improvement is to choose the materials that will be used as parents to produce new varieties that have higher productive potential and better adaptation to the environmental conditions where they will be grown. CIAT has the enormous privilege to be the depository for the World Cassava Germplasm Bank. With more than 6000 varieties from Africa, Asia, and the Americas, the Bank contains a major proportion of not only the current genetic variability of *Manihot esculenta*, but also numerous wild species from which valuable genes can be extracted. The materials held in the Germplasm Bank were contributed by many countries and, together, are considered as humanity's patrimony. Use of this germplasm permits development of materials not only for Colombia, but also for the rest of the world.

Not all genetic variability is usable, as many varieties held by the Germplasm Bank lack characteristics that make them suitable as parents. However, their conservation is considered as a way of guaranteeing the crop's competitiveness or its future use in the event a new phenomenon occurs that the varieties currently disseminated are unable to overcome, for example, when a new disease or pest makes a sudden appearance. Only then will some materials, which had previously not offered any advantages, become valuable genetic resources.

A recent situation illustrates the strategic importance of germplasm banks. In several regions of the Departments of Cauca, Valle del Cauca, and Tolima, a whitefly problem had been gradually but constantly evolving over recent years to the point that it became a true constraint to production in these regions.

Responding to this growing problem, CIAT began evaluating materials in the Germplasm Bank, in the hope of finding varieties that would offer some type of resistance or tolerance to whiteflies. A variety from Ecuador (M Ecu 72) was identified as having excellent levels of resistance to these insects (Bellotti et al. 1999). In fact, the resistance present in M Ecu 72 was later confirmed to be of the antibiosis type. Accordingly, with support from the Colombian Government, through the Ministry of Agriculture and Rural Development (MADR), the resistant variety was included as progenitor in crosses for the inter-Andean valley region, where this problem was most severe. The antibiosis of M Ecu 72 is the first source of resistance reported for crops affected by whiteflies.

In addition to materials from the Germplasm Bank, cassava clones resulting from genetic improvement begun at CIAT in the early 1970s are also heavily used. For example, many of the genotypes selected as parents had high dry matter productivity per hectare (e.g., M Tai 8, SM 1565-15, and SM 1219-9). Other parents presented excellent qualities for the food-processing industry (M Per 183 and SM 1460-1), recognized combining ability to produce good progeny (SM 805-15 and SM 1565-17), or special characteristics such as resistance to root rots (CM 4574-7). An important modification, introduced in year 2000, was a more frequent inclusion of materials that possess a pulp with an intense yellow color, as a result of high carotene content. These materials may possibly have specific industrial uses, as they present low HCN levels (thus reducing the problem of drying cassava for the feed concentrate industry) while providing greater nutritional value. For the snack industry (fried cassava chips), an added advantage is that the product has a more attractive presentation.

Another new development with regard to progenitors for use in producing new genotypes is the introduction, through IITA, of African materials that possess resistance to the African cassava mosaic virus (ACMV). Fortunately, this disease does not appear in the Americas, but its insect vector (*Bemisia tabaci*) has recently been detected feeding on cassava in Brazil, Ecuador, Dominican Republic, and Puerto Rico (Bellotti et al. 1999). Hence, to introduce resistance to this severe disease before its eventual appearance is to be prudent, particularly as American cassava varieties are highly susceptible to African mosaic. Because selection cannot be made for resistance (as the disease is not present), molecular markers identified at CIAT will be used. The introduced materials were obtained through embryo rescue from sexual seed to ensure there were no risks of inadvertently introducing the disease into the country—as already mentioned, viral diseases are not transmitted through botanical seed. In addition to this precaution, special measures of plant health prevention were taken.

Acquiring plants from botanical seed and selecting the respective progeny

Once recombinant cassava seeds are produced, their progeny should be evaluated to select, from the massive number of genotypes, those few that surpass, in one or more characteristics, the best of the currently available materials. This is a slow, costly, but very important process. It gradually reduces the number of

genotypes for evaluating, while increasing the quantity of vegetative seed available for successive evaluations and/or multiplications.

Cassava is characterized by a notable genotype-by-environment interaction that results in a marked specificity of adaptation of varieties to specific environmental conditions. For example, varieties for the subhumid Caribbean usually do not adapt to humid Caribbean or Eastern Plains. As a result, selection must be made in each ecological region. In this regard, the country is seen to be highly favored by CIAT carrying out its selection activities in Colombia, as this guarantees excellent adaptation of germplasm to prevalent environmental conditions. For similar reasons, CIAT is highly favored by having possibly available such contrasting environments within a single country.

For each ecoregion, an independent evaluation scheme is carried out. Figure 18-7 illustrates the way in which these evaluations are currently conducted for each ecoregion. The sexual or botanical seed is sown in mesh houses to prevent the possibility of transferring diseases such as frogskin and then transplanted to the field at 2 months old (Stage F1).

These plantings are carried out in isolated plots to maintain the materials as free as possible of disease vectors (particularly, whiteflies) and thus reduce to the utmost the probability that these materials will contain communicable diseases. At 10 months, these plants are "harvested" to produce eight stakes or cuttings. All the stakes from one plant are packed together, suitably identified, and transported to the respective area of specific adaptation (e.g., subhumid Caribbean). On collecting the stakes, roots are reviewed to confirm that they do not have symptoms of diseases such as frogskin. The eight stakes are planted in individual furrows of eight plants in trials known as *clonal evaluation trials* (CET).

The enormous genetic variability, based on so many crosses among selected progenitors, can be appreciated in the CET. To exploit this great variability, several very large segregating families must be evaluated. Currently, between 1500 and 2000 clones are being planted in these trials. As expected, many of these clones will present different, possibly undesirable, characteristics. Hence, at this stage, selection is highly drastic, reducing the number of clones that will pass to the next stage of evaluation and selection to 200–300. As each genotype is represented by a relatively reduced number of plants (up to eight) planted with one replication, selection in the CET is based mostly on highly heritable characteristics (e.g., plant type, dry matter content in roots, capacity to produce storage roots, harvest index, and resistance to certain insects or diseases).

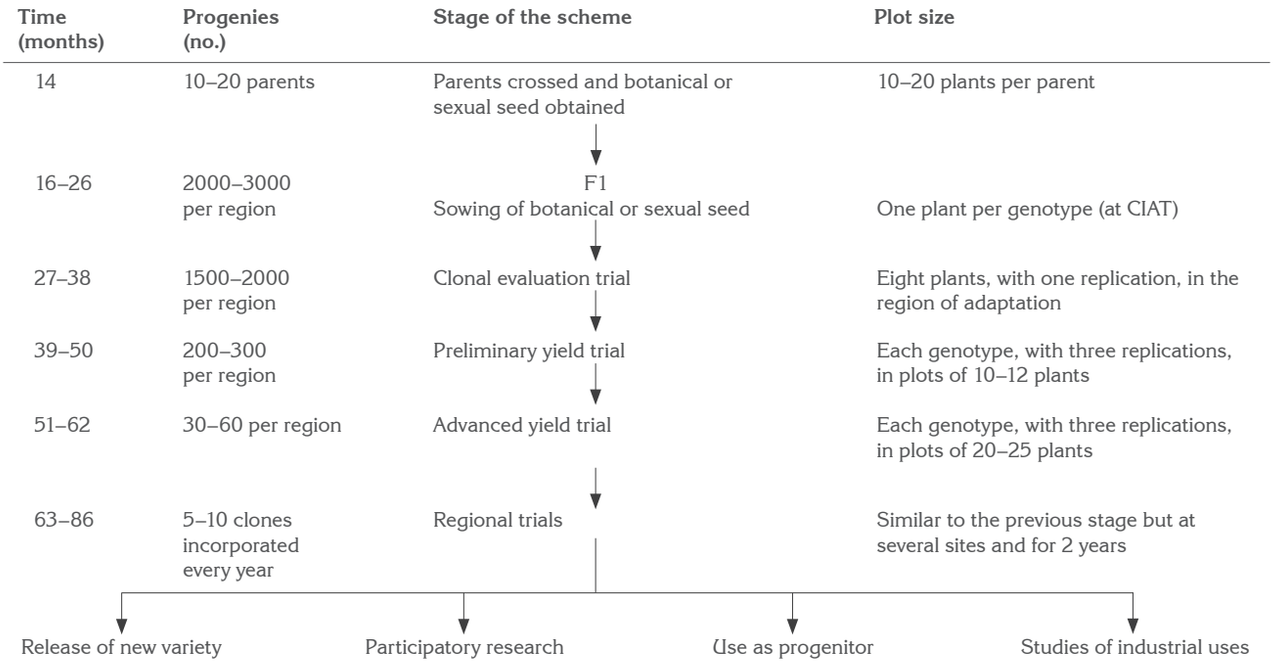


Figure 18-7. Basic cassava improvement scheme for each typical cassava-producing region in Colombia.

Figure 18-8. Clonal evaluation trial at Santo Tomás, Atlántico, Colombia, showing variation in the capacity for leaf retention.

Figures 18-8 and 18-9 illustrate the type of variation that can be observed among families evaluated in a CET. Figure 18-8 (Santo Tomás, Atlántico) illustrates how, in some families, at 5 months old, leaves tend to drop relatively quickly during plant development (whether for genetic reasons or the presence of biotic or abiotic factors), whereas other families maintain their leaves over longer periods. This capacity for leaf retention is a favorable influence (dry matter yield is about an extra 2 t/ha), as seen when the families were harvested 6 months later.

Figure 18-9 illustrates segregation for resistance to leaf diseases (bacterial blight and superelongation) typical in the Orinoquian Region. In this particular case, stakes of highly susceptible materials were planted to separate plots, which had been planted one behind the other. The plants originating from these stakes served as sources of inoculum, that is, as "spreaders", to ensure that disease pressure is relatively high and uniform throughout the whole trial.

Once this first selection in the CET is made, thus reducing the number of families to evaluate and increasing the quantity of available seed, evaluations start with larger plots and with replications. As the process advances (Figure 18-7), selection focuses more and more on characteristics of low heritability such as yield. This is because, only through the use of special experimental designs, inclusion of replications, and

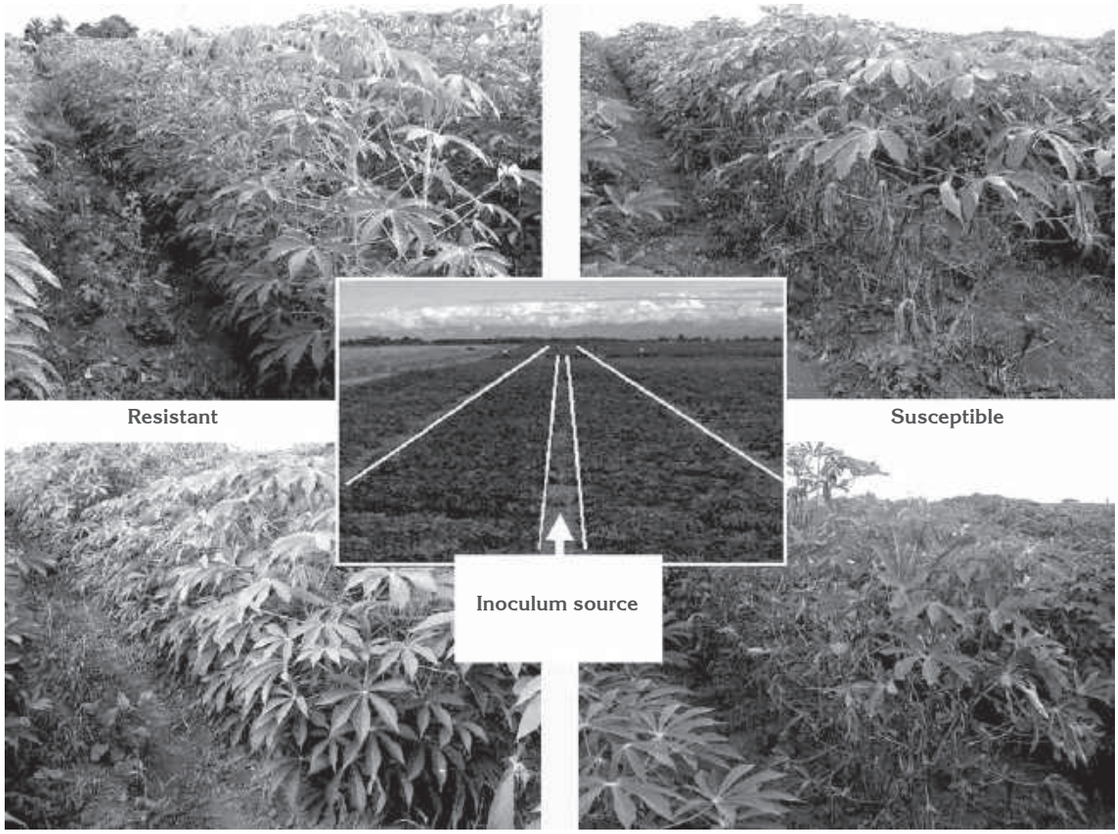


Figure 18-9. Clonal evaluation trial at CORPOICA–La Libertad, Villavicencio, Meta, showing resistance and susceptibility to leaf diseases.

evaluations across several sites, can the environmental effects influencing the expression of low-heritability characteristics be satisfactorily reduced.

At typical harvest time (e.g., February and March in the North Coast) the first two plants in the furrow are harvested to measure dry matter content (Figure 18-10). This characteristic modifies considerably according to the time at which roots are harvested. As a result, it should be measured in the representative season. The remaining plants are left in the field until the rains begin, when they are then harvested and potential yield evaluated in relation to volume of roots produced. Other variables are integrated into a *selection index* (SI), which is processed and analyzed by computer to quickly and efficiently choose the best 200 to 300 of 1500 to 2000 genotypes.

Cuttings from the remaining six plants and from only selected materials are used in *a preliminary yield trial* (PYT), with three replications of plots with 10–12 plants each. In other environments, such as the Eastern Plains or inter-Andean valleys, where the dry period is not so marked, fluctuations in dry matter content are not strong. Hence, all the plants of each furrow are harvested when the crop is usually planted. This permits identification of the best clones while all plants are also used as sources of vegetative seed. Stakes from selected materials and not used in the three replications are planted in a separate nursery to serve as sources of planting material for the next evaluation stages.

The best 30 to 60 clones identified in the PYT are selected to continue on to the next selection stage, known as *advanced yield trials* (AYT). These are carried out, using three replications, but with plots of 20–25 plants. From this stage on, harvests are carried out at the optimal and typical time (e.g., February and March for the North Coast) but only for the 6 to 9 plants in the center of the plot (Figure 18-11). These plants always have all around them other individuals of the same clone and their harvest permits estimating their characteristics more precisely.

The remaining 14 to 16 peripheral plants of each plot that were not harvested are left as sources of planting material, and used at planting time (e.g., May for the North Coast). These plants, located on the outside of each plot, are not evaluated precisely, because they are competing with plants of other varieties that may, for example, be more or less vigorous or more or less aggressive. As these plants are affected by their neighbors, their performance is not representative of the variety. They can nevertheless be used as sources of planting material without problems. This distinction is not made in the earlier stages of the improvement scheme because not enough vegetative seed is available for planting plots with 20 to 25 plants.

Between 5 and 10 of the best genotypes from the AYT are incorporated into *regional trials* (RT), which are planted in various representative sites of each ecoregion and with three replications per site. As, in each year, a new selection cycle is initiated, this means that, in a given region and at the same time, all the selection stages as described above can be found growing. Regional trials are conducted continuously. They include the current best clones in each region and cover the different purposes for which they may be destined (e.g., fresh consumption or industry). They also serve as checks.

Figure 18-10. Clonal evaluation trial at Santo Tomás, Atlántico, Colombia, after the first two plants of each row are harvested to ascertain the correct measurement of dry matter content.

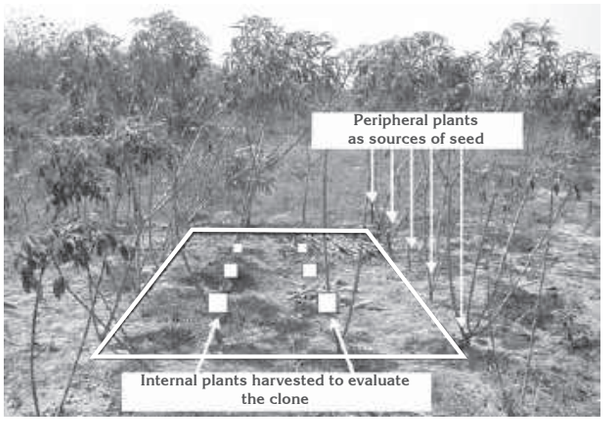


Figure 18-11. Plots with internal plants harvested and the peripheral plants left standing. These latter will be used as sources of planting material.

Those materials that do not surpass the checks are eliminated from the RT after 2 years and new promising genotypes planted after continual identification in the AYT. Ultimately, some new clones will surpass the checks in one or more characteristics in the RT. These materials are then evaluated for eventual release as varieties. This task is typically carried out by CORPOICA.

Results of the last regional trials held in the Caribbean coast, Eastern Plains, and inter-Andean valleys ecoregions

Below, we briefly describe some relevant results of the last selection stages in RT held in different regions of the country. In each case, the calculation of a selection index (SI) is included. This parameter condenses into a single number numerous variables that the breeder assesses. Its use permits even the consideration of variables that may have more weight than others (Baker and Rodgers 1986). The index is currently frequently used, as follows:

$$SI = [\text{fresh-root yield} \times 10] + [\text{dry matter contents} \times 8] + [\text{harvest index} \times 3] + [(-\text{plant type}) \times 3]$$

To remove the problem of the units in which each variable is measured (and which would influence the weight of each in the SI), each variable is standardized, following the statistical formula (Steel and Torrie 1988):

$$(X_i - \mu)/\sigma$$

where,

X_i is the average of a given variety,
μ is the average of all clones, and
σ is its standard deviation.

The coefficients of each term (10 for fresh-root yield, 8 for dry matter content, and 3 for harvest index and plant type) reflect the relative importance of each variable within the SI. These weights are subjective and may vary from one evaluation to another.

The variables included in the SI formula are the most important, but not the only ones to take into account in the selection process. The materials searched for are not only those with high yield potential (fresh-root yield), but also clones with high dry matter content (%) in roots, as this facilitates starch extraction and the drying of chipped cassava destined for animal feed.

The *harvest index* measures the proportion of the plant's total biomass that is represented by roots. This variable is particularly important in initial selection stages when not enough replications are available for each genotype (Kawano et al. 1998).

The fourth factor included in the formula is plant type. This variable is measured by using a visual scale that ranges from 1 (excellent) to 5 (highly undesirable). In this case, low values are preferred, in contrast to the first three variables where the highest values are preferred. Hence, this variable receives a negative sign in the formula.

The SI permits ranking the materials to facilitate final selection. In addition to the variables included in the index, other variables (e.g., resistance to pests or diseases) are reviewed. Sometimes, a material with an excellent SI has to be discarded for other reasons that make them totally unacceptable. In calculating, an SI close to zero describes varieties of average performance. When SI is positive, the varieties are superior (the higher the positive value, the greater will be the material's genetic superiority). Similarly, a negative SI reflects a performance that is below that of the average of the materials evaluated (the higher the negative value, the worse is the material's general performance).

Caribbean Region. Below we present data from three RT conducted in sites of the subhumid coast: Pitalito, Santo Tomás, and Molineros (Table 18-2), all in the Department of Atlántico. In this table, the clones have been ordered according to their rank in relation to the performance of their respective selection indices in each of the three sites. Of the 60 varieties evaluated, the results of the best 15 varieties are presented, as well as some checks that represent materials available to farmers.

Clone M Tai 8, known in Asia as 'Rayong 60', was the result of collaboration between CIAT and the Thai Government (Kawano 1992). Until recently, it was the best material available for industrial purposes and was planted to a large area of the country's Atlantic Coast. Yet, in these regional trials, it occupied tenth place in regional trials, thereby suggesting that a new generation of materials could very soon surpass the excellent performance of M Tai 8. Some of these materials are already being spontaneously disseminated (e.g., CM 4919-1) and others have proven to adapt well to other environments (e.g., SM 1411-5), which stood out in Lower Cauca, in Caucasia, Antioquia).

Table 18-2. Results of the 15 best of 60 genotypes, plus four local checks, from three regional trials conducted at each site in the Department of Atlántico, Colombia. Each trial consisted of three replications with plots of 25 plants each.

Clone	Pitalito					Santo Tomás					Molineros				
	Fresh roots (t/ha)	Dry matter (t/ha)	Dry matter (%)	Sel.[a] index	Rank	Fresh roots (t/ha)	Dry matter (t/ha)	Dry matter (%)	Sel.[a] index	Rank	Fresh roots (t/ha)	Dry matter (t/ha)	Dry matter (%)	Sel.[a] index	Rank
15 best genotypes															
SM 1438- 2	52.8	19.8	37.6	34.9	1	38.7	14.2	36.9	20.3	4	18.4	6.4	34.1	22.7	4
SM 1665- 2	49.9	17.3	34.7	22.9	5	47.7	15.7	32.9	23.9	1	19.2	5.5	28.7	16.3	9
SM 1669- 7	37.4	14.1	37.7	23.2	4	30.3	12.0	39.5	17.5	7	17.2	5.7	32.6	21.1	6
SM 1778-45	41.2	14.4	34.9	14.9	9	36.3	12.5	34.1	16.0	10	16.7	4.9	29.2	12.4	13
CM 4919-1	37.0	13.0	35.1	17.0	7	34.0	12.0	35.2	18.2	5	12.3	3.9	31.9	7.1	21
SM 1669- 5	31.5	11.6	36.9	8.4	16	33.8	12.3	36.5	16.8	8	15.1	4.6	30.9	15.2	10
SM 1411- 5	34.9	12.5	35.4	7.7	17	33.1	11.1	33.5	8.7	18	22.9	7.0	30.5	32.1	2
SM 1565-17	48.6	15.4	31.6	9.9	14	36.3	10.5	29.2	8.3	21	23.3	6.2	26.5	24.3	3
SM 1511- 6	34.9	12.3	35.2	7.5	18	29.9	11.5	38.5	14.6	12	15.8	4.6	29.2	14.7	11
M Tai 8	33.3	11.8	35.6	7.2	20	33.0	11.6	35.1	15.9	11	14.9	4.6	31.1	10.6	16
CM 6119-5	30.6	11.5	37.6	12.6	11	29.1	11.0	37.6	13.2	15	12.7	3.8	29.8	2.6	27
CM 3306-19	42.7	12.7	29.8	-1.5	34	33.4	10.3	30.9	8.7	19	23.8	7.6	32.2	39.0	1
SM 1778-53	34.0	11.9	35.0	3.0	23	23.5	8.5	36.3	1.2	32	19.9	5.8	29.2	21.2	5
SM 1973-25	43.6	16.7	38.1	26.0	3	36.0	13.3	37.6	16.5	9	10.2	2.8	27.4	-15.4	50
M Ven 25	32.0	11.3	35.0	0.7	31	40.8	14.4	35.2	22.3	2	12.2	3.8	30.7	1.3	29
Average	39.0	13.7	35.3	13.0	14.2	34.4	12.1	35.3	14.8	11.6	17.0	5.1	30.3	15.0	13.8
SD	7.1	2.5	2.3	10.2	10.0	5.6	1.8	2.8	6.0	8.3	4.3	1.3	2.0	13.2	13.3
Checks															
CG 1141-1	24.0	8.7	36.2	-7.2	43	22.0	7.6	34.7	-5.7	42	14.7	4.2	29.0	6.5	23
CM 3306-4	30.4	11.1	36.3	1.4	28	20.4	7.5	36.6	-10.7	48	12.2	3.7	30.8	-3.2	36
M Col 1505	28.3	9.6	33.9	-10.7	46	30.0	10.2	34.1	1.9	31	11.2	3.0	27.3	-7.0	41
M Col 2215	21.5	7.9	36.8	-11.8	49	19.8	7.3	36.4	-9.6	47	12.1	4.0	33.4	6.10	24.0
Average	27.2	9.7	35.6	-5.5	39.4	26.6	9.4	35.4	-0.4	34.0	12.5	3.8	30.2	0.7	30.6
SD	4.4	1.5	1.2	6.2	9.3	8.9	3.0	1.1	13.6	19.1	1.3	0.4	2.3	5.9	7.8
All 60 genotypes															
Average	33.7	11.7	34.8	0	30.5	26.8	9.3	34.0	0	30.5	13.1	3.8	29.1	0	30.5
SD	8.3	3.0	2.0	14.7	17.5	8.6	3.0	5.1	18.0	17.5	4.3	1.4	3.0	16.0	17.5

a. Sel. = selection.

Table 18-2 also shows the poor performance of materials in Molineros (average fresh-root yield of the 60 materials was 13.1 t/ha), compared with Pitalito and Santo Tomás (33.7 and 26.8 t/ha, respectively). This was due to a severe drought at the first site, where it had begun 2 months before the rains normally cease. It is precisely because of such variation, which frequently and unpredictably affects agricultural activities, that evaluations should be carried out in different environments and, if possible, for more than one cycle.

Across environments and time, genetically superior materials with stable production are gradually identified. In Molineros, dry matter content (29.1%) was considerably less than at the other sites (34.8% and 34.0%) because the rains began before the normal time. This meant that harvest was carried out when shoot growth was already observed in the plants. Dry matter content in cassava roots declines drastically when growth is reinitiated after prolonged drought, as the plant consumes part of its root reserves.

On average, the 15 best clones yielded across the three sites 10.3 t/ha of dry matter, while the averages for the total of the three experiments and for the checks were, respectively, 8.3 and 7.6 t/ha. This reflects the crop's enormous potential for genetic improvement. Even in advanced selection stages, not all materials were satisfactory. A fundamental aspect of this stage is the expansion to include numerous sites. We emphasize that when these materials are transferred to farmers' fields, productivity is usually reduced because of numerous factors, many of which cannot not be controlled by the farmers.

In these advanced stages of selection, when the number of materials to select has been considerably reduced, evaluations are started for characteristics that can be measured only in a limited number of progenies. For example, trials may begin on culinary quality and cyanogenic glucoside content to determine whether the cassava is "bitter" or "sweet". Thus, when the regional trials are finished, the excellent agronomic performance and stable productivity of the genotypes can also be assured, as can be the information on different characteristics that will help define the potential use of these materials (e.g., starch production, energy source for animal feed, and fresh-root market).

Another example that illustrates the importance of evaluating materials in different environments is that of the clone SM 1433-4. This material was included among the 60 described in Table 18-2 (but its performance is not shown as it was not among the best 15). This clone performed well under subhumid Caribbean conditions, where reduced precipitations limited the development of bacterial blight (*Xanthomonas axonopodis* pv. *manihotis*). In wetter conditions, however, this pathogen spreads more easily, as happened in the Departments of Sucre and Córdoba, where SM 1433-4 proved to be excessively susceptible to this disease.

Eastern Plains. The materials adapted to this environment characteristically tolerate acid soils. Bacterial blight and superelongation (caused by the fungus *Sphaceloma manihoticola*) are the principal diseases that affect cassava in this type of environment. Many of the materials developed here have performed very well in other regions of the country such as Quindío, Antioquia, Huila, and Tolima.

Table 18-3 presents the averages of three RT conducted in Restrepo, Matazul, and La Libertad, all in the Department of Meta. Because of the effects of genotype-by-environment interaction (i.e., differential performance of genotypes in different environments), identifying materials that show excellent development in the three sites was not readily possible. However, CM 6438-14 (released in 2001) and CM 6740-7 (CORPOICA–Reina) performed very well, surpassing the check material ('Brasilera'). Other clones also performed well in this evaluation, as in previous years (SM 1363-11, SM 1821-7, and SM 1143-18). Clone CM 4574-7 also performed well and showed resistance to root rots.

Clones CM 4574-7 and CM 6438-14 are particularly adapted to savanna conditions, while clone CM 6740-7 adapts better to conditions that are not as extreme such as found at "La Libertad" Experiment Station (Villavicencio), and under the conditions of the Piedemonte, a hilly region lying between the Eastern Cordillera of the Andes and the Eastern Plains. We point out that, except for CM 6438-14, these experimental clones are among those materials selected to participate as parents in crosses to be carried out during year 2000.

During 2001, CORPOICA released the clone CM 6438-14, with a name that honors the memory of farmer Juan Vergara, who constantly promoted the cassava crop in the Orinoquia and shared his experience and progressive vision with the team in charge of this crop's genetic improvement. CM 6438-14 (Figure 18-12) has high levels of resistance to bacterial

Table 18-3. Average of the most relevant variables of clones evaluated in three regional trials for the Orinoquian Region (Restrepo, CORPOICA–La Libertad, and Matazul, all in the Department of Meta). Order is based on the selection index across the three environments.

Clone	Fresh-root yield (t/ha)	Dry matter content (%)	Dry matter yield (t/ha)	Plant type (1–5)	Harvest index (0–1)
SM 1363-11	24.44	36.61	8.90	3.00	0.51
SM 1152-13	23.89	35.34	8.42	4.00	0.54
SM 1794-18	22.19	36.14	8.09	3.33	0.50
CM 6438-14	20.59	35.90	7.49	3.67	0.52
SM 1821-7	23.27	33.88	7.98	3.00	0.53
SM 1143-18	21.88	32.18	7.11	4.00	0.59
SM 1854-23	22.10	32.28	7.22	3.67	0.58
M Bra 502	21.54	33.91	7.30	3.33	0.49
CM 6921- 3	18.49	34.84	6.54	4.33	0.48
CM 6740-7	18.73	34.19	6.42	3.33	0.55
Brasilera	18.80	33.90	6.49	3.67	0.52
CM 4574-7	19.38	34.03	6.58	3.00	0.53
SM 1483-1	22.93	32.07	7.42	2.67	0.48
SM 2219-11	21.64	31.48	6.84	3.00	0.53
CM 6975-14	19.14	34.80	6.70	2.00	0.47
SM 1241-12	18.89	31.08	5.82	3.67	0.58
CM 523- 7	14.54	34.03	5.09	4.00	0.54
SM 1862-25	17.07	33.31	5.56	3.33	0.51
SM 1697-1	20.32	31.09	6.46	3.33	0.48
CM 7052- 3	19.66	30.52	6.08	3.00	0.52
SM 1812-69	18.02	30.72	5.71	3.33	0.56
SM 1694-2	14.41	34.21	4.92	4.00	0.44
SM 1565-15	17.25	33.09	5.82	2.67	0.47
CM 2177- 2	16.27	32.30	5.28	4.00	0.45
SM 1674-1	14.91	32.39	5.02	3.67	0.53
SM 1859-26	19.10	30.14	5.81	2.33	0.54
CM 7073- 7	14.10	33.45	4.74	3.00	0.47
CM 5306- 8	14.85	32.44	4.76	3.33	0.42
SM 2068-3	17.01	30.65	5.27	2.00	0.45
SM 1881-17	13.86	28.91	4.11	3.33	0.42
Minimum	13.86	28.91	4.11	2.00	0.42
Maximum	24.44	36.61	8.90	4.33	0.59
Average	18.98	33.00	6.33	3.30	0.51
SD	3.10	1.91	1.19	0.58	0.04

blight and superelongation, and can thus present large volumes of young foliage at harvest.

Clone CM 6740-7 or 'Reina' (Figure 18-13) demonstrates its extraordinary potential, both for fresh roots and dry matter. In fact, being unquestionably superior, this material replaces the last cultivar released in the region (CM 523-7 or 'Catumare'). Furthermore, 'Brasilera' had been used until now for the production of pre-cooked cassava croquettes. However, CM 6740-7 has the advantage of a higher dry matter content than 'Brasilera' and a higher yield potential. 'Reina' will serve not only as animal feed but also for the food-processing industry.

Inter-Andean valleys. This ecosystem shares many characteristics with the Eastern Plains. Some of their sites present acid soils and share the same typical diseases (bacterial blight and superelongation). Unsurprisingly, therefore, clone CM 6740-7 is also an outstanding performer this region. For this type of environment, high dry matter yield is a significant

Figure 18-12. The new cultivar for the Orinoquian Region (CM 6438-14). Its name honors the memory of local farmer Juan Vergara Carulla.

Figure 18-13. Clone 6740-7 or 'CORPOICA–Reina' was recently released for the Colombian Orinoquia but has excellent adaptation to other regions of the country.

criterion for selection (clone SM 1219-9 has shown excellent potential). Other materials are also being looked at for good culinary quality (landraces M Per 183 and M Bra 383 not only have high yield potential, but also excellent culinary quality and characteristics for the food-processing industry).

Table 18-4 presents the yields of the best clones in the RT held at CIAT–Palmira and harvested in May 2000. On average, the evaluated clones yielded more than 7 t/ha of dry matter. The best 10 clones had dry matter yields of almost 10 tons (9.77 t/ha), whereas the five checks (including variety Catumare or CM 523-7) had average dry matter yields of 6.35 t/ha.

Table 18-5 presents the results of four consecutive harvests carried out on varieties adapted to this ecosystem, in the Municipality of Jamundí, south of the City of Cali. The first harvest was carried out 7 months after stakes were planted. Even at that time, the crop's general performance was satisfactory overall (average of 11.2 t/ha of dry matter).

The consecutive harvests helped identify clones with high-yielding potential in early development. Being a perennial plant, cassava can be harvested at any time without reference to reasons of physiology or senescence to determine optimal time (except for dry matter content, which is lower when the plant renews growth after an adverse condition such as drought).

Many farmers find it strategic to have early and late varieties, so that root production is more or less continuous. During these harvests, data on the production of young foliage were also taken. On average, this site presented small variations over time (fluctuating around 8 t/ha), but, depending on variety, foliage production ranged between 6 and 14 t/ha when roots were harvested. This information is also useful for determining optimal harvest times for each variety, taking into account the production of both roots and foliage.

Variety dissemination and release

When a material demonstrates genetic superiority across numerous environments and over several years, it will be profiled as a candidate for official release by institutions accredited for this purpose in the country. In Colombia, first the Colombian Institute of Agriculture (ICA), and later CORPOICA, traditionally fulfilled this important role. Hence, close collaboration exists between CIAT and these institutions.

Two modalities exist for the final evaluation of materials and to confirm their genetic advantages. The traditional scheme involves planting trials with replications over several years at different sites to confirm the new varieties' superiority. In these cases, checks are always planted that adequately represent the best clones available to farmers at that time. A new variety must be superior to the checks in one or more characteristics and must demonstrate sufficient stability across variable environmental conditions. Hence, new varieties can only be officially released after having been evaluated for several years and in different environments, thereby determining its stability and tolerance or resistance to different production constraints, whether of biotic or abiotic origin.

Table 18-4. Results of the 10 best of 48 varieties evaluated in the regional trial conducted at CIAT–Palmira, Colombia.

Clone	Yield (t/ha)		Dry matter (%)	Evaluation foliage (1–5)	Harvest index	Selection index
	Fresh roots	Dry matter				
10 best genotypes						
CM 8370-11	31.89	13.07	41.00	2.00	0.63	13.60
SM 1855-15	23.67	10.00	42.25	2.00	0.65	9.70
SM 1602-13	32.19	12.10	37.60	2.67	0.61	9.01
SM 1636-24	27.93	10.95	39.20	3.00	0.59	6.38
SM 1741-1	19.30	8.01	41.50	2.00	0.60	5.84
SM 2141-1	19.59	8.62	44.00	2.33	0.56	5.71
SM 1557-17	21.52	8.70	40.45	2.33	0.61	5.33
SM 1871-33	23.56	9.54	40.50	3.00	0.58	4.42
CM 3306-4	18.07	7.94	43.95	3.00	0.62	3.95
CM 8370-10	20.81	8.72	41.90	2.67	0.54	3.95
Average	23.85	9.77	41.24	2.50	0.60	6.79
SD	5.14	1.76	1.98	0.42	0.03	3.09
Checks						
CM 523-7	22.41	9.36	41.75	3.00	0.63	5.27
M Bra 12	18.19	6.66	36.65	3.00	0.58	-1.35
M Per 183	19.78	6.78	34.30	3.00	0.60	-1.49
M Col 1505	14.19	5.45	38.45	3.00	0.53	-3.22
M Col 1468	9.89	3.48	35.20	4.00	0.51	-9.75
Average	16.89	6.35	37.27	3.20	0.57	-2.11
SD	4.92	2.14	2.96	0.45	0.05	5.36
All 48 genotypes						
Average	18.17	7.03	38.50	2.91	0.56	0
SD	4.93	2.10	3.10	0.41	0.07	5.17

The second way to identify and validate the genetic superiority of materials is through *participatory research*. With this methodology, segregating materials are delivered to farmers who will then conduct the final selection of materials according to their own selection criteria. This system has the great advantage that, once a variety is selected by a farmer (or group of farmers), it would then not need promoting, as it will usually be immediately adopted by the farmers. It also has the advantage of being more specific to certain more uniform environments (e.g., for a given village district or municipality) than the traditional improvement scheme, which targets broader environments (e.g., the Caribbean or Orinoquian Region).

Whatever the improvement system used, the stages described in this chapter are always included. First, parents with desired attributes for exploitation should be selected. The parents are then crossed among themselves to produce a large number of segregating progenies. Each seed resulting from pollination constitutes a new genetic entity, which means that crossing produces great genetic variability. The more costly and slower activity is to select genetically superior materials from the wide variability generated by the crosses. Current technological developments enable selection to be more efficient and effective in terms of the use of resources at hand. Ultimately, of the thousands of crosses made every year, only some clones will be identified by CIAT as being superior. Of these, only some will be released as varieties by CORPOICA.

Biotechnology

The second half of the 20th century has been witness to a dizzying development of technology in the area of what is now known as "biotechnology". Perhaps the most significant characteristic of biology is that the genetic code is universal. This means that the information codified in a bacterium, for example, can

Table 18-5. Results of four successive harvests of crops of 15 elite clones at 7, 8, 9, and 10 months old. Data are from local plots in the Municipality of Jamundí (Valle del Cauca, Colombia).

Clone	Age of crop in months												Average
	7			8			9			10			
	Fresh-root yield	Dry matter content		Fresh-root yield	Dry matter content		Fresh-root yield	Dry matter content		Fresh-root yield	Dry matter content		
	(t/ha)	(%)	(t/ha)	(t/ha)	(%)	(t/ha)	(t/ha)	(%)	(t/ha)	(t/ha)	(%)	(t/ha)	
CM 7951-5	40.5	36.5	14.8	41.1	34.8	14.3	57.3	36.3	20.8	63.0	39.8	25.0	18.73
SM 1741-1	45.1	36.7	16.5	35.3	31.2	10.8	38.3	37.0	14.2	44.4	38.8	17.2	14.68
SM 1460-1	38.1	34.1	13.0	32.8	34.5	11.3	38.1	35.0	13.3	46.5	35.2	16.4	13.50
SM 1557-17	37.0	34.8	12.9	39.8	33.0	13.1	36.6	35.4	13.0	41.5	34.6	14.3	13.33
SM 909-25	33.8	34.7	11.7	34.8	30.9	10.5	42.5	35.9	15.2	39.4	37.8	14.9	13.08
M Bra 383	33.9	28.5	9.7	38.4	34.9	13.4	34.5	36.8	12.7	41.3	38.7	16.0	12.95
SM 1219-9	34.5	34.0	11.7	44.4	32.3	14.3	33.5	32.4	10.8	39.8	36.3	14.4	12.80
SM 1543-16	32.3	34.8	11.2	26.8	33.2	9.0	36.0	34.9	12.6	49.3	35.8	17.6	12.60
CM 7514-7	29.1	39.1	11.4	29.6	38.5	11.4	28.4	40.7	11.5	36.3	41.2	14.9	12.30
CM 3306-4	35.1	37.4	13.1	29.8	36.6	10.9	30.5	38.0	11.6	34.8	39.1	13.6	12.30
M Per 183	33.9	28.5	9.7	38.4	34.9	13.4	36.0	30.1	10.8	50.8	30.1	15.2	12.28
CM 6740-7	23.9	32.6	7.8	37.5	33.4	12.5	34.0	34.4	11.7	29.1	36.3	10.6	10.65
CM 523-7	29.6	34.4	10.2	33.0	34.0	11.2	36.1	35.7	12.9	23.8	34.8	8.2	10.63
CM 849-1	19.9	33.9	6.7	25.1	32.5	8.3	21.3	33.8	7.2	22.0	35.5	7.7	7.48
SM 653-14	23.9	32.6	7.8	33.9	16.9	5.8	22.5	35.0	7.8	19.8	36.4	7.3	7.18
Average	32.2	34.8	11.2	33.6	33.4	11.2	35.0	35.4	12.4	38.8	36.7	14.2	12.30
Minimum	19.9	28.5	6.7	25.1	16.9	5.8	21.3	30.1	7.2	19.8	30.1	7.3	7.18
Maximum	45.1	39.1	16.5	44.4	38.5	14.3	57.3	40.7	20.8	63.0	41.2	25.0	18.73

be interpreted by most living organisms of the planet, because all use the same code. This has major implications for agriculture.

First, if a gene of economic interest exists in any living organism, this gene can be ultimately identified, multiplied, and transferred to a crop where it can be expressed in the same way as it did in its natural environment. This is the case of genes for resistance to insects or herbicides. Second, the technologies developed for one crop can serve for another crop. Hence, cassava has benefited enormously from all the knowledge generated mainly for cereals (e.g., rice, wheat, and maize) and legumes (e.g., soybeans and beans).

The tools developed for biotechnology may be grouped into three large categories, each of which has specific uses: tissue culture, molecular markers, and genetic transformation. This is a very dynamic field of research and a detailed description of protocols and updated results goes beyond the purpose of this publication.

Changes in the Implementation of the Cassava Genetic Improvement Scheme

From the viewpoint of quantitative genetics, the cassava improvement scheme described earlier in this chapter is essentially based on the selection of numerous segregating clones derived from a cross between two progenitors that were selected for a diversity of reasons and purposes. This selection is based on phenotypic characteristics, the variance (σ^2_P) of which can be separated as follows:

$$\sigma^2_P = \sigma^2_A + \sigma^2_D + \sigma^2_{Ep} + \sigma^2_E$$

where,

σ^2_A is the variance due to additive genetic effects,
σ^2_D is the variance due to the effects of genetic dominance,
σ^2_{Ep} is the variance due to epistatic genetic effects
σ^2_E is the variance due to environmental effects (experimental error), as well as all the components of the genotype-by-environment interaction.

Only the additive fraction of the variability observed (on which selection of genotypes is based) can be taken advantage of by the present system of recurrent selection. Both σ^2_D and σ^2_E introduce a "distortion" because, even though they influence the performance of a determined genotype, their effects cannot be transmitted to later generations, unlike genes that have additive effects.

Non-additive components of genetic variance (σ^2_D and σ^2_{Ep}) for the main characteristics of cassava have been demonstrated to be highly significant (Cach et al. 2005, 2006; Calle et al. 2005; Jaramillo et al. 2005; Pérez et al. 2005a, 2005b). Hence, whatever method increases the proportion of additive effects in the selection process will greatly increase its efficiency. Another equally valid alternative is to implement an improvement method that can also take advantage of the effects of dominance and epistasis. Some alternatives for improving cassava that may be implemented in the near future are presented below.

Improvement schemes that include self-fertilizing stages offer some advantages that have been reported in the literature. With successive self-fertilizations, different loci in the genome are obliged to progressively reach the stage of homozygosis. This is prejudicial for individual performance (particularly for cross-pollinated crops such as cassava or maize), because vigor and productivity will gradually diminish. However, this process has the advantage of eliminating deleterious or undesirable genes from the population that remain "hidden" because of the generalized heterozygosity of these types of crops in their natural state. The totality of effects of these undesirable genes is known as the "genetic load", which is estimated to be prominent for cassava. However, as progress is made in the degree of inbreeding of segregating populations, the proportion of total phenotypic variance that is additive variance increases (Hallauer and Miranda 1988).

Table 18-6 illustrates the effects of successive self-fertilizations in the distribution of genetic variance. The obvious result is that, with total homozygosis, σ^2_D is eliminated as a component of phenotypic variance. Another obvious result is that the additive effects present in the F1 generation (full-sib family) now has double the influence than in the original situation. From the genetic viewpoint, a homozygotic line is stable (on using it as progenitor, the genetic segregation mentioned previously does not occur), in contrast to what happens with hybrid F1, which, even if it could reproduce vegetatively, its use as a progenitor is affected because the genetic effects of dominance cannot be transmitted to later generations.

The industry of maize hybrids is based precisely on the design of the progenitors, which, on combining, specifically produce a material of excellent performance

Table 18-6. Distribution of genetic variance between and within families when increasing inbreeding through successive self-pollinations.

Family	Proportion of homozygosis	Between families		Within families	
		σ^2_A	σ^2_D	σ^2_A	σ^2_D
Full siblings	0	1/2	1/4	1/2	3/4
F_2	50.00	1	1/4	1/2	1/2
F_3	75.00	3/2	3/16	1/4	1/4
F_4	87.50	7/4	7/64	1/8	1/8
F_∞	100.00	2	0	0	0

in the field. The process of self-fertilization of cassava thus offers two very attractive advantages: (1) it contributes to the automatic reduction of the genetic load in populations that have been improved in part, and (2) it permits the design of parents for producing more competitive hybrids. Current improvement concentrates on producing and identifying good hybrids from selected progenitors. In the future, such emphasis will produce individuals especially designed to be optimal progenitors and thus generate outstanding hybrids. The great advantage is that this process guarantees a more sustained genetic progress, which is quick, at least from the theoretical viewpoint.

Now, some problems exist that explain why, so far, these ideas have not been implemented, principally:

a. The genetic load in cassava is so large that reaching high degrees of homozygosis is difficult with plants that can survive. Although this is currently a limitation, it also justifies the urgent need to begin cleaning out the genetic load from the crop as soon as possible. We point out that tolerance of inbreeding can be increased in cross-pollinated crops, as was shown irrefutably for maize. No scientific reason exists to assume that the same cannot be achieved for cassava (Contreras R et al. 2009).

b. Because of the cassava plant's peculiar method of reproduction, self-fertilization can be greatly delayed. To achieve a high degree of homozygosis, at least 4 or 5 successive self-fertilizations are needed. In cassava, this requires about 10 years. However, a procedure exists that is widely used for other crops whereby totally homozygotic materials, known as *doubled haploids* can be immediately obtained (Griffing 1975). This procedure normally uses gametophytic tissue, which is subjected to tissue culture that is initially haploid and becomes doubled haploid through the automatic or induced duplication of the number of chromosomes (CIAT 2009).

For the reasons given above, changes are planned for the way the cassava genetic improvement project at CIAT will be carried out in the future. Below, we briefly describe the scheme that may be implemented over the next few years. We emphasize that this is only at a preliminary phase of definition and many changes will surely be introduced, depending on how the crop responds at different stages.

Development of homozygous progenitors

Important efforts are underway to develop a protocol for the production of doubled haploids through approaches such as microspore, anther, or ovule culture or through wide crosses with *Ricinus communis*.

Taking advantage of general combining ability

By definition, to eliminate deleterious genes in each segregating population, its characteristics as progenitor are improved, as the deleterious genes can no longer be transmitted to later generations. Genetic designs exist for improving, in a systematic and efficient way, genes with additive effects, those that, in an integral way, define the general combining ability of each individual or population.

Defining heterotic groups and taking advantage of specific combining ability

Once the genetic load has been successfully reduced in the populations, improvement can start by focusing on producing progenitors that mutually complement each other from the genetic viewpoint. This implies the start of producing materials that, when crossed with each other, will produce exceptional hybrids. This is precisely what occurs when parents of commercial maize hybrids are crossed; the parents have been designed and gradually improved to produce, each time, more productive hybrids with a more stable performance. This process inevitably derives from the definition of heterotic groups, that is, groups that characteristically demonstrate good hybrid vigor when crossed with each other.

For cassava, because the presence of heterotic groups has not yet been determined, a reasonable way to begin would be to define the genetic distances between the lines produced during the last stage described above. Once the heterotic groups are defined, we can then begin to effect a selection directed towards taking advantage of not only the additive effects (σ^2_A), but also dominance (σ^2_D) and epistasis (σ^2_{Ep}). These latter effects are also known as *specific combining ability*, and the improvement method that can exploit them efficiently is known as *reciprocal recurrent selection* (Hallauer and Miranda 1988).

Major emphases on qualitative aspects of the cassava root for different types of consumption

Recently, notable advances have been made to generate cassava with distinct qualitative characteristics. For the starch industry, mutations have been identified, whereby the starch does not contain amylose ("*waxy*" starch) or it has small granules and higher than normal contents of amylose (Ceballos et al. 2007b, 2008). Typical characteristics of normal cassava starch have also been studied in detail (Sánchez et al. 2009).

In the ethanol industry, the existence of "sugary" cassava has been known for a long time. This cassava accumulates sugar polymers simpler than starch. In 2004, Carvalho and co-workers carried out a detailed description of this type of material, which was also identified recently by the cassava improvement project at CIAT. The costs of converting this type of root to ethanol would be considerably lower, but how much energy per hectare this type of cassava could produce is still not clear.

In terms of nutritional quality, CIAT first characterized (Chávez et al. 2005) and then triplicated the original levels of carotenoids in roots through a system of rapid recycling of materials (CIAT 2009). In 2008, materials with more than 18 μg of total carotenoids per gram of fresh root had already been obtained. As well as nutritional advantages, high carotenoid contents offer tolerance of postharvest physiological deterioration (Sánchez et al. 2005; CIAT 2008). Variability indices exist for protein contents in roots, even though this type of research requires more precise quantification methods (Ceballos et al. 2006).

References

Allard RW. 1960. Principles of plant breeding. John Wiley & Sons, New York, USA. 485 p.

Baker RJ; Rodgers D. 1986. Selection indices in plant breeding. CRC Press, Boca Raton, FL, USA. 218 p.

Beebe S; González AV; Rengifo J. 2000. Research on trace minerals in the common bean. Food Nutr Bull 21(4):387–391.

Bellotti AC; Smith L; Lapointe SL. 1999. Recent advances in cassava pest management. Ann Rev Entomol (USA) 44:343–370.

Blair MW; Fregene MA; Beebe SE; Ceballos H. 2007. Marker-assisted selection in common beans and cassava. In: Guimarães EP; Ruane J; Scherf BD; Sonnino A; Dargie JD, eds. Marker-assisted selection: current status and future perspectives in crops, livestock, forestry and fish. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. p 81–115.

Cach NT; Pérez JC; Lenis JI; Calle F; Morante N; Ceballos H. 2005. Epistasis in the expression of relevant traits in cassava (*Manihot esculenta* Crantz) for subhumid conditions. J Hered 96(5):586–592.

Cach NT; Lenis JI; Pérez JC; Morante N; Calle F; Ceballos H. 2006. Inheritance of relevant traits in cassava (*Manihot esculenta* Crantz) for subhumid conditions. Plant Breed 125(2):177–182.

Calle F; Pérez JC; Gaitán W; Morante N; Ceballos H; Llano G; Álvarez E. 2005. Diallel inheritance of relevant traits in cassava (*Manihot esculenta* Crantz) adapted to acid-soil savannas. Euphytica 144(1-2):177–186.

Carvalho LJCB; de Souza CRB; Cascardo JCM; Junior CB; Campos L. 2004. Identification and characterization of a novel cassava (*Manihot esculenta* Crantz) clone with high free sugar content and novel starch. Plant Mol Biol 56:643–659.

Ceballos H; Iglesias CA; Pérez JC; Dixon AGO. 2004. Cassava breeding: opportunities and challenges. Plant Mol Biol 56:503–516.

Ceballos H; Sánchez T; Chávez AL; Iglesias C; Debouck D; Mafla G; Tohme T. 2006. Variation in crude protein content in cassava (*Manihot esculenta* Crantz) roots. J Food Compos Anal 19:589–593.

Ceballos H; Fregene M; Pérez JC; Morante N; Calle F. 2007a. Cassava genetic improvement. In: Kang MS; Priyadarshan PM, eds. Breeding major food staples. Blackwell Publishing, Ames, IA, USA. p 365–391.

Ceballos H; Sánchez T; Morante N; Fregene M; Dufour D; Smith AM; Denyer K; Pérez JC; Calle F; Mestres C. 2007b. Discovery of an amylose-free starch mutant in cassava (*Manihot esculenta* Crantz). J Agric Food Chem 55(18):7469–7476.

Ceballos H; Sánchez T; Denyer K; Tofiño AP; Rosero EA; Dufour D; Smith A; Morante N; Pérez JC; Fahy B. 2008. Induction and identification of a small-granule, high-amylose mutant in cassava (*Manihot esculenta* Crantz). J Agric Food Chem 56(16):7215–7222.

Chávez AL; Bedoya JM; Sánchez T; Iglesias C; Ceballos H; Roca W. 2000. Iron, carotene and ascorbic acid in cassava roots and leaves. Food Nutr Bull 21(4): 410–413.

Chávez AL; Sánchez T; Jaramillo G; Bedoya JM; Echeverry J; Bolaños EA; Ceballos H; Iglesias CA. 2005. Variation of quality traits in cassava roots evaluated in landraces and improved clones. Euphytica 143:125–133.

CIAT (Centro Internacional de Agricultura Tropical). 1991. Participación de los productores en la selección de variedades de yuca. In: Hernández R, LA, ed. Proc workshop held at CIAT, Cali, September 1991. Working Document No. 99. Cali, Colombia. 112 p.

CIAT (Centro Internacional de Agricultura Tropical). 2008. Improved cassava for the developing world–Annual report 2007. Cali, Colombia.

CIAT (Centro Internacional de Agricultura Tropical). 2009. Improved cassava for the developing world–Annual report 2008. Cali, Colombia.

Cock J. 1985. Cassava: new potential for a neglected crop. Westview Press, Boulder, CO, USA. 240 p.

CONPES (Consejo Nacional de Política Económica y Social). 2000. Documento CONPES 3076. Bogotá, Colombia.

Contreras R, M; Pérez JC; Ceballos H; Baena D; Morante N; Calle F. 2009. Analysis of inbreeding depression in eight S_1 cassava families. Crop Sci 49:543–548.

Davis JP; Supatcharee N; Khandelwal RL; Chibbar RN. 2003. Synthesis of novel starches *in planta*: opportunities and challenges. Starch/Stärke 55:107–120.

Dudley JW; Lambert RJ; Alexander DE. 1974. Seventy generations of selection for oil and protein concentration in the maize kernel. In: Dudley JW, ed. Seventy generations of selection for oil and protein in maize. Crop Science Society of America, Madison, WI, USA. 212 p.

Echeverri J; Chávez AL; Sánchez T; Calle F; Ceballos H; Roca W. 2001. Exploring the gentic potential to improve micronutrient content of cassava. Paper presented at the XX IVACG Meeting, Hanoi, Vietnam, 12–15 Feb 2001.

Ellis RP; Cochrane MP; Dale MFB; Duffus CM; Lynn A; Morrison IM; Prentice RDM; Swanston JS; Tiller SA. 1998. Starch production and industrial uses. J Sci Food Agric 77:289–311.

Fehr WR, ed. 1987. Genetic contributions to yield gains of five mayor crop plants. Crop Science Society of America, Madison, WI, USA. 101 p.

García L, R; Herrera J. 1998. Producción de leche a base de pastos y suplementación con forraje de planta integral de yuca (*Manihot esculenta*) o de boniato (*Ipomoea batata*). Rev Cuba Cienc Agríc 32(1):29–32.

Griffing B. 1975. Efficiency changes due to use of doubled-haploids in recurrent selection methods. Theor Appl Genet 46:367–386.

Hallauer A; Miranda F. 1988. Quantitative genetics in maize breeding. 2nd ed. Iowa State Univ. Press, Ames, IA, USA. 500 P.

IITA (International Institute of Tropical Agriculture). 1979. Annual report. Ibadan, Nigeria.

Jaramillo G; Morante N; Pérez JC; Calle F; Ceballos H; Arias B; Bellotti AC. 2005. Diallel analysis in cassava adapted to the mid-altitude valleys environment. Crop Sci 45:1058–1063.

Jennings DL. 1970. Cassava in Africa. Field Crop Abstr 23(3):271–275.

Kawano K. 1978. Genetic improvement of cassava (*Manihot esculenta* Crantz) for productivity. Tropical Agriculture Research No. 11. Ministry of Agriculture and Forestry, Yatabe, Tsukuba, Ibaraki, Japan. p 21.

Kawano K. 1992. CIAT cassava germplasm and its role in cassava varietal improvement in Asia. In: Howeler RH, ed. Regional cassava breeding, agronomy and utilization research in Asia. 3rd symposium, held in Malang, Indonesia, 1990. Regional Cassava Program for Asia of the Centro Internacional de Agricultura Tropical. p 170–184.

Kawano K. 2003. Thirty years of cassava breeding for productivity—biological and social factors for success. Crop Sci 43:1325–1335.

Kawano K; Narintaraporn K; Narintaraporn P; Sarakarn S; Limsila A; Limsila J; Suparhan D; Sarawat V; Watananonta W. 1998. Yield improvement in a multistage breeding program for cassava. Crop Sci 38(2):325–332.

Kleese RA. 2000. Designing crops for added value: a vision, a mission. In: Murphy CF; Peterson DM, eds. Designing crops for added value. American Society of Agronomy, Madison, WI, USA. 267 p.

Martin FW; Ruberte R. 1976. Germination and longevity of the cassava seeds. Trop Root Tuber Crops Newsl 9:54–56.

Morante N; Moreno X; Pérez JC; Calle F; Lenis JI; Ortega E; Jaramillo G; Ceballos H. 2005. Precision of selection in early stages of cassava genetic improvement. J Root Crops 31:81–92.

Munyikwa TRI. 1997. Isolation and characterisation of starch biosynthesis genes from cassava (*Manihot esculenta* Crantz). Thesis. Wageningen Agricultural University, Wageningen, Netherlands. 128 p.

Pérez JC; Ceballos H; Jaramillo G; Morante N; Calle F; Arias B; Bellotti AC. 2005a. Epistasis in cassava adapted to mid-altitude valley environments. Crop Sci 45:1491–1496.

Pérez JC; Ceballos H; Calle C; Morante N; Gaitán W; Llano G; Álvarez E. 2005b. Within-family genetic variation and epistasis in cassava (*Manihot esculenta* Crantz) adapted to the acid-soils environment. Euphytica 145(1–2):77–85.

Sánchez T; Chávez AL; Ceballos H; Rodríguez-Amaya DB; Nestel P; Ishitami M. 2005. Reduction or delay of post-harvest physiological deterioration in cassava roots with higher carotenoid content. J Sci Food Agric 86(4):634–639.

Sánchez T; Mafla G; Morante N; Ceballos H; Dufour D; Calle F; Moreno X; Pérez JC; Debouck D. 2009. Screening of starch quality traits in cassava (*Manihot esculenta* Crantz). Starch/Stärke 61:12–19.

Steel RGD; Torrie JM. 1988. Bioestadística: principios y procedimientos. McGraw-Hill/Interamericana de México, S.A. de C.V., Mexico. 622 p.

Vasal SK. 2000. The quality protein maize story. Food Nutr Bull 21(4):445–450.

Wright CE. 1965. Field plans for a systematically designed polycross. Res Exp Rec Minist Agric North Irel 14:31–41.

Ye XS; Al-Babili A; Klöti J; Zhang P; Lucca P; Bayer IP. 2000. Engineering the provitamin A (ß-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. Science 287(5451):303–305.

CHAPTER 19

Methodology for Hardening Large Numbers of *In Vitro* Cassava Plants

Roberto J. Segovia[1], *Armando Bedoya*[2], *William Triviño*[3], *Hernán Ceballos*[4], *Martin Fregene*[5], *Guillermo Gálvez*[6], *and Bernardo Ospina*[7]

Introduction

Tissue culture, a technique used to micropropagate plants, has been successfully applied in cassava (*Manihot esculenta* Crantz) for the massive production of disease-free *in vitro* plants, increasing productivity and, in certain cases, improving longevity. *In vitro* micropropagation is successfully used to produce cassava plantlets free of pathogens associated to diseases such as frogskin, cassava mosaic, and bacterial blight. Traditional micropropagation has low multiplication rates, which can be improved by using more efficient multiplication systems such as the automated temporary immersion device known as RITA® or other automated temporary immersion systems (ATIS)[8].

After 6 to 11 months in sterilized rooms under artificial conditions of light, temperature, moisture, and nutrients, the plantlets produced by such systems are like test-tube babies—weak and unadapted. As a result, they need to undergo a stage of acclimatization or hardening before they can be transferred to their final site in the field. In cassava, this process is very delicate, constituting a bottleneck in the massive production of cassava planting materials by tissue culture techniques.

1. Agronomist, formerly of Greenhouse Management, CIAT, Cali, Colombia. E-mail: rjsssegovia@gmail.com
2. Field technician, formerly of CLAYUCA, Cali, Colombia.
3. Field technician, CLAYUCA.
4. Breeder, Cassava Program, CIAT. E-mail: h.ceballos@cgiar.org
5. Plant geneticist and molecular breeder. Director, Bio Cassava Plus Program. Danforth Center, St. Louis, USA. E-mail: MFregene@danforthcenter.org
6. Virologist, formerly of CIAT-Biotecol, Cali, Colombia.
7. Executive Director, CLAYUCA. E-mail: b.ospina@cgiar.org
8. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Hardening massive numbers of *in vitro* cassava plants inevitably incurs in **loss** of plantlets, mainly when these are moved from the artificial to the natural environment (soil) and must adapt to new microclimatic conditions. Where the transfer is not carried out using the appropriate technology, the percentage of loss is very high (between 50%–95%), which affects the crop's agronomic progress while increasing the costs of implementing this alternative technology. It also discourages progressive farmers who would otherwise rapidly and safely produce disease-free planting materials or massively produce a new promising variety over a short period of time.

Other drawbacks of the acclimatization process are the cost and size of the facilities needed, such as greenhouses and screenhouses. These two factors reduce the feasibility of applying this new technology—and other similar ones—which could have a significant impact on agricultural production.

Researchers from the Latin American and Caribbean Consortium to Support Cassava Research and Development (CLAYUCA, its Spanish acronym), in association with others of Biotechnology of Colombia Ltd. (Biotecol, its Spanish acronym) and CIAT, have developed a methodology that enables the massive production of cassava planting materials, also known as plantlets. In 2001, a large number of plants were produced using ATIS. Through efforts described below, a sustainable and economic technology for functional hardening was achieved, significantly minimizing the percentage of plantlet loss during the hardening process (HP).

Stages of the Hardening Process

The six stages required for an efficient and successful HP are as follows:

Stage 1: Pre-operational activities

A successful HP demands prior planning, which includes preparing a detailed timetable of all activities integrating the process: definition of who will carry it out; selection and adaptation of facilities; laboratory tests; purchase of equipment, materials, and inputs; and confirmation from the biotechnology laboratory of the number of *in vitro* plants that can be "hardened" per week. A good rule of thumb is that approximately 300 cassava plantlets can be hardened per square meter of useful area of greenhouse or screenhouse.

Human resources. Labor should be qualified; if not, personnel should at least receive training in basic aspects of the HP methodology. The number of workers required will depend on their experience and the number of plants entering the process. A novice worker can handle about 200 plants per day while an expert can handle up to 600 (see below, "Preparing for Transplanting").

Facilities. Facilities usually consist of a work area and either a screenhouse or a greenhouse, sometimes both. Select the best of what is available, then make any necessary adaptations.

The ***work area*** comprises a depot for soil and sand, a small storage shed to keep materials and inputs, a "soil patio" for mixing, and a cool site for transplanting; the latter should be protected from direct sunlight and strong winds and should also have a washing area and table.

The ***screenhouse*** should be roofed and adapted for automatic climate control. Microsprays should be suspended either over the tables or from the roof as well as installed along the floor to control temperature and relative humidity, especially during the first days of the HP. Although plantlet development is favored by good light, this should not come directly from the morning, noon, or afternoon sun during the first 8 days of acclimatization.

A protective screen can be installed, using one of the following options: (1) sheets of polystyrene foam covered with aluminum foil; (2) venetian blinds externally covered with aluminum foil; and (3) polypropylene meshing externally covered with several sheets of aluminum foil (each 30 cm wide) and separated at 5-cm intervals. So far, CIAT has found the third option to be the best.

The protective screen should be highly functional, installed on the sides of the ***screenhouse*** facing East (sunrise) and West (sunset), at least 1 or 2 m above the tops of the bags containing the plantlets. The screen should be withdrawn gradually as the sun traces its path through the sky to let light enter the facility. The aluminum foil reflects the sun's rays and prevents the heating of the area where the plantlets are being hardened.

The maximum temperature within a screenhouse fluctuates between 33 and 38 °C, and the minimum between 18 and 22 °C. For details on the design and construction of a CIAT screenhouse type II, consult Roca and Mroginski (1991).

The ***greenhouse*** should have an automatic microspray irrigation system installed, which is controlled by a solenoid valve and control clock. This type of system reduces the cost of labor needed to irrigate the plantlets by 90%.

Both the screenhouse and greenhouse should have a space set aside to acclimatize transplanted plantlets, which can be increased by as much as three times as the plants grow for 2 or 3 months after transplanting. The degree of increase will depend on the cassava variety, its growth rate, and plant development.

For example, 10,000 plants are needed to plant 1 hectare of cassava. CLAYUCA's HP methodology initially places 10,000 plantlets in an area of 25 to 35 m^2 in the screenhouse or greenhouse, depending on the size and type of bags used for transplanting. Two months after transplanting, these 10,000 plants will need an area of 50 to 70 m^2.

Laboratory tests. To correct any potential problem, all soil, sand, and water to be used should be first submitted to chemical and biological analyses.

Equipment, materials, and inputs. The following elements are needed to acclimatize the cassava plantlets:

- Soil mill, sieve and mixer; sterilizer; fumigator; protective equipment for fumigation and pesticides
- Test tubes, balance, flask washer, scissors, plastic or bamboo trays
- Wide container (e.g., tray) with agar to place plantlets removed from their flasks
- Bucket, spade, wheelbarrow, and garden

spades as well as a hose and irrigator
- Black plastic bags (7 x 14 cm) with perforations for drainage as well as transparent plastic bags (1 x 1 m)
- Field book, registration forms, indelible marker, pencil, and plastic mini-stakes for identification of plantlets

All implements used should be disinfected to prevent possible contamination of plantlets. For example, if roots or leaves are cut with scissors, these should be disinfected in a soapy solution every time a cut is made.

Stage 2: Operational or technical activities

The success of the HP depends on the comprehensive management of a series of operations that range from receiving the *in vitro* plants to their transplanting in the field.

Receiving* in vitro *plants. Boxes containing flasks with *in vitro* plants are received from the biotechnology laboratory. The flasks with plantlets are quickly removed from the boxes, placed at intervals in a cool place with artificial lighting or indirect sunlight, then counted and numbers recorded according to variety.

In this step, a **pre-selection** is also carried out, consisting of separating the flasks according to the height and vigor of the *in vitro* plants and eliminating those observed to be contaminated, broken, damaged, or malformed.

Pre-adapting the plantlets. If the transportation of the *in vitro* plants in closed boxes has taken several days, the flasks are placed as indicated in the previous step but left until the plantlets recover. Other option is to leave the *in vitro* plants for 1 or 2 days at the facilities where they will undergo the HP. This time can be used to make a second pre-selection of vigorous *in vitro* plants.

Preparing the substrate. To prepare the substrate in which plantlets will be grown, one part of previously pulverized and sieved black soil (i.e., from the non-clay arable layer) is mixed with three parts of washed and sieved coarse sand. The substrate should be steam-sterilized if the presence of nematodes and fungi is suspected. If no sterilization equipment is available, then:

- Place the sand in a metallic pipe or drum, add sufficient water and heat to 100 °C.
- Spread a thin layer of soil over black plastic, cover with a piece of transparent plastic, forming a hermetic seal between both plastics and leave for 1 week under direct sunlight.

Preparing for transplanting. Before transplanting, make sure the facilities are fully disinfected. Fill the small black plastic bags for the *in vitro* plants with substrate, prepare the mixture of fertilizer and fungicide, and arrange trays and large bags for use in miniature humidity chambers.

Likewise, retrain personnel in transplanting procedures. This exercise will determine the personnel's productive capacity. Skilled technicians can transplant about 600 plants per working day, while beginners can only handle about 200 plants.

Disinfecting and cleaning the site. Rigorously disinfect the entire facility with sodium hypochlorite and organize equipment and implements to facilitate their use. Cleaning should also extend to the transplanting site and the screenhouse or greenhouse where the plantlets will be hardened.

Preparing the bags. Fill either black or transparent plastic bags (7 x 14 cm) with the previously prepared mixture of sand and soil (see above) to three quarters their volume. Firmly press the mixture into the bag to obtain a compact substrate. Such compaction will later stimulate root growth, making them longer and thicker.

Preparing the trays. Place the bags containing the already compacted substrate on the trays and prepare the following solution: mix 1 g of a soil fungicide (e.g., Banrot) and 2 g of a phosphorus-rich fertilizer (e.g., formula 10-52-10) in 1 liter of deionized water (or rainwater). Immediately irrigate each bag with 10 cc of this mixture (first irrigation).

Preparing miniature humidity chambers. Introduce the base of each tray into a transparent plastic bag (1 x 1 m when folded) that has been rolled down, concertina style, to its base in such a way that the bag can later be quickly unfolded upwards and its opening firmly tied shut. This will function as a "humidity chamber".

Stage 3: Transplanting

Transplanting is traumatic for the plantlets, especially when carried out by unqualified or inexperienced personnel. Plantlets undergo microclimatic stress when

moved from their flasks to the miniature humidity chambers, suffering dehydration; nutrient stress, as they change from a nutrient-rich substrate to one very poor in nutrients (soil/sand mixture); and almost unavoidable mechanical damage to several parts of the plantlet (e.g., root cap, absorbent hairs, roots, stem, and leaves). The success of the plantlets' acclimatization and survival mainly depends on the care with which transplanting is done.

Transplanting must be performed immediately after the *in vitro* plants are extracted from their flasks. When this process is carried out for the first time and the environmental conditions of the facilities are not well known, then transplanting should be carried out on a daily basis at 17:00 to prevent the plantlets from **dehydrating**.

Transplanting activities include:

Selection. A **first selection** is carried out, choosing those flasks with the most vigorous plantlets (intense green color, erect, and between 5 and 7 cm tall).

Extracting the* in vitro *plants. This operation consists of the following steps:

- Remove the plastic tape and flask covers.
- Add deionized water or rainwater to the flask to moisten the agar substrate and facilitate extraction of both plantlet and agar.
- Hold the flask in one hand while gently smacking the flask with the other to loosen the agar from the flask's walls. If it does not separate, use a spatula, taking care not to damage the roots.
- Carefully remove the plantlet by inclining the flask; do not use tweezers because the stem may suffer damage.
- Place the plantlet in a wide container, such as a deep tray containing deionized water or rainwater. Use your hand to gently move the water to dislodge the agar.
- Gently remove particles of agar still adhered to the roots with the flask washer.
- Conduct a **second selection** of vigorous plantlets to eliminate small, poorly formed, or weak plantlets.

Transplanting into bags. With one hand, place the plantlet in a bag, introducing the roots and lower part of the stem. This hand must be held rigid to prevent breaking the absorbent hairs and roots. With the other hand, add a fourth of the substrate, ensuring that the roots remain in their "normal position" that is, as they were in the flask, thus preventing physical or physiological damage that could be caused by a change of position.

Once transplanting has been achieved for all the bags in the tray, the plantlets receive a second irrigation with 10 cc of the previously used fertilizer and fungicide mixture.

Humidity chambers and hardening. Now the real process of hardening the plantlets begins:

- Label the tray indicating the name of the variety, the number of bags, the date and hour of transplanting, and the transplanter's name.
- Place each tray at the bottom of the large transparent bag (1 x 1 m) and tie the opening shut with a piece of rope, converting it into a miniature humidity chamber.
- Transfer the humidity chambers to the facility where the HP will be carried out. Tie the string to a wire strung over the chambers to prevent the upper part of each chamber from folding over on top of the plantlets and damaging them.

Stage 4: Maintaining the transplanted plantlets

In this stage, considerable attention must be given to the microclimatic changes occurring within the facility, the irrigation required by plantlets, their nutrition, and the presence of pests and diseases.

The bags containing the plantlets should not be moved during the first month after transplanting to avoid damaging the roots, especially the cap and absorbent hairs. These parts are particularly fragile in this early stage of development. Damage or breakage in root tissues increases the probability of pathogen invasion and slows down growth and development. Such care is also of considerable importance in Stages 5 and 6 of the HP.

Microclimate and humidity chambers. Between 8 and 12 days after transplanting (DAT), remove the string closing the humidity chamber—preferably in the afternoon—and completely open the large transparent bag to allow plantlets to adapt to the microenvironment of the facility.

If a tendency to wilting is observed, then reclose the bag and continue the humidity chamber treatment.

If plantlets have adapted well to the

microenvironment by the second or third day after opening the large bag (i.e., 10 to 15 DAT), the bag is rolled down to the tray's base or removed altogether, leaving the tray exposed with its plantlets.

During this step, plantlets must be protected from strong dehydrating winds.

Irrigation. If the plantlets have been irrigated with the correct amount of nutrient solution (see above) and the environment within the miniature humidity chamber is appropriate, plantlets will not need irrigation.

However, if and only if, the first symptoms of physiological wilting appear in plantlets after being removed from the humidity chamber, apply a third irrigation to the substrate. To reduce the risk of attack of pathogens, take care not to wet the leaves. Irrigate each plantlet with 10 cc of a nutrient solution consisting of a mixture of 2 g of phosphorus-rich fertilizer to promote root formation (e.g., formula 10-52-10) and 1 g of Agrimins (a fertilizer rich in minor elements) per liter of deionized water (or rainwater).

Depending on the microclimatic conditions of the facility and the turgor of the plantlets, schedule one or two irrigations per day, each with 10 cc of water normally used to irrigate other plants.

Between 21 and 25 DAT, install a microspray irrigation (MSI) system in the screenhouse, which significantly reduces labor costs. At CIAT, plantlets receive from 2 to 3 minutes of MSI in the morning and, if necessary, another 2 or 3 minutes in the afternoon.

- The use of MSI requires that plantlets be rigorously inspected to detect any pathological problems.

- The "secret" of this operation, which is crucial to the success of the HP, is to apply irrigation when the first symptoms of physiological wilting are observed. This ensures an adequate moisture level of the substratum, thus preventing possible pathogen attack in the root area. It is important to remember that, at this stage, cassava plantlets are highly susceptible to excess moisture in the substrate.

Fertilizer applications. The substrate used (1 part of soil to 3 parts of sand) is of low fertility, and the application of fertilizers is therefore indispensable. Every 8 days the plantlets will receive applications of macro- and micronutrients to ensure their normal development.

A phosphorus-rich compound (e.g., formula 10-52-10) is first applied to enhance root development. This application is alternated at 8-day intervals with a complete fertilizer containing macro and minor elements. If the formula 10-52-10 is not available on the market, it can be replaced by a combined formula including 10-30-10 and Agrimins. Fertilizer application is suspended once the color of the plantlets is normal for the varieties to which they belong.

If symptoms of deficiency of any element appear, affected plantlets can be given an application of foliar fertilizer containing simple or complete fertilizers. Zinc deficiency tends to appear in plantlets during the first month and can be corrected by adding Zn to the soil in one of the irrigations at a rate of 3 g dissolved in 1 liter irrigation water and applied at 10 cc per plant.

Stage 5: Separating the plantlets

Between 30 and 34 DAT, the plantlets have now become plants and therefore need more light as well as higher temperatures to grow and develop. Plants are spaced at a greater distance, in an area double or triple that initially occupied.

Stage 6: Transplanting plants to the field

The plants remain in the screenhouse or greenhouse for 60 to 90 days before being taken to the field. In case of restricted space or labor, plants can be taken to the field 30-40 days after transplanting.

Transfer. When transporting the bags from the greenhouse (or screenhouse) to the field, protect plants from strong air currents that could cause abrasion or dehydration.

Adaptation and final transplanting. The plants should be grouped together and placed in the site chosen for planting and left for 3 to 6 days so that they can adapt to the new environment. Plants are then transplanted to their final field sites. For the next few days, the farmer should closely monitor the site for the appearance of any nutritional deficiency or presence of pests or diseases to apply the corresponding integrated management practice as required.

Reference

Roca WM; Mroginski LA, eds. 1991. Cultivo de tejidos en la agricultura: Fundamentos y aplicaciones. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. 970 p.

CHAPTER 20

Mechanized Systems for Planting and Harvesting Cassava (*Manihot esculenta* Crantz)

Bernardo Ospina Patiño[1], Luis Fernando Cadavid L.[2], Martha García[3], and César Alcalde[3]

Background

The progress made recently in developing cassava varieties with high yield potential has helped improve the crop's productivity and competitiveness. It has facilitated its entry in various markets, especially those of balanced feeds for animals, and of industrial applications such as starch, glues, and bioethanol.

To compete in these markets, the costs of producing cassava must be kept as low as possible. The crop requires intensive labor, especially for planting and harvesting. In countries such as Brazil, much progress has been made in developing mechanized planting and semi-mechanized harvesting systems for the cassava crop. In Colombia, the Latin America and Caribbean Consortium to Support Cassava Research and Development (CLAYUCA)[4] has recently been evaluating and adapting models of planters and harvesters for the cassava crop. These models were based on those developed in southern Brazil.

This chapter describes some of the technologies currently available to mechanize cassava planting and harvesting.

Importance of Agricultural Mechanization

The principal aim of agricultural mechanization is to ensure optimal conditions for crop development at all stages of its life cycle. It therefore implies the direct reduction of necessary labor, production costs, time spent at each task per unit area, and the final cost of the agricultural product. Hence, the planted area can be increased, thereby justifying the initial investment in machinery.

With the current trend towards economic globalization, agricultural sectors of developing countries face severe competition with agricultural products imported from developed countries where they were produced mostly under complex subsidy schemes for supporting agricultural activities. Consumers tend to choose the cheaper imported products, thus creating problems in marketing agricultural products produced domestically and endangering the developing countries' more fragile and vulnerable rural economies. Under these conditions, farmers urgently need access to technologies that will help them reduce their production costs and improve the productivity and competitiveness of their farming systems.

Mechanization of the cassava crop is priority for Colombian agriculture, if projections for that crop in national and international markets are to be taken into account. However, the current technological offer of machinery in local and international markets is narrow. The adaptability of such machinery to the country's conditions must first be assessed. We use the cassava crop's recent situation in Colombia and other cassava-producing countries of Latin America and the Caribbean (LAC) to illustrate this aspect.

The continuous growth of the poultry and balanced-feed sectors has meant an increased demand of raw materials, mainly cereals such as maize. National production is insufficient for supplying this growing demand, forcing countries to import, annually, massive volumes of maize that total several millions of tons. Balanced-feed markets see cassava as an alternative raw material that can be used as an energy source.

1. Executive Director, CLAYUCA, Cali, Colombia. E-mail: b.ospina@cgiar.org
2. Soil Agronomist, formerly of Cassava Production Systems, CLAYUCA. E-mail: luisfernandocadavidlopez@yahoo.es
3. Formerly Agronomy Students, 2001–2002, UNIVALLE, Cali, Colombia.
4. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

If cassava is to be incorporated in these markets, the crop needs to be traded at prices that compete favorably with imported maize prices. Considerable progress has recently been made in developing new high-yielding cassava varieties, but this was not enough to significantly reduce production costs or increase competitiveness.

Importance of soil preparation

As for any other crop, cassava requires good soil preparation as according to climate, soil type, vegetation cover, topography, the degree of mechanization the crop receives, and other agronomic practices.

An adequately prepared soil guarantees a propitious bed for the "seed" and, thus, high levels of germination and production. The seedbed should generally be about 20 cm deep, with a loose soil that is free of lumps to facilitate both horizontal and vertical root growth.

Soil preparation usually begins in the dry season, except in regions with very humid climates, where the land is prepared at the end of the heavy rains and stakes are planted at the beginning of the dry season. Advantage is therefore taken of the remaining small but copious rains to initiate root development. In areas with less rain, plowing before the dry season is sometimes necessary to take advantage of the rains as, later, the land dries up and hardens too much for tilling. In many regions, the disk plow is being replaced by other tools such as the chisel plow, which helps conserve soil structures.

Whenever this task can be mechanized, many cassava farmers prepare the soil with a simple plowing, followed by disk plowing. Thus, they obtain good conditions for planting, ventilate the soil, and control weeds. These days, soil structure and other physical properties must be evaluated to select the most suitable mechanization system. The concepts of sustainability and minimal tilling must also be applied where possible.

A common practice in Brazil, wherever planting is mechanized, is to prepare furrows, 10 to 20 cm deep, to plant stakes in a horizontal position. The first pass with a disk plow is made 30 days before planting; the second just before the stakes are planted. The goal is to improve soil conditions and eliminate weeds that may compete with the crop during its establishment.

Planting cassava on land that slopes at more than 15% is not recommended. If the crop is planted on such slopes, contour furrowing should be carried out, especially during the crop's first months of growth, to prevent erosion, which can become a serious problem, particularly if the soil is also sandy (Ribeiro 1996).

Planting

The introduction of new technologies has modified cassava cropping practices, particularly planting method and stake position. These two practices are fundamental for increasing yield and ensuring marketing of the product (Cuadra and Rodríguez 1983).

Cock et al. (1978) proposed several planting methods that take into account climate, soils, available equipment, topography, and farmers' customs. These methods are manual, semi-mechanized, and mechanized.

In Colombia, cassava is usually planted on ridges or on the flat. The selection of one site over another for planting depends on the area's humidity and soil texture (Figures 20-1 and 20-2).

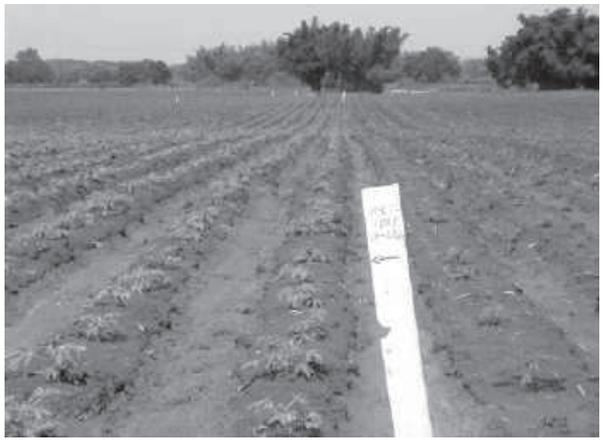


Figure 20-1. Plot in which cassava was planted on ridges.

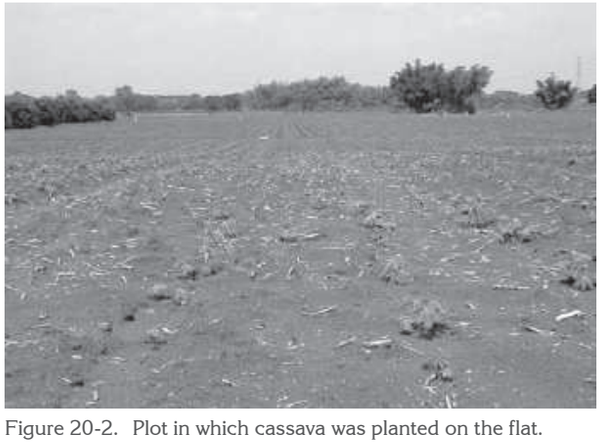


Figure 20-2. Plot in which cassava was planted on the flat.

Importance of soil type

Any method for planting cassava stakes should ensure shoot growth (i.e., "germination") and stake rooting. For these to happen, the soil must have adequate moisture and be well prepared. The planting method used will depend mainly on soil type and climate:

- In soils with a *clayey texture* and receiving more than 1200 mm of rainfall, ridges should be constructed to facilitate drainage, thereby effectively improving crop establishment and yield. It also facilitates manual harvesting (Lozano 1978).

- Conceição (1976) reports that planting stakes horizontally, at 10 cm deep and in furrows, facilitates commercial harvesting (Figure 20-3). Planting on ridges gives good results if weeds do not constitute a serious problem.

- In *heavier* and compacted soils, cassava should be planted in beds or on ridges. Such soils become saturated with water in the rainy season and are thus poorly aerated. They favor the spread of root rots, which cause crop losses.

- However, Lulofs (1970) reported that planting on the flat in this type of soil is satisfactory, although planting on ridges may increase yield, better control erosion, and facilitate harvesting. Significant differences in cassava production between the two methods were not found. Planting on ridges produced fewer roots than did planting on the flat, but it also reduced the amount of weeding needed and the physical effort required for harvesting.

- In soils with a *sandy texture*, as predominate in tropical dry climates, cassava is planted on the flat. In such soils, stakes should be planted vertically or on a slant (Figure 20-4), burying them by about 5 cm (the stake itself is about 20 cm long). One problem is potential damage caused by excessive soil heat to buried buds. These buds usually receive more heat than the buds remaining above ground. Any damage caused affects crop yield (Cadavid L. et al. 1998).

Importance of planting method

Four *important variables* must be taken into account when determining the method for planting cassava, whether manual or mechanized:

- planting depth
- stake length
- stake position
- spacing between plants and between furrows

Each has a different value according to the soil type and climatic conditions of the region in which planting is to be carried out (Figures 20-3 and 20-4).

Planting depth. To encourage tuberous root production, the stake should not be planted deeper than 10 to 15 cm. The fine roots responsible for taking up essential elements and water will extend to greater depths should the crop suffer hydric stress or drought.

Manual planting is traditional in all cassava-growing regions. Stakes, 20 cm long, are planted vertically or on a slant in a furrow, whether on a ridge or on the flat, to a depth of 5 to 10 cm. Planting is in the direction of bud growth, ensuring that a large number of buds is buried under the soil, with the number depending on the variety.

Figure 20-3. Stake planted horizontally.

Figure 20-4. Stake planted on a slant.

Several experiments have shown that the buried part of the stake should not be planted more deeply than 10 cm as, at greater depths, harvesting can be difficult. Shallow planting (<5 cm) may mean plants being carried away by water, or developing surface roots and thus becoming prone to lodging. Shallow planting will also hinder certain agronomic practices. In sandy soils, planting depth should not be less than 5 cm, as water may settle the earth and expose the planted stake.

Stake length. In any cassava production system, stake size and quality play a significant role in obtaining high yields.

Stake quality depends on several factors: stem age and thickness when selected for cutting, stake size, cassava variety, storage time, and mechanical damage suffered by the stake during preparation, transport, storage, and planting. Farmers commonly use a stake length that is between 15 and 25 cm.

Gurnah (1974) demonstrated that, where moisture is adequate (1000 mm annual rainfall) and stakes are planted between 2 and 8 internodes deep, yield is higher when the number of internodes increases from 2 to 5. Beyond this number, yield did not subsequently increase. Vertical stake length therefore depends on the number of desired internodes (i.e., between 3 and 5). That number, in its turn, depends on the phenotypic characteristics of the variety being planted (Figure 20-5). A high value for shoot growth ("germination") is guaranteed if the stake is fresh and newly cut.

Stake position. In Colombia, stakes are usually planted on a slant or vertically (Figure 20-4). When the stake is cut at right angles to its length (Figure 20-6), roots are distributed consistently around the periphery of the cut. If the stake is planted horizontally, the roots are more separated and harvesting is easier than when stakes are planted vertically or on a slant (Figure 20-7). Cock et al. (1978) found that neither the angle of the cut nor the position in which the stake is planted significantly affects yield.

Trials carried out at the Centro Internacional de Agricultura Tropical (CIAT) indicate that, under field conditions, stakes planted vertically are always quicker to root and germinate. Planting them horizontally is recommended when the operation is mechanized and soil moisture is appropriate.

No significant differences were found in root production between stakes planted on a slant, vertically, or horizontally. However, continuous observation suggests that vertical planting favors initial growth and reduces plant lodging (Solórzano 1978). Recent data obtained by CIAT scientists in Honduras also suggest that vertical or slanted planting helps plants maintain straight stems and

Figure 20-5. Number of internodes in a stake, compared with its length, cassava variety CM 533-4 (ICA Negrita)

Figure 20-6. Cassava stake cut at right angles to its length.

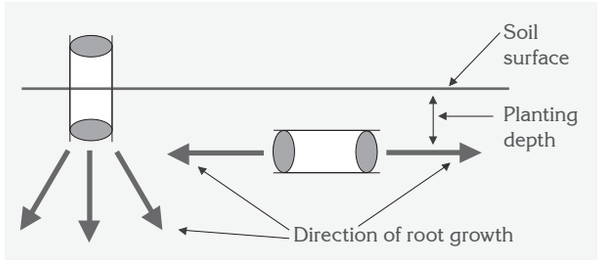


Figure 20-7. Diagram shows cassava root growth according to the position in which stakes are planted.

reduce heavy adventitious rooting. Although Conceição (1976) recommends planting horizontally in furrows for mechanized planting, CIAT data indicate that stakes planted vertically or on a slant can facilitate mechanical harvesting.

In regions with average to heavy soils and rainfall between 1000 and 2000 mm/year, planting stakes either horizontally or vertically makes no difference, as moisture is sufficient for germination.

In regions with sandy soils and irregular rains, planting stakes vertically is safest. Furthermore, stake length can be reduced from 20 cm to 10–15 cm. Thus, they take better advantage of available moisture. Vertically planted stakes also serve to disseminate heat.

Planting density. Planting density has an indisputable effect on crop production. It depends on factors such as soil fertility, cassava variety, topography, stake planting method, crop's purpose, planting time, harvesting time, and climate. Adopting a single spacing system that responds to all these variables is therefore impossible.

Cassava plants growing in a given area compete among themselves for water, light, and nutrients. Hence, the ideal spacing for planting each variety depends on soil fertility or planting time. Once determined, individuals can be better distributed in the field and more efficient advantage can be taken of production factors (Normanha and Pereira 1974).

In the cassava-producing areas of Rio de Janeiro, Brazil, a spacing of 1.20 m between furrows was found to present the best results, given the region's soils. No significant differences were found between spacing distances of 0.5, 0.7, and 0.9 m between plants in terms of root production for either industrial or commercial purposes. The spacing most used in Colombia is 1 m between plants and 1 m between furrows.

Planting systems and available machinery

The technological offer currently available for the cassava crop includes several machines that incorporate human activity for their correct operation. Three systems exist for planting cassava: one is totally manual, where only farmers' labor intervenes, as still happens in many cassava-producing countries of the developing world.

The second system is *semi-mechanized*, that is, it includes an initial step of chisel plowing that breaks the soil and leaves lines marked with small furrows. Stakes are then placed manually at the desired density and in a horizontal position within each furrow in the line. They are then covered with soil.

The third system is *mechanized*. It involves a planting machine to which a worker manually feeds stakes that were previously cut to the desired size. A tractor is needed to move the planter. Some models integrate the application of fertilizers into the planting operation of cassava stakes.

For Colombia and other South American countries, the progress made in this field in southern Brazil has been of great importance. Brazilian machines have been evaluated under local conditions with good results, including the definition of the basic requisites for their adaptation.

Evaluating two Brazilian prototypes for mechanized cassava planting

Performance. CLAYUCA imported two cassava planters from Brazil, one model that plants two furrows, and the other three. They were evaluated under the soil and climatic conditions of the Department of Valle del Cauca, Colombia. The 3-furrow model planted 9.2 ha/day, using four workers (3 planters and 1 tractor driver) over an 8-hour working day. The 2-furrow model could plant 6.2 ha/day, using three workers (2 planters and 1 tractor driver). These results compared most favorably with results obtained for the manual planting system, which usually requires a minimum of 7 working days to plant 1 ha. The results translated into savings of almost 50% of costs of manual planting when the 2-furrow planter was used, and 57% for the 3-furrow planter.

Mechanized planting is a viable alternative for cassava growers. However, the minimum area needed for recovering investment costs is 30 ha. The 2-furrow prototype was considered a better option, as it allows for variations in distances between furrows and between plants, stake length, and planting depth.

Two-furrow cassava planter, model PC-20. Figure 20-8 shows the principal technical characteristics of this prototype:

- Hydraulic lift system
- Stakes are cut by circular saws operated by power takeoff (PTO)

Figure 20-8. Two-furrow cassava planter, model PC-20.

- Distance between plants varies between 40 and 90 cm
- Distance between furrows varies between 0.8 and 1.2 m
- Stem ends are discarded
- 100-kg capacity hopper for granulated fertilizer
- Double concave disks for hilling
- Depth control in furrow aperture
- Approximate output: 7 ha/day
- Required minimum power: 70 hp
- Capacity seed deposit: 1.5 m^3

Three-furrow cassava planter, model PMT-3. Figure 20-9 shows the principal technical characteristics of this prototype:

- Hydraulic lift system
- Stakes cut by jaws operating from the steering wheel's traction

Figure 20-9. Three-furrow cassava planter, model PMT-3.

- Distance between plants is set at 90 cm
- Distance between furrows is set at 1 m
- Stem ends are not discarded
- Two hoppers, each with a 50-kg capacity, for granulated fertilizer
- Double concave disks for hilling
- No depth control in furrow aperture
- Approximate output: 12 ha/day

Parameters evaluated for prototype performance. Prototype performance was evaluated on two principal parameters:

Soil conditions.

- Chemical and physical characterization of soils in three regions where the work was developed
- Water content and apparent density (degree of soil compaction)

Prototype operation. The variables measured to determine the operation of the two prototypes were:

- Uniformity in planting depth
- Uniformity in length of the planted stake
- Uniformity in spacing between plants
- Mechanical damage to stakes
- Output in the field
- Production costs

Results Obtained

Table 20-1 presents results of experimental work. Data obtained at each site are the average of three replications. In each case, the parameter is expressed as a percentage, which indicates results according to the given conditions of the machines' operation. For example, if the desired stake length is 20 cm, the prototype is adjusted to the stake's dimensions. The parameter's results—uniformity of size—indicates the machine's efficiency in planting stakes of this size. The data obtained is based on an 8-hour working day and only the workers feeding the machine are included. For manual planting, comparisons are estimated by assuming that the same number of workers who feed the planting machine is used.

Discussion

Uniformity of spacing between plants

This parameter depends on the feeding mechanism of each prototype (Figure 20-10). It also depends on the degree of soil preparation. Overall, the functionality of the 2-furrow prototype was 92%. The advantage of this

Table 20-1. Comparing the performance of mechanical cassava planters with manual planting.

Parameter	Site 1	Site 2	Site 3	Average	Manual planting
(A) The 2-furrow cassava planter					
Uniformity of spacing between plants (%)	91.3	92.6	94.3	92.7	97.7
Uniformity of stake length (%)	98.0	97.3	98.0	97.7	98.3
Uniformity of planting depth (%)	94.5	96.6	96.6	95.9	100.0
Mechanical damage to stakes (%)	10.0	10.0	9.6	9.98	0
Output (ha/hour)	0.42	0.39	0.38	0.39	0.02[a]
Output (ha/day)[b]	6.72	6.24	6.08	6.34	1.00
				i.e., a 6-fold difference	
(B) The 3-furrow cassava planter					
Uniformity of spacing between plants (%)	74.0	77.0	87.3	79.4	98.1
Uniformity of stake length (%)	96.1	96.1	95.6	95.9	98.6
Uniformity of planting depth (%)	95.6	96.6	97.6	96.6	100.0
Mechanical damage to stakes (%)	36.6	25.0	22.3	27.9	0
Output (ha/hour)	0.37	0.42	0.36	0.38	0.02[a]
Output (ha/day)[b]	5.92	6.72	5.76	6.13	1.00
				i.e., a 6-fold difference	

a. The value for this output was calculated as the number of hectares planted per hour per worker, assuming a working day of 8 hours and 6 workers.

b. Assuming a working day of 16 hours.

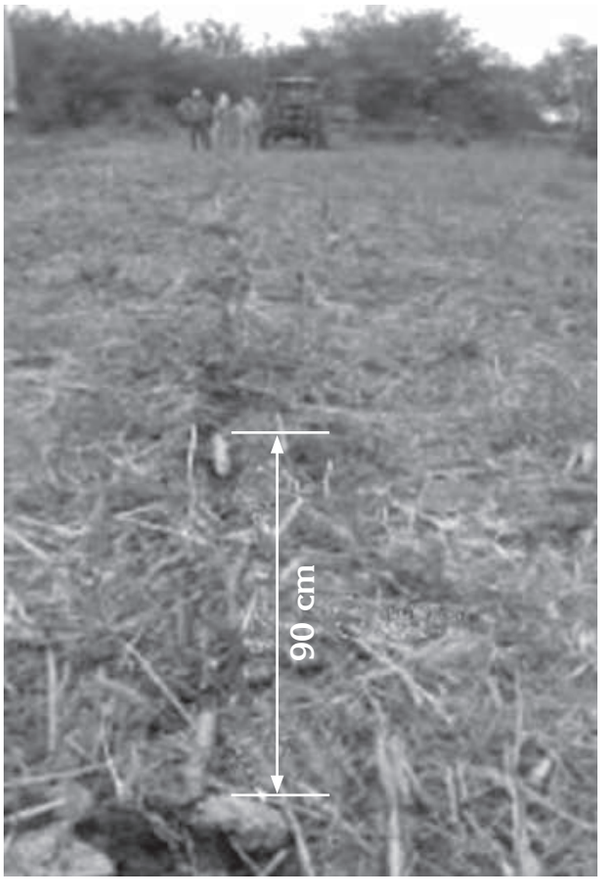


Figure 20-10. Planting distance in mechanized planting.

prototype is its device for discarding ends. Another advantage is that it permits different planting distances. The 3-furrow prototype does not include a device for discarding ends, and all stakes are cut to the same size. The functionality of this prototype was less than the 2-furrow type, having values of about 80%.

Uniformity of stake size

Although this parameter is independent of soil preparation, it plays a significant role in ensuring a high germination rate. Stake length and internode number are well known to affect sprouting. The 2-furrow prototype presented good functionality (97.7%) when 15-cm stakes were used (Figure 20-11). The 3-furrow prototype had lower results of about 95.9%. The stake length obtained was only 11 cm, which may be too short if the variety planted has few internodes.

Uniformity of planting depth

The two prototypes did not present major differences, as both machines obtained about 96% for this parameter, which is important for germination. Planting depth depends on soil preparation. If the planting area is not well prepared, the machine will vary in its regulation of planting depth. This effect is minimized with the 2-furrow planter, which has a device to control depth (Figure 20-12).

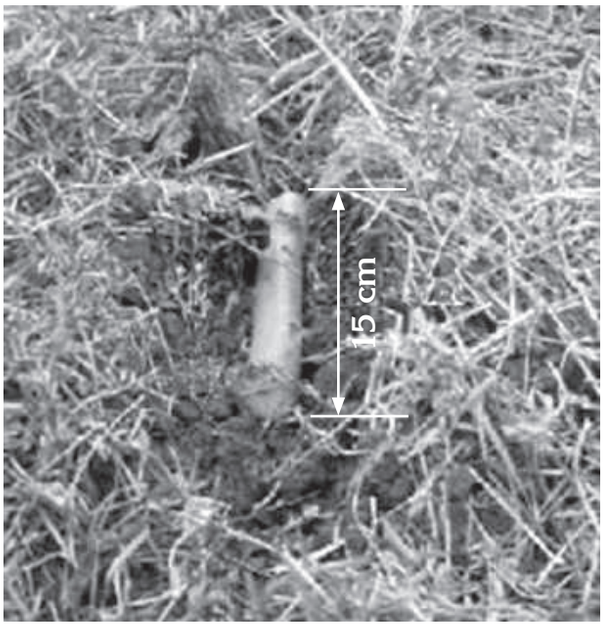


Figure 20-11. Cassava stake length in mechanized planting.

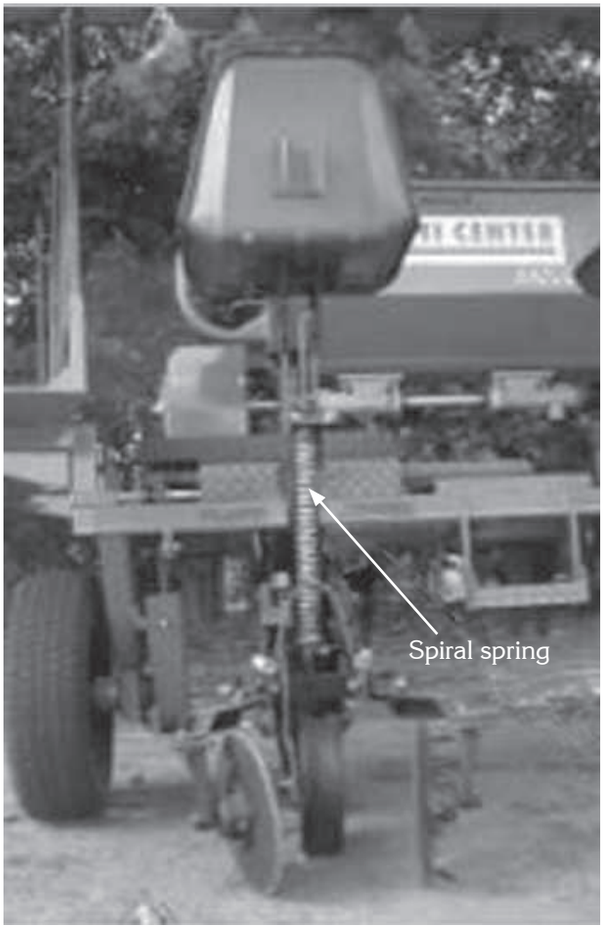


Figure 20-12. Planting-depth device used in the 2-furrow planter. Note the spiral spring.

Mechanical damage to stakes

For the two prototypes, the degree of damage to planting materials was evaluated. Differences were a consequence of the cutting device in each machine. In the 2-furrow prototype, the cutting system comprises circular saws that operate from the tractor's power takeoff. Damage to stakes from this device is minimal, being less than 10%. The 3-furrow planter had a lower functionality of about 28% because the cutting device uses a system of jaws that operate from the steering wheel's traction.

Prototype outputs

This parameter indicates the capacity of the two prototypes to plant according to given distances between rows and between plants. The machine's effectiveness is affected by parameters such as soil conditions (preparation and water content), the tractor's power, and the efficiency of the workers feeding the machine (Table 20-1). The 2-furrow planter had an average output of 6.3 ha/day or 0.8 ha/hour, using two people for an 8-hour working day. The 3-furrow prototype had an average output of 9.2 ha/day, employing three workers for an 8-hour working day, which corresponds to an average of 1.15 ha/hour. In neither case is the tractor driver included. The traditional planting system required six workers to plant 1 ha for an 8-hour working day.

Economic impact

The two prototypes evaluated did not differ significantly in operation, as the use of either one represented an important reduction in production costs. Table 20-2 illustrates the values obtained for the total operational costs of the two planters, compared with the traditional system, and the production costs of 1 ha of cassava.

The use of the 2-furrow planter reduced planting costs by 51% against the traditional system. With the 3-furrow prototype, planting costs were reduced by 55.6%. Compared with the 2-furrow prototype, the 3-furrow planter further reduced costs by US$2.30/ha.

The 2-furrow prototype was then modified by its manufacturers to improve efficiency and output. CLAYUCA validated the new 2-furrow prototype, *model Bazuca 1* (Figure 20-13), which had the following characteristics:

- Hydraulic lift system
- Distance between furrows varies from 0.85 to 0.96 m

Table 20-2. Production costs of planting 1 hectare of cassava, Valle del Cauca, Colombia, 2000.

Activity	Unit	Quantity (US$)[a]	Unit value	Total cost (US$)
(A) Traditional manual planting				
Cutting stakes	Workers/day	2	4.60	9.20
Chemical treatment for stakes				6.10
Labor for stake treatment	Workers/day	0.5	4.60	2.30
Manual planting	Workers/day	6	4.60	27.60
Replanting	Workers/day	1	4.60	4.60
Total costs of planting 1 ha				49.80
Total production costs of planting 1 ha				566.00
Estimated output was 1 ha/day				
Planting costs as proportion of total costs 8.8%				
(B) Mechanized planting, using a 2-furrow prototype				
Cutting and stacking stems	Workers/day	3	4.60	13.80
Adjusting fixed costs for planter	US$/ha	1.28	9173.00	5.30
Workers for mechanized planting	Workers/day	0.33	4.60	1.46
Wage for tractor driver	Workers/day	0.16	9.60	1.54
Replanting	Workers/day	0.5	4.60	2.30
Total costs of planting 1 ha				24.40
Total production costs of planting 1 ha				477.00
Estimated output was 6.2 ha/day				
Planting costs as proportion of total costs 5.1%				
(C) Mechanized planting, using a 3-furrow prototype				
Cutting and stacking stems	Workers/day	3.0	4.60	13.80
Mechanized planting costs, fixed and variable	US$/ha	0.87	3.94	3.42
Workers for mechanized planting	Workers/day	0.33	4.60	1.50
Wage for tractor driver	Workers/day	0.108	9.60	1.04
Replanting	Workers/day	0.5	4.60	2.30
Total costs of planting 1 ha				22.10
Total production costs of planting 1 ha				471.00
Estimated output was 9.2 ha/day				
Planting costs as proportion of total costs 4.7%				

a. Exchange rate (year 2000) was 1 U.S. dollar = $2,100 Colombian pesos; value of wage (worker/day) was therefore 10,000 Colombian pesos or US$4.60.

Figure 20-13. The modified 2-furrow cassava planter, Planti Center model Bazuca 1.

- Distance between plants varies from 0.30 to 0.96 m
- Tractor power: 60 to 75 hp
- Operational speed: 4 to 6 km/h
- Stake length: 13.5 cm
- Does not discard ends
- Cuts stems with saws
- 150-kg capacity hopper for fertilizers
- Output: 5–7 ha/day

The basic difference between this new model and the previous one is the device that feeds the stems to the machine. It was changed to a central hopper, contrasting with that of the previous model, which included a circle of multiple feeding points. Both the *Planti Center PC-20* and the *Bazuca 1* have devices for

direct planting, which contributes to soil sustainability, as no heavy machinery is needed for soil preparation (Figure 20-14).

The Brazilian metalworking sector that makes the cassava planters and harvesters is dynamic. It includes several companies that continually innovate and present new prototypes to the market. Already, new prototypes with greater efficiencies exist. For example, 4- and 6-furrow planters are already being used for cassava planted to large extensions in agroindustrial projects (Figure 20-15).

Recently, a 1-furrow prototype (Figure 20-16) was launched on the market. It creates ridges, while simultaneously planting and applying fertilizers. This machine may represent a great advance for production systems where farmers operate small production areas and are limited by the lack of machinery for soil preparation. The characteristics of this new prototype are:

- Hydraulic lift system
- Distance between furrows vary from 0.85 to 0.96 m
- Distance between plants vary from 0.31 to 0.96 m (13.5-cm stake) and 0.42–1.30 m (18.5-cm stake)
- Tractor power: 45 hp
- Operational speed: 4 to 6 km/h
- Stake length: 13.5 cm; 18 cm (optional)
- Does not discard ends
- Cuts stems with saws
- 150-kg capacity hopper for fertilizers
- Output: 2–3 ha/day

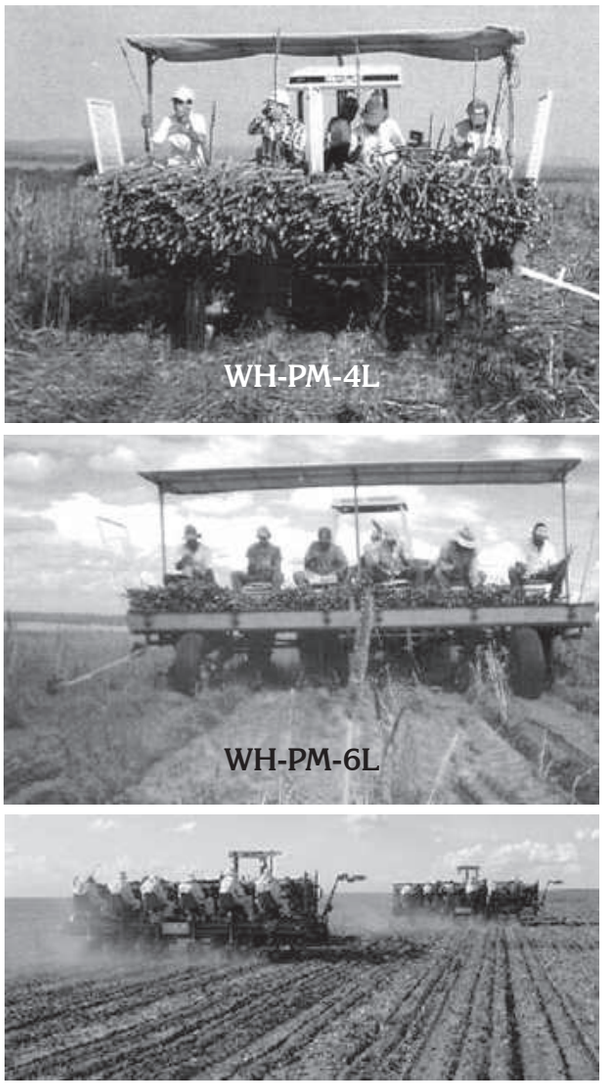


Figure 20-15. Four- (top) and six-furrow (middle and bottom) cassava planters.

Figure 20-14. Two angles of the direct-planting device in the 2-furrow cassava planter, Planti Center model PC–20.

Figure 20-16. One-furrow cassava planter–ridger.

To decide which mechanized system is the best for a given case, the following factors should be taken into account:

- The type of tractor and its available power
- The planting method for stakes (planting on the flat or on ridges)
- Conventional or direct planting

Mechanized planting, by itself, does not guarantee a higher output or higher germination rate for stakes. Essential conditions are fresh, recently cut, stakes, and good soil preparation. Other tasks should be carried out without exception.

The introduction of these technologies positively modifies the production cost structure for cassava. Planted area can be increased and final costs reduced, thus leading to higher profits. Furthermore, when high yields are obtained, costs are further reduced, but this is achieved only if minimal conditions are guaranteed to enable the planter to operate well.

Table 20-3 presents CLAYUCA's recent results after adapting the mechanized cassava planting technology, using prototypes developed in Brazil. Farmers should, however, include in their cost structure those costs incurred by the machine's depreciation and maintenance, so that calculations may approach closer to reality.

Cassava Harvesting

One task in cassava cultivation that is very difficult to mechanize is harvesting. Reasons include limitations that result from the shape and distribution of roots in the soil, the depth at which they are found, the collection of foliage residues and planting materials (stakes), and the adherence of soil to roots. The best time for harvesting—the crop's final stage—is defined by the farmer in terms of the crop's productivity, and the roots' starch content and culinary properties. Harvesting perhaps most influences the crop's cost structure, as it requires many working days.

In Colombia, the harvest represents more than 30% of the cassava crop's production costs, mainly because manual, rudimentary, and, sometimes, inefficient methods are used. Hence, some mechanization of the work is needed to increase operational efficiency, given that any mechanical method or device helps, even noticeably so, to reduce not only production costs, but also energy expenditure and fatigue on the part of the workers doing the harvesting (Toro M et al. 1976).

In northern Colombia, to obtain an average yield of 12.5 t/ha, 25 workers are needed for an 8-hour working day. Consequently, the daily output per worker is 500 kg/day. This value, however, does not include collection of planting materials or selection of roots and their packaging (B Ospina Patiño 2001, pers. comm.).

Manual harvesting

Certain tasks are common to any cassava harvesting, whether manual and mechanical. These are carried out in two stages:

- The cutting and selecting of (1) forage (cassava leaves and other aerial parts) and (2) planting materials. Only 20 to 40-cm lengths of the stems are left still attached to the roots underground, so that these may be more easily extracted or pulled out of the soil.

- The second stage is to extract, collect, clean, and package the roots.

Manual harvesting comprises four modalities:

Using hands. In light or sandy soils, roots can be easily pulled out by hand, without need of tools.

Table 20-3. General cost structure for planting cassava, according to three methods applied to flat areas in the Department of Valle del Cauca, Colombia, 2000.

Activities[a]	Unit[b]	Quantity	Unit value (Col$)[b]	Total value (Col$)[b]	RCD[c] (%)
(A) Manual planting					
Cutting stakes	Working day	5	10,000	50,000	
Inputs for stake treatment	Global			13,410	
Labor for stake treatment	Working day	0.5	10,000	5,000	
Manual planting	Working day	6	10,000	60,000	
Replanting	Working day	1	10,000	10,000	
Total for labor				138,410	10.38
Total cost per hectare				**1,333,610**	
(B) Planting with a 2-furrow machine					
Cutting and stacking stems	Working day	3	10,000	30,000	
Costs of machine, F and V	Col$/hour	1.28	9,174	11,761	
Costs of tractor, F and V	Col$/hour	1.28	12,743	16,337	
Workers for mechanized planting	Working day	0.32	10,000	3,200	
Tractor driver	Working day	0.16	21,000	3,360	
Replanting	Working day	0.50	10,000	5,000	
Total for labor				69,658	6.41
Total cost per hectare				**1,086,350**	
(C) Planting with a 3-furrow machine					
Cutting and stacking stems	Working day	3	10,000	30,000	
Costs of machine, F and V	Col$/hour	0.87	8,600	7,482	
Tractor costs, F and V	Col$/hour	0.87	12,743	11,086	
Workers for mechanized planting	Working day	0,326	10,000	3,260	
Tractor driver	Working day	0,108	21,000	2,268	
Replanting	Working day	0.50	10,000	5,000	
Total for labor				59,096	5.74
Total cost per hectare				**1,029,878**	

a. F and V = fixed and variable costs.
b. The exchange rate (year 2000) was 1 U.S. dollar = $2,100 Colombian pesos.
c. RCD = ratio between the costs of planting stakes and the total direct costs of cropping, expressed in percentage.

Using a lever. In soils with textures ranging from loamy to clayey and presenting problems of compaction, extraction is facilitated by tying the stem with a chain or rope to a pole that is 2.5 to 3 m long. The pole must be sufficiently straight and firm to serve as a lever against the soil.

Using a puller. This technique is a modification of the previous one. The stem is subjected to a puller, comprising a claw attached to a pole 2.5 m long or more, depending on the worker's height. The claw is fixed at 30 cm from that end of the pole supported by the soil. The claw is hooked onto the stem close to its base and leverage is applied downwards on the pole so that the claw pulls the roots upwards out of the soil, as in the previous method (Figures 20-17 and 20-18).

Figure 20-17. Puller used by Thai farmers to harvest cassava.

Figure 20-18. Thai farmer using a puller.

This tool is commonly used in cassava-producing regions of Thailand.

Using a band. In the Colombian Coffee Belt, where soils usually have a medium texture, a type of belt or band is widely used. The farmer ties the band onto himself, then passes it over his back and shoulder, and ties it to the stem. That end of the band tied to the stem may be a strong rope or chain, which the farmer grasps and shakes to loosen the plant while his body acts as a lever.

Semi-mechanized harvesting

CLAYUCA has adapted and evaluated semi-mechanized systems of harvesting cassava. The importance of this activity lies in the excessive costs of manual harvesting, which requires 25 to 35 working days to harvest an average production of 30 t/ha. CLAYUCA imported two prototype harvesters developed in Brazil and evaluated their operation under the specific soil and climatic conditions of regions in Colombia where cassava is planted. Both the harvesters had the following components:

- A disk to cut the soil crust or plant cover
- An element to remove earth such as another blade or subsoiler
- A device to separate roots from soil adhering to the machine

Operation. Before a harvester is used, the following factors should be taken into account:

- Soil moisture. Dry soil makes harvesting cassava more difficult. However, soil moisture should be such that machinery can enter the plot without too much soil adhering to it.
- Planting density. These machines can loosen the soil of two furrows at once, as the blade's "wing span" is 1.2 m. If furrows are less than 90 cm apart, losses may occur because roots may be buried or broken. If the blade is more than 1.2 m wide, then the roots will not loosen satisfactorily.
- Tractor's operational speed. This speed should be constant throughout harvesting because any sudden change, when the implement is digging, will modify the implement's working depth, thus increasing losses through broken or buried roots.

To quantify yield for comparing with manual harvesting, the daily output per worker should be separated from the machine's output, which depends on tractor speed. A speed of 4 km/h is mostly used. It can be increased, however, depending on soil moisture and texture. Hence, a machine's average daily output is 6.4 ha.

Prototype descriptions. Model P 900 Flexible (Figure 20-19) has the following characteristics:

- Weight: 200 kg
- Daily output: 5 to 8 ha/8-h day
- Operation: harvests two furrows at the same time
- Planting distances are 80 to 100 cm
- Includes front cutting disk, which facilitates work
- Minimum soil removal, functioning as a subsoiler and leaving the soil prepared
- Works in soils difficult for manual harvesting
- Before operation, stems must be cut at 20 to 40 cm above soil surface
- Works at depths of 40 to 60 cm, depending on tractor type being used
- The tractor needs more than 90 hp of power

The rigid-blade model (Figure 20-20) is similar to the previously described model. However, instead of having points or weeding hoes, it has a solid blade system in the form of a "V". This system may generate compaction, damaging the soil.

Parameters evaluated. The principal parameters for evaluating the two prototypes were:

- Operation with each harvest method (ha/day)
- Root losses: entire roots (%), broken roots (%), and buried roots (%)
- Output of manual harvesting (kilograms of roots per day)

Figure 20-19. Prototype of a cassava harvester, model P 900 Flexible.

Results obtained. For harvester output, the results obtained during the prototype's evaluation were as follows (values are the average of several replications and trials):

- Operational speed: 7 km/h
- Depth of work: 30–40 cm
- Tractor power: 90 hp
- Maximum width of work: 2.4 m
- Output: 1.1 ha/h

The greatest benefits obtained from using this machine are reduced number of working days and less labor, with workers being limited to removing rubble and packing cassava. Under the traditional system, a worker pulls up between 500 and 800 kg/8-h working day. With semi-mechanized harvesting, CLAYUCA obtained yields of more than 1300 kg/worker per working day. In Brazil, harvesting systems have been developed with these machines to obtain outputs as high as 4000 kg/worker per working day. CLAYUCA also found that when semi-mechanized harvesting is

Figure 20-20. Prototype of a cassava harvester with a rigid "V"-shaped blade.

incorporated into a cassava production system, harvesting costs drop by 42.8%. That is, harvesting costs are reduced by 6% in the relative cost of labor to total production costs per hectare (Table 20-4).

Economic impact of semi-mechanized harvesting on cassava production. The importance of using harvesters for the cassava crop lies in reducing the number of workers needed for this activity. Table 20-5 presents the results obtained when prototype P 900 Flexible was evaluated in Colombia, and compares them with those of the manual system. Introducing the harvester reduced total production costs by 12%. Also, total harvesting costs were reduced by 42%. Such reductions stemmed from a 52% cut in labor costs. Economic impact is also created through the larger number of roots harvested per unit area, as the semi-mechanical harvester removes many more roots than do traditional harvesting systems.

Mechanized harvesting

In the continual search to improve the cassava crop's productivity and competitiveness, great progress was recently made in southern Brazil to develop a prototype that completely mechanizes cassava harvesting. A group of cassava growers and processors in Brazil financed the development and adaptation of a prototype that was based on a potato harvester. The prototype eliminates all labor from the initial harvesting phase, using workers only for selecting and packaging roots. This prototype is now being evaluated. Preliminary results are so far highly satisfactory. Two prototype models are being evaluated:

Model WH-15.2L. Figure 20-21 illustrates its characteristics:

- Weight: 700 kg
- Daily output: 5 ha/8-h day
- Cutting width: 80 cm
- Required power: 100 hp
- Works with a mat system, where soil is removed from the roots, using blades
- Before operation, stems must be cut at 20 to 40 cm above the soil surface

Model WH-CM 4000. Figure 20-22 shows that this model is similar to the previous model. It also does the following:

- Roots are mechanically taken up to a large sack ("big bag" type)
- It possesses a work platform where workers remove roots from stems

Table 20-4. General cost structure (cost/ha) for harvesting cassava, applying manual and semi-mechanized methods, in flat areas of the Department of Valle del Cauca, Colombia, 2000.

Activities[a]	Unit	Quantity	Unit value (Col$)[b]	Total value (Col$)[b]	RCD[c] (%)
(A) Manual harvesting					
Pulling up roots	Working day	25	10,000	250,000	
Packaging	Sack	180	90	16,200	
Fique string	Roll	1	5,500	5,500	
Total for labor				271,700	20.4
Total cost per hectare				**1,333,610**	
(B) Semi-mechanized harvesting					
Costs of machine, F and V	Col$/hour	1.14	4,014	4,576	
Costs of tractor, F and V	Col$/hour	1.14	18,203	20,751	
Workers for pulling up roots	Working day	10.5	10,000	105,000	
Tractor driver	Working day	0.15	21,000	3,150	
Packaging	Sack	180	90	16,200	
Fique string	Roll	1	5,500	5,500	
Total for labor				155,177	14.4
Total cost per hectare				**1,086,350**	

a. F and V = fixed and variable costs.
b. The exchange rate (year 2000) was 1 U.S. dollar = $2,100 Colombian pesos.
c. RCD = ratio between the costs of harvesting cassava and the total direct costs of cropping, expressed in percentage.

Table 20-5. Costs per hectare of harvesting a cassava crop, Valle del Cauca, Colombia, 2000.

Activity	Unit	Quantity	Unit value (US$)	Total value (US$)
(A) Manual harvesting[a]				
Harvest workers	Workers/day	30	4.60	138.00
Packaging	Sack	180	0.04	7.20
Fique string	Roll	1	2.50	2.50
Total harvest costs				147.70
Total costs per hectare				566.00
Harvest costs as proportion of total costs 26.1%				
(B) Semi-mechanized harvesting[a]				
Harvest workers	Workers/day	14	4.60	64.40
Packaging	Sack	180	0.04	7.20
Harvest costs per hectare, fixed and variable				9.50
Tractor driver				1.20
Fique string	Roll	1	2.50	2.50
Total harvest costs				84.80
Total costs per hectare				498.00
Harvest costs as proportion of total costs 17.1%				

a. With a production of 15 to 25 t/ha.

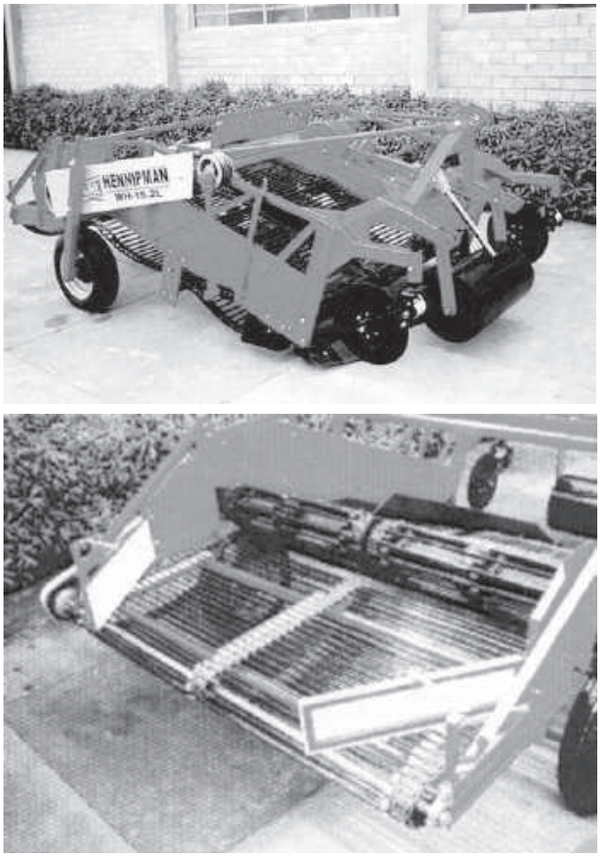


Figure 20-21. Prototype of a mechanical harvester, model WH-15.2L.

- The *big-bag* sack is released by a hydraulic system, enabling the machine to operate continuously
- Average capacity is 7 to 10 t/h
- Required power is 120 hp
- Cutting width is 240 cm
- The machine weighs 3500 kg

For the two machines to operate adequately, the crop must first be pruned to remove all aerial parts. The machine has blades 1.80 m wide, which are located at the front. They penetrate the soil to a depth of 30 cm, pull up the roots, and send them to a mechanical mat, where plant residues and some soil are removed. The roots immediately fall into a second higher mat, where the remaining adhering soil is removed. These first two phases are totally mechanized.

The roots then reach a third mat where workers remove the roots from their stems and place them in a central mat that takes them up to a *big-bag* sack (500-kg capacity) at the back of the machine. A worker controls the filling of this sack. When full, a device operates to deposit the sack on the ground and insert another sack, while allowing the machine to operate continuously (Figure 20-22, central right). The harvester is followed by a machine that winches the sacks off the ground and into a truck. The sack's

Figure 20-22. Prototype of mechanical harvester, model WH-CM 4000. Also shown are the use of the *big-bag* sack (central right) and the winch in operation (bottom right).

bottom opens up, discharging the roots in their entirety into the truck (Figure 20-22, bottom right).

This process completely eliminates the need for labor to carry roots to the truck. In some trials, this machine was able to lift as much as 70 tons of cassava during an 8 h working day, using 14 workers. These figures translate to an output of almost 5 t/worker per day. In a traditional harvest, for the same volume of roots, a minimum of 40 people would be needed.

Impact of mechanizing cassava planting and harvesting. The economic impact of mechanized harvesting can also be determined by the various technological options available to farmers to help them

increase productivity and competitiveness. In the cassava production systems of Colombia, for example, part of the cassava production is traded as raw material for the balanced-feed market, competing in price against imported grains, mainly maize. Cassava production systems aim to keep production costs per ton of cassava as low as possible so to attract the interest of processing plants that transform cassava chips into flour destined for balanced-feed industries.

Table 20-6 summarizes cassava production costs for the traditional production system, where traditional varieties are used and neither planting nor harvesting is mechanized. Table 20-7 shows costs for a modern technology system where planting is mechanized and harvesting is semi-mechanized. The traditional system produces 1 ton of cassava at a 12% higher cost than the system with mechanized planting and harvesting. This significantly higher profit, complemented by increased yields from high-yielding improved varieties (instead of traditional varieties), can represent economic success for the farmer.

Figure 20-23 presents an analysis carried out by CLAYUCA that compares different technological options available to improve the efficiency of cassava production. If the farmer maintains the traditional varieties, cost reductions are slightly less than for improved varieties. In any case, with traditional varieties, the introduction of mechanized planting and harvesting enables farmers to reduce costs per ton of cassava to US$21.20 (versus US$29.40 for the traditional system), a significant reduction of 27.9%. At this level, cassava harvesting begins to be highly competitive with imported grains.

The ideal situation is where farmers have easy access to improved varieties, and are also introduced to mechanized planting and harvesting. Such a technology package helps farmers reduce production costs per ton of cassava to US$17.50 (versus US$29.40 for the traditional system). This price represents a reduction of 40.5% in production costs, against the traditional production system. Such a highly competitive price enables the crop to become incorporated into different markets.

Social impact. The social impact of mechanizing cassava planting and harvesting is highly significant. Field labor, especially for harvesting, becomes more humane, as workers can more easily carry out their work, thereby increasing their efficiency. With the possibility of developing more competitive systems, business is encouraged to invest in agroindustrial projects involving cassava. This, in its turn, helps stimulate rural economies and generate jobs and income for farmers.

On increasing the competitiveness of one segment of the cassava production chain, that is, supply, with cassava produced at lower prices, a simultaneous effect is generated in the segment of demand, which stimulates markets. Cassava becomes more attractive as a raw material in many industrial fields. Benefits are thus generated for all participants in the production chain.

Environmental impact. The environmental impact of introducing mechanized cassava planting and harvesting has two aspects: first, mechanized or semi-mechanized harvesting leaves the soil practically ready for planting, thus avoiding the use of heavy machinery to prepare the soil before planting. Indeed, in some regions of Brazil, after cassava is pulled up, direct planting is immediately carried out. The second aspect is that, by removing most of the roots from the earth, fewer roots remain to rot and thus become foci of bacterial or fungal diseases. Hence, a mechanized cassava crop contributes to the general ecosystem by using fewer agricultural defenses.

Conclusions

1. The introduction of mechanized prototypes for planting and harvesting is a practice that has high potential for reducing labor costs, thus contributing to the crop's competitiveness.

2. The costs of the prototypes—between US$6500 and $15,000 for the planter and about US$4000 for the harvester (FOB Brazil)—is attainable. Farmer organizations (associations or cooperatives) can easily acquire and administer these prototypes to set up cassava production systems at lower cost and improve the crop's competitiveness.

3. The operation of both planter and harvester is simple and easily adapted for farmers and their families.

4. For field workers, for whom manually pulling up cassava roots is arduous work, the possibility of using a harvester means a more comfortable and healthier harvest, with an improved output for labor.

Table 20-6. Cassava production costs, using the traditional system.

Activity	Unit	Quantity	Unit cost (Col$)	Cost/ha (Col$)
Direct expenses				
Land preparation				**150,000**
Plowing	Pass	1	50,000	50,000
Raking	Pass	2	35,000	70,000
Furrowing	Pass	1	30,000	30,000
Stakes and planting				**353,000**
Cost of stakes	20-cm stake	10,000	20	200,000
Transport	Sack	12	2,000	24,000
Inputs for stake treatment		1	25,000	25,000
Labor for stake treatment	Wage	1	13,000	13,000
Manual planting	Wage	7	13,000	91,000
Weed control				**295,000**
Preemergent herbicides		1	70,000	70,000
Labor for applying preemergent herbicides	Wage	1	13,000	13,000
Manual weeding	Wage	13	13,000	169,000
Postemergent herbicides	Liter	1	30,000	30,000
Labor for applying postemergent herbicides	Wage	1	13,000	13,000
Liming				**88,000**
Dolomite lime	Sack	10	7,500	75,000
Labor for applying lime	Wage	1	13,000	13,000
Fertilizer applications				**296,000**
10–20–20	50-kg sack	7	33,000	231,000
Labor for applying fertilizers	Wage	5	13,000	65,000
Pest and disease control				**63,500**
Insecticides and fungicides		1	37,500	37,500
Labor for applying pesticides	Wage	2	13,000	26,000
Manual harvesting				**339,200**
Cutting and collection	Wage	23	13,000	299,000
Packaging	Sack	360	95	34,200
Fique string	Roll	1	6,000	6,000
		Subtotal direct costs		**1,584,700**
		Direct production costs per ton (25 t/ha)		**63,388**
Indirect costs				
Financial costs (24%)				380,328
Lease of 1 ha land per year				300,000
		Subtotal indirect costs		**680,328**
		Total production costs per hectare		**2,265,028**
Total production costs per ton (25 t/ha)				**90,601**

5. The argument against the use of prototypes—that they reduce labor as a source of employment—needs to be analyzed according to the specific context. In many cases, where the crop's commercial planting is promoted, investors will not become involved with cassava as a business unless they are certain that production costs are competitive. In this case, mechanized planting and harvesting become indispensable conditions. If the unit is in a context of small-scale cassava cultivation, farmer adoption of mechanized planting and harvesting would be insignificant.

Table 20-7. Cassava production costs, using a mechanized system.

Activity	Unit	Quantity	Unit cost (Col$)	Cost/ha (Col$)
Direct expenses				
Land preparation				**150,000**
Plowing	Pass	1	50,000	50,000
Raking	Pass	2	35,000	70,000
Furrowing	Pass	1	30,000	30,000
Stakes and mechanized planting				**289,005**
Cost of stakes	20-cm stake	2000	100	200,000
Transport	Sack	12	2,000	24,000
Inputs for stake treatment		1	25,000	25,000
Labor for stake treatment	Wage	1	13,000	13,000
Mechanized planting	Wage	0.32	13,000	4,167
Cost of machine	Col$/ha	0.78	2,100	1,638
Tractor: rent + driver + fuel	Day	1	8,200	8,200
Replanting	Wage	1	13,000	13,000
Weed control				**293,000**
Preemergent herbicides		1	70,000	70,000
Labor for applying preemergent herbicides	Wage	1	12,000	12,000
Manual weeding	Wage	13	13,000	169,000
Post-emergent herbicide	Liter	1	30,000	30,000
Labor for applying postemergent herbicides	Wage	1	12,000	12,000
Liming				**88,000**
Dolomite lime	Sack	10	7,500	75,000
Labor for applying lime	Wage	1	13,000	13,000
Fertilizer applications				**296,000**
10–20–20	50-kg sack	7	33,000	231,000
Labor for applying fertilizers	Wage	5	13,000	65,000
Pest and disease control				**63,500**
Insecticides and fungicides		1	37,500	37,500
Labor for applying pesticides	Wage	2	13,000	26,000
Semi-mechanized harvesting				**183,036**
Cutting and collecting stems	Wage	9	13,000	117,000
Cutting and collecting stakes	Wage	1	13,000	13,000
Packaging	Sack	360	95	34,200
Fique string	Roll	1	6,000	6,000
Cost of machine	Col$/hour	1.80	842	1,516
Tractor + driver	ha	1	11,320	11,320
		Subtotal direct costs		**1,362,540**
		Direct production costs per ton (25 t/ha)		**54,502**
Indirect costs				
Financial costs (24%)				327,010
Lease of 1 ha of land per year				300,000
		Subtotal indirect costs		**627,010**
		Total production costs per hectare		**1,989,550**
Total production costs per ton (25 t/ha)				**79,582**

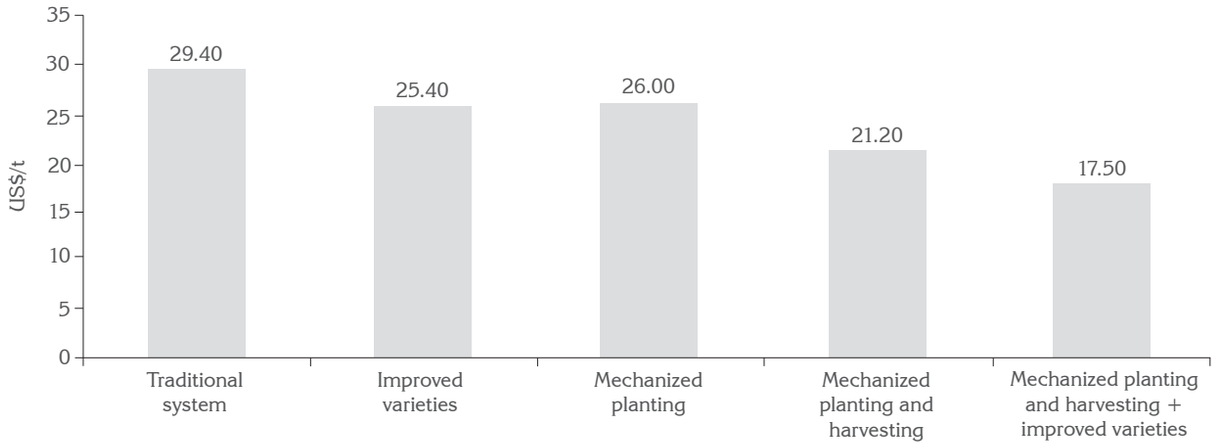


Figure 20-23. Differences in cassava production costs (in US$) according to technological option.

References

Cadavid L, LF; El-Sharkawy MA; Acosta A; Sánchez T. 1998. Long-term effects of mulch, fertilization and tillage on cassava grown in sandy soils in northern Colombia. Field Crops Res 57:45–56.

Cock JH; Castro M, A; Toro M, JC. 1978. Agronomic implications of mechanical harvesting. In: Weber EJ; Cock JH; Chouinard A, eds. Proc Workshop on Cassava Harvesting and Processing held in Cali, Colombia. International Development Research Centre (IDRC), Ottawa, Canada. p 60–65.

Conceição AJ da. 1976. A mandioca. In: Curso Intensivo Nacional de Mandioca, Cruz das Almas, Brasil. Empresa de Pesquisa Agropecuária de Minas Gerias (EPAMIG); Centro Nacional de Pesquisa de Mandioca e Fruticultura (CNPMF), Cruz das Almas, Bahia, Brazil. p 435–440.

Cuadra MA; Rodríguez MS. 1983. Estudio de diferentes métodos de plantación de la yuca (*Manihot esculenta* Crantz) y su relación con el rendimiento en el ecosistema de la provincia de Guantánamo. Cienc Téc Agric Viandas Trop 6(1–2):51–60.

Gurnah AM. 1974. Effects of method of planting, the length and types of cuttings on yield and some yield components of cassava (*Manihot esculenta* Crantz) grown in the forest zone of Ghana. Ghana J Agric Sci 7(2):103–108.

Lozano JC. 1978. Posibles efectos del ecosistema en algunas especies de cultivos tropicales. Fitopatol Colomb 7(2):94–107.

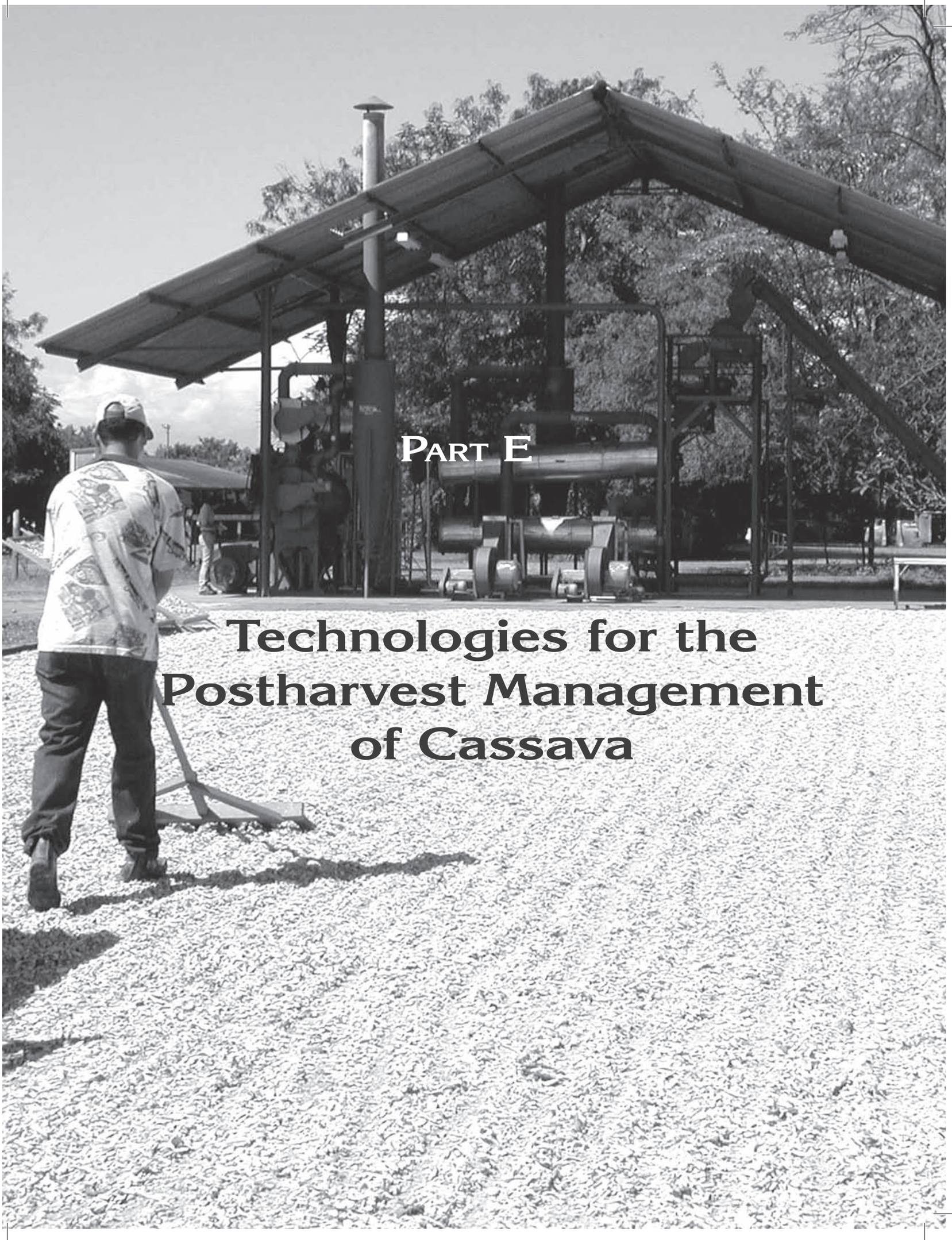
Lulofs RB. 1970. A study of method and costs for commercial planting of tapioca in Kedah. In: Blencowe EK; Blencowe JW, eds. Crop diversification in Malaysia. Incorporated Society of Planters, Kuala Lumpur, Malaysia. p 149–166.

Normanha ES; Pereira AS. 1974. Resultados e experiencias sobre épocas de plantío da mandioca. Rev Agric (Piracicaba) 22 (4/6):135–142.

Ribeiro FJ. 1996. Cultura da mandioca. Escola Superior de Agricultura [of the] Universidade Rural do Estado de Minas Gerais, Viçosa, Brazil. 80 p.

Solórzano H, A. 1978. Resultados de investigación para la yuca. In: Transferencia de resultados de investigación agropecuaria a los agentes de producción de la Región XII–Loreto, Tarapoto, Perú, vol 2. Centro Regional de Investigación Agropecuaria del Oriente y Cooperación [of] IICA–Peru, Lima. p 19–31.

Toro M, JC; Celis E; Jaramillo E. 1976. Métodos de cosecha de yuca. In: Curso sobre producción de yuca. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia. p 225–232.



Part E

Technologies for the Postharvest Management of Cassava

CHAPTER 21

Natural Cassava Drying Systems

Bernardo Ospina Patiño[1], *Rupert Best*[2], *and Lisímaco Alonso*[3]

Cassava is a major tropical crop. It has high potential for the development of agroindustries such as the manufacture of balanced rations for animals. However, if cassava starch is to replace cereal grains in such industries, the crop's starchy roots must first be dried.

Cassava can be dried either naturally or artificially. Methods differ not only in the technology used but also in their costs. Natural drying takes advantage of solar and wind energy, which restricts drying times to the year's dry seasons. In contrast, artificial drying demands a different type of energy such as fossil fuels (oil, coal, or gas) or agricultural residues (sugarcane bagasse or rice husks). It does not depend on climatic conditions.

Despite being restricted to dry times of the year, sun and wind drying is usually economic and very useful in sites where other energy sources are limited or costly. Natural cassava drying is simple and easy for farmers to carry out.

Farmers may organize themselves into associations and cooperatives for the integrated exploitation of the cassava crop (i.e., production, processing, and marketing), thus creating an alternative to the instability of the fresh-cassava market. Such organization also presents the possibility of marketing a higher production (Best and Gómez 1983).

Producing Dried Cassava Chips

Dried cassava chips are produced as follows: cassava roots are harvested, weighed, and chipped. The chips are then dried, packed, and stored. Optional operations may include washing the roots before chipping, or milling the already dried chips, depending on market requirements (Figure 21-1).

Harvest

Cassava is harvested manually and is transported in several vehicles to the drying plant, either packed or in bulk (Figure 21-2). As soon as possible, the roots are subjected to quality control. At harvest, stem fragments are removed, stones and accompanying lumps of earth are discarded, and those roots that look infested are separated.

Cassava roots that have low dry matter (DM)[4] content negatively affect the efficiency and profitability of the process. They are therefore considered as being of lesser quality. Dry matter content depends not only on the variety planted and on edaphoclimatic conditions, but also on the age and plant health of the crop at harvest.

Once harvested, the roots should be taken quickly to the plant so that they are immediately processed. Roots that are processed later than 48 hours after harvest will deteriorate rapidly and their drying results in a poor quality product.

Weighing the fresh roots

In the drying plant, cassava roots are weighed on a platform scale that can carry several sacks at once, thus facilitating the operation (Figure 21-3).

Weighing the roots before drying and the chips afterwards permits the determination of "yield", both for

1. Executive Director, CLAYUCA, Cali, Colombia. E-mail: b.ospina@cgiar.org
2. Chemical Engineer, formerly Leader, Rural Agroenterprise Development (RAD) Project, CIAT, Cali, Colombia. E-mail: r.best@cgiar.org
3. Agricultural Engineer, Postharvest Management Systems, CLAYUCA. E-mail: l.alonso@cgiar.org

4. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, abbreviations, and Technical Terminology*, this volume.

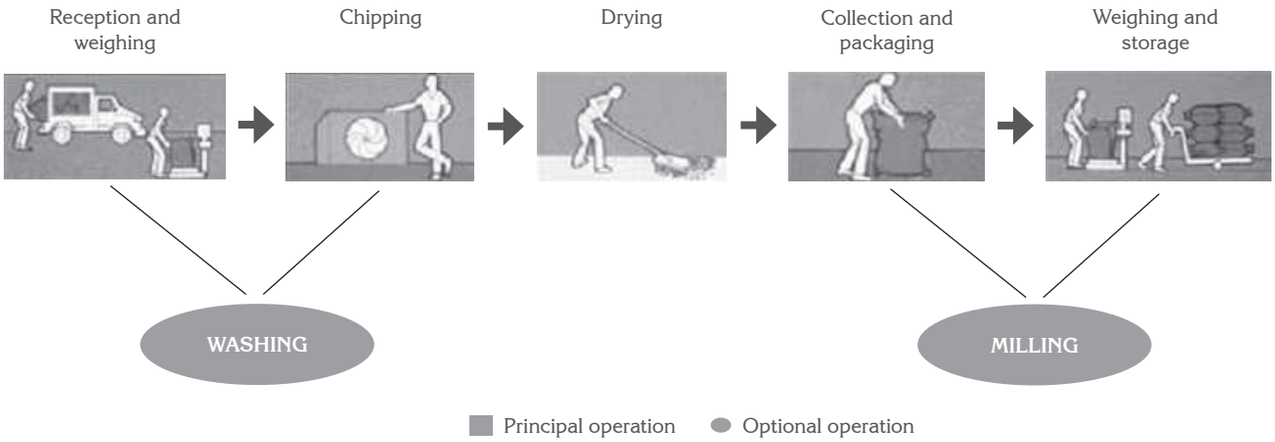


Figure 21-1. Obtaining dried chips from cassava roots, using natural processing.

Figure 21-2. Manual harvesting of cassava roots and their transport to the drying plant.

the cassava varieties used and the process itself. Cassava varieties differ in their yields of dried chips. Hence, identifying the region's best yielding varieties becomes highly important. Furthermore, a given variety may present a certain yield in one drying process and another in a different process. To control such differences, the variety must be evaluated and weighed according to the evaluation of different lots of roots.

Washing

If soil is left adhering to fresh roots, the dried product may have high ash content, especially of silica, which will reduce its quality.

Soil adheres to roots when they are harvested during a rainy season or from heavy soil. Hence, the

Figure 21-3. Weighing sacks of cassava roots.

roots must be washed in either small troughs or washing machines, as shown in Figure 21-4. These machines consist of a rotary drum that shakes the roots while washing them with a pressurized water jet applied inside or outside the drum. In a natural drying plant, cassava roots almost never need washing because drying occurs at the same time as harvesting, that is, in summer. The roots therefore arrive from the field with little soil adhering.

Cassava roots destined for animal feed do not need to have the inner or outer root peel removed.

Chipping

To dry roots more quickly, as large a root surface area as possible should be exposed to the air. This is

(A) **(B)**

Figure 21-4. Washing cassava roots in troughs **(A)** or with a machine that features a rotary cylindrical drum **(B)**.

Figure 21-5. Cassava chipping machine in operation, using a "Thailand" type disk.

achieved by cutting them into small and uniform pieces, that is, into chips, a task that can be carried out with a chipping machine (Figure 21-5).

Drying

The drying of cassava chips involves eliminating most of the moisture they contain when they are fresh. The resulting dried product can be stored over long periods, without deterioration. The most common methods of drying chips can be classified according to level of technology and cost:

- Continuous drying in rotary dryers or conveyor belt
- Drying by batches in dryers with static layers and using forced hot air
- Natural drying, using solar and wind energy, on concrete floors or on inclined trays

Selection of method depends largely on the amount of cassava roots to be dried, availability of capital, labor costs, and availability of relatively inexpensive energy sources. In this chapter, natural drying is described.

Natural drying takes advantage of solar energy and of the action of air currents to evaporate moisture from cassava chips. Two technologies are available: drying on concrete floors (or in Spanish called *patios*) and drying on inclined trays.

Technology 1:
Drying Cassava Chips on Concrete Floors

With this technology, cassava chips are spread out on concrete floors so that they are exposed to the direct action of both solar radiation and the latent heat of surrounding air currents. This stage includes two basic operations: spreading the chips in the drying area and turning them over frequently until they are completely dry.

Spreading the chips

A wheelbarrow is used to deposit freshly cut chips into small heaps that are then raked out uniformly over the drying floor's surface (Figure 21-6).

Each square meter of floor should carry 8 to 12 kg of fresh chips, a load that should dry within 2 days under normal climatic conditions. A larger amount of chips per square meter will delay drying, thus reducing the drying plant's efficiency and degrading the chips' final quality. A smaller quantity, however, will not take advantage of the plant's productive capacity.

Turning the chips

All the chips must be consistently dried so that the end product is of good quality. To achieve uniform drying, the chips should be turned over every 2 hours (i.e., 6 to 8 times a day), especially during the initial hours of drying, when most of the moisture is lost.

At night, the chips may remain spread out on the concrete floor, unless rain is likely. In this case, the chips should be stacked at the highest level of the concrete floor and protected by a plastic or canvas cover. The next morning, they are spread out again. Turning over, done with a wooden rake, should continue until the chips are dried. The rake's tines form furrows that expose moist areas of floor to direct solar radiation (Figure 21.7).

Figure 21-6. Wooden rakes are used to spread cassava chips over the concrete floor.

Collecting and packing

When the chips' moisture content is 10% to 12%, they are collected and packed. In drying plants, this level of moisture is determined by feel. If the chips are sufficiently dry, they break easily when squeezed between fingers. They can also be used as writing chalk.

Collecting chips requires two types of shovels: one wide and wooden, and used to pile up the dried chips (Figure 21-8); the other is short and metal, and used to

Figure 21-7. Cassava chips are turned over every 2 hours, using wooden rakes. The rakes may be constructed at the plant itself, especially for this task.

Figure 21-8. Dried cassava chips are collected by piling them up in the concrete floor, using a wooden shovel.

pack the heaps into bags or sacks of either polypropylene or fique (also called *cabuya*; from the plant *Furcraea andina* Trel.). For this task, two people are usually needed: one to keep the sack's mouth open as the other shovels in the dried chips. A metal funnel can also be used, with its stem emptying into an open sack suspended from a framework (Figure 21-9). A fique sack can carry 40 to 50 kg, but if the dried chips are tamped down as the sack is filled, the weight can be higher (Figure 21-10).

Milling

Transporting cassava chips to distant places is costly because of their low weight per unit of volume. Hence, chips are sometimes milled to obtain flour, which is then packed in bags of either polypropylene, paper, or cloth. Milling is carried out with a hammer mill, to which cloth filters are adapted to capture the fine powder that results from the operation (Figure 21-11).

Figure 21-9. A metal funnel facilitates packing the dried cassava chips.

Figure 21-10. Tamping down dried chips in sacks. Sacks weighing over 50 kg can then be obtained.

Figure 21-11. Milling dried cassava chips.

However, cassava is usually marketed as chips because quality control of flour in consumer companies or concentrate-feed factories is not easy.

Storage

The drying plant should have a storeroom where the dried chips are kept until shipped to purchasing companies. The sacks should be stacked on wooden platforms or pallets (Figure 21-12).

If storage conditions are adequately controlled, the dried chips (i.e., with 10% to 12% moisture content) can be stored for as long as 6 to 12 months without their quality deteriorating. Optimal conditions are achieved if the storeroom is kept very clean and if aeration mechanisms are installed that adequately move moisture between storeroom and exterior.

If storeroom humidity is too high, the dried chips absorb the moisture, which, together with high starch content, stimulates the growth of fungi on the chips. These produce toxins that ultimately prevent the chips' use as animal feed.

Figure 21-12. In the storeroom, sacks of dried cassava chips should be stacked on pallets or wooden platforms.

Stored dried chips can also be attacked by insect pests. At least 38 species of insects, mostly of the order Coleoptera, have been identified, although the important ones are those that can reproduce in the chips. Studies conducted at CIAT indicate that *Araecerus fasciculatus* and *Sitophilus oryzae* can cause major losses of dried chips (Figure 21-13).

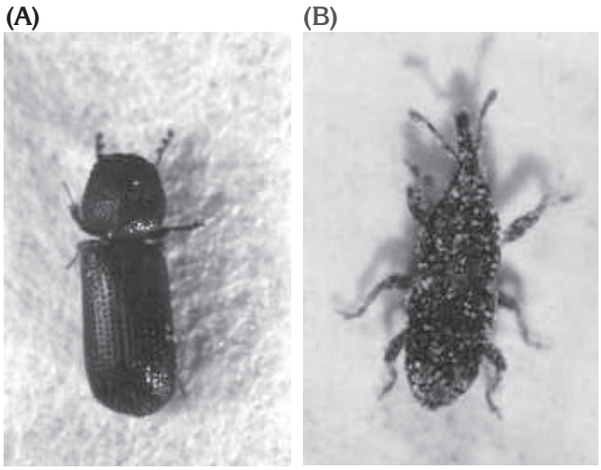


Figure 21-13. The weevils *Araecerus* sp. **(A)** and *Sitophilus oryzae* **(B)** can cause major losses to stores of dried cassava chips.

Figure 21-14 illustrates the moisture loss curve at different stages of the drying procedure for cassava chips, from harvest to storage, and indicates the normal duration of each stage.

Quality standards for dried cassava chips

Dried chips are used mainly to totally or partially substitute cereal grain in the formulation of balanced feeds for animals. Their quality should therefore be adjusted to the standards required by the companies processing this product (Table 21-1). In addition to

Table 21-1. Basic standards for quality as required by companies using dried cassava.

Component or aspect	Standard
Moisture content (%)	12.0
Crude fiber, maximum (%)	5.0
Ash, maximum (%)	3.5
Fungi and yeasts, maximum count (cfu/g)	100,000
Aflatoxins and ochratoxins	Absent
Total cyanide (ppm)	100
Coliforms, total (cfu/g)	600
Presentation	Chips

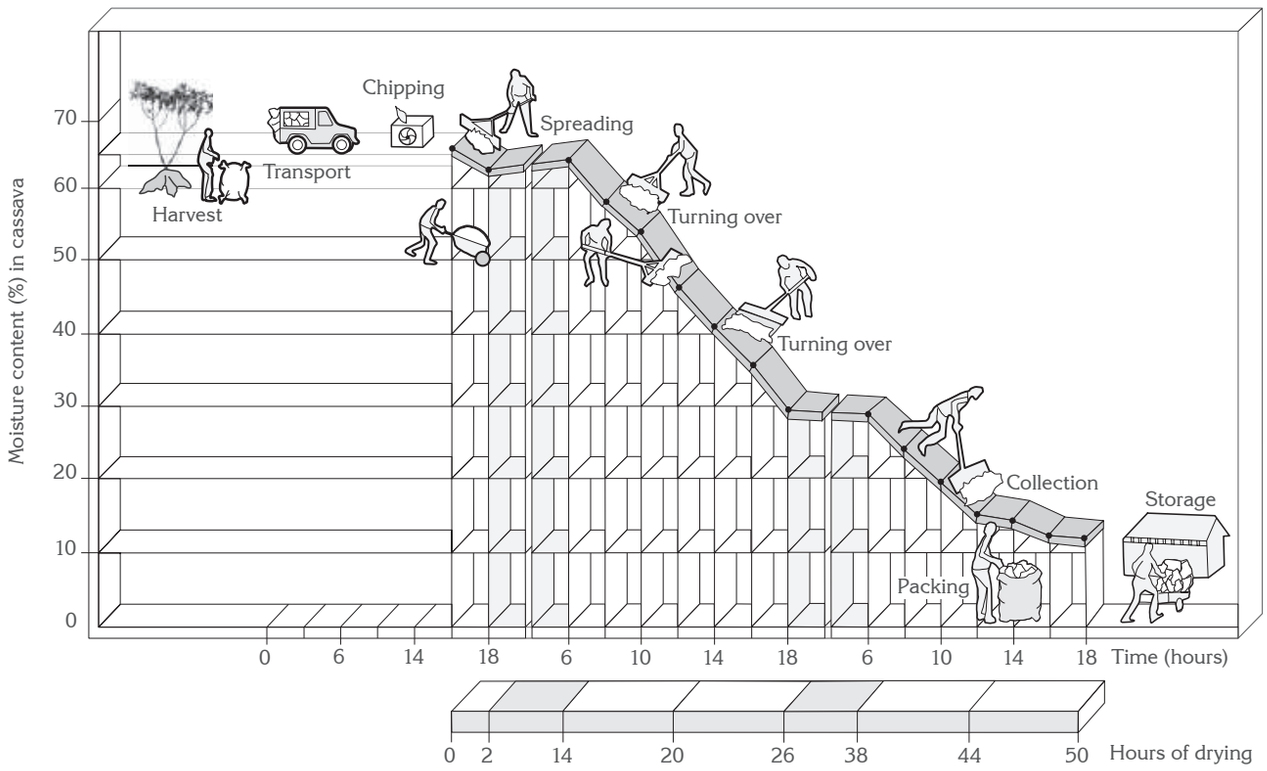


Figure 21-14. Moisture loss curve at different stages of drying cassava chips, assuming normal conditions. The duration of each stage and of the entire process is also indicated.

these standards, the product should comply with the following requisites: it should be fresh, have no fermenting odor, and present no signs of insect attack or contamination.

Infrastructure of a cassava drying plant

Before installing a cassava drying plant, its location should be carefully chosen with respect to its distance from sites supplying the raw material and access to good roads. Also desirable are nearby sources of water and electric power. The minimum infrastructure of a drying plant consists of a drying concrete floor, an area for chipping, and a storeroom.

Drying concrete floor. Cassava chips are exposed to solar radiation on a surface designed to resist exposure to the sun, that is, it will not crack. It must also be smooth to permit easy sliding of the rakes and shovels used to spread, turn over, and collect cassava chips. The drying area should not be surrounded by trees, buildings, or other similar obstacles that may reduce natural ventilation or shade the area. Furthermore, the natural slope of the land should be taken into account so that the concrete floor has a slope that allows rainwater to drain.

The construction of a drying floor is specific to each region, making it highly advisable that farmers participate in its construction, as it will be built under their organization. Hiring an expert mason should always be recommended so that he leads the works. Construction is as follows:

- The first step is *to choose the area* that the patio will occupy. Plant cover is removed, the land leveled, and the exposed surface compacted. Good compaction guarantees the work's quality. During compaction, the center of the concrete floor should remain at a higher level than the sides. Such "crowning" will facilitate rapid drainage of rainwater.

- The *floor's foundations* are then made at the perimeter of the concrete floor. The foundations should be 20 to 30 cm wide and 30 to 40 cm deep, and built with either poured or block concrete. The floor itself is also made of either poured or block concrete. If only people are passing through its area, then the floor may be 10 cm thick, but if heavy motor vehicles are expected to circulate on the floor, then it should be 15 to 20 cm thick and reinforced with iron. The concrete should be a mixture of cement, clean sand, gravel that is free of earth and lumps, and water. The proportions for mixing depend on the soil's characteristics. In general, clayey soils require a mixture of cement, sand, gravel at 1:2:3, and sandy soils at 1:3:4. However, the correct proportions of these components depend on the mason's or builder's experience. Table 21-2 indicates the quantities of the elements needed to prepare one cubic meter of concrete according to the specified mixture.

- The third step is *to pour the concrete* onto the area prepared for the floor. The area of construction should be divided into slabs of 2×2 m, leaving narrow separations in between, into which "expansion joints" are placed. These are simply wooden strips that are removed at the end of the work (Figure 21-15A). To reduce the risk of the floor cracking, pieces of iron rod should be placed between slabs, so that they serve as joining elements when the slabs meld (Figure 21-15B).

- The fourth step, once the floor is cast, is *to finish and correct* it, including fixing any remaining cracks. The wooden strips serving as expansion joints are then removed and the separations between slabs filled with either a mortar made of cement and sand or with tar. Figure 21-16 shows the final appearance of a drying area.

The division of the drying area into 2×2 m slabs has the advantage of helping workers distribute adequate amounts of cassava chips per unit of area.

Table 21-2. The quantities of cement, sand, gravel, and water needed to prepare 1 cubic meter of concrete, according to the proportions required.

Proportions	Component			
	Cement (kg)[a]	Sand (m^3)	Gravel (m^3)	Water (L)
1:2:2	420	0.670	0.670	192
1:2:3	350	0.555	0.835	158
1:2:4	300	0.475	0.950	135
1:3:3	300	0.715	0.715	135
1:3:4	260	0.625	0.835	124
1:3:5	230	0.555	0.920	101
1:3:6	210	0.500	1.000	94

a. One cubic meter of cement is sufficient for 12.5 m^2 of flooring, 8 cm thick.

(A) **(B)**

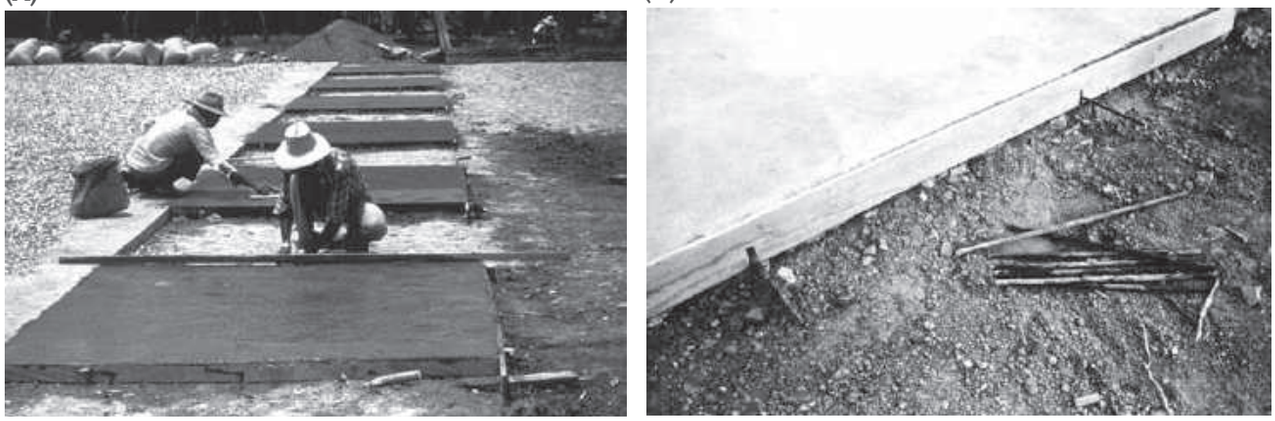


Figure 21-15. Expansion joints are placed between concrete slabs **(A)**, together with iron rods **(B)**.

Figure 21-16. Final appearance of a drying concrete floor for cassava chips.

Applying the recommended load of fresh chips at 12.5 kg/m^2 of floor, a slab of 4 m^2 (2 × 2 m) should receive 50 kg. This quantity is about the same as a wheelbarrow load. Simply put, a barrow load per slab is the optimal load for the drying area.

Chipping area. The area where the chipping machine is installed should be sufficient to allow workers to move easily and also leave room for the raw material to be chipped. A chipping area of 16 m^2 (i.e., 4 × 4 m) is adequate for plants that have 500 to 1000 m^2 of drying floor.

This area should also have roofing to shade the workers and prevent the chipping machine from deteriorating through the action of sun and rain. In addition, next to this area, roofing should be built to cover the reception site for the roots, protecting them from sun and rain, and preventing their quality from deteriorating. This additional roofing can be constructed with typical materials of the region (Figure 21-17).

Figure 21-17. View of the roofing complex used to cover the cassava chipping machine and to protect the fresh cassava roots received for processing.

The chipping area should be close to where roots are received to prevent unnecessary movement within the plant. The slope of the floor in this area should be away from the drying area so that washing water from the chipping machine and rainwater do not drain over the chips being dried (Figure 21-18).

The chipping area will be subject to vibrations and its floor must therefore support a higher weight per unit area than that of the drying area. Its floor should therefore be resistant, having foundations that are of poured or block concrete. The foundations should be 40 cm deep and 40 cm wide, and the floor 15 cm thick, being composed of a mixture at 1:3:5 (Figure 21-19). A wooden framework supports this area's roofing, which may consist of zinc sheets, asbestos-cement tiles, or typical materials of the region (e.g., palm leaves).

Storeroom. The storeroom guards the dried cassava chips, tools, and equipment used for drying. The storeroom's size depends on the drying plant's capacity, periodicity of shipping the product, and future expansions of drying capacity.

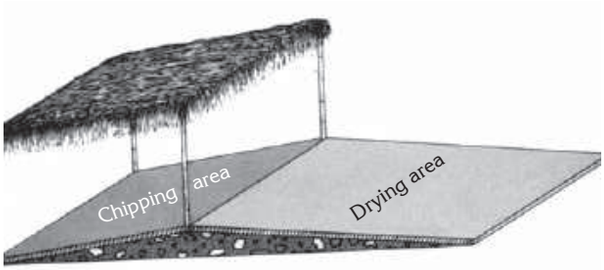


Figure 21-18. The floor of the cassava chipping area must slope away from the drying area for the chips.

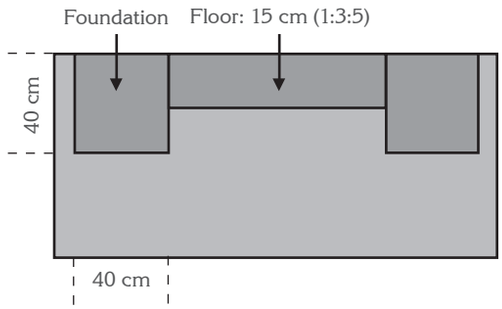


Figure 21-19. The cassava chipping area should have a resistant floor.

About 350 kg of dried chips can be stored in 1 m^3 of storeroom. One that is 140 m^3 (10 × 4 × 3.5 m) can store about 30 t of dried chips, which is the production of a 1000-m^2 drying concrete floor over 18 days. If the dried product is shipped from the plant every 2 weeks, the storeroom will not have problems of congestion or aeration. A 1-m space should be left between the top of the stored stack of dried chips and the storeroom's ceiling.

The storeroom's foundations should be 30 to 50 cm deep and 40 cm thick. If the walls are very long, columns should be constructed in the wall every 3 or 4 m and the foundation under each column should be 60 to 70 cm (Figure 21-20).

The storeroom's basic structure consists of the following elements:

- Lower tie beams placed immediately above the foundations, and perfectly joined to give the walls solid support.
- Columns.
- Walls made of brick or concrete blocks.
- Upper tie beams to bind the columns and support the roofing (Figure 21-21).

Figure 21-20. Laying down a foundation to support the external walls of a storeroom.

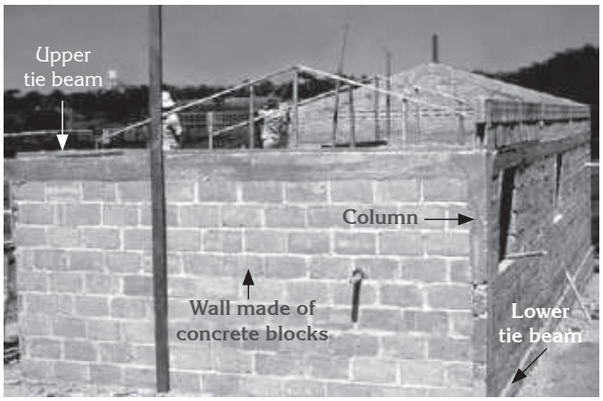


Figure 21-21. Elements of a storeroom's basic structure.

The storeroom should have mechanisms that control aeration or change of air. The opening of all doors for a short time is also useful. Concrete fretwork placed along the upper lengths of the walls (Figure 21-22) forms a good system for ventilating the storeroom, particularly when insecticide applications

Figure 21-22. Wall with concrete fretwork running along its upper length.

are carried out. However, such fretwork is not suitable for long-term storage.

The roofing consists of a framework of wooden beams that support asbestos-cement tiles, zinc sheets, or typical materials of the region. It should be gabled, with adequate slopes.

Before constructing the storeroom floor, a cement base must be set to serve as an initial floor to prevent moisture from creeping up to the surface of the real floor. On this base, the final floor, consisting of a reinforced but thin slab of concrete, is placed. It must be as smooth as possible. The bags of dried cassava chips must not be allowed to have direct contact with the floor. Hence, wooden platforms or pallets that rise 10 to 15 cm high from the floor should be installed and the sacks of dried chips stacked on these.

The storeroom's external structures should include a pathway around it and good drainage that will prevent rainwater from accumulating and forming muddy areas.

Equipment for a drying plant

The minimum equipment for a drying plant consists of the following: platform scale, chipping machine, tools for drying and collecting chips (wheelbarrow, wooden rakes, and shovels), sacks, and a plastic or canvas cover to protect the concrete floor when necessary.

Platform scale. The platform scale should be able to weigh several sacks at once. A 500-kg capacity is acceptable for natural drying plants.

Chipping machine. Commonly used models are known as "Thailand" (Figure 21-23A) or "Colombia" (Figure 21-23B) types. The "Thailand" machine basically consists of a metal structure and cutting disk. The structure supports the pulleys, linchpin for the disk, and feed hopper. The motor's support is also coupled to the machine's main structure, as in the "Colombia 1" type (Herrera et al. 1983), (Figure 21-23B).

The machine may be powered by either an electric or internal combustion (gasoline or diesel) motor. The gasoline motor should have between 8 and 10 hp (Figure 21-24), whereas an electric motor may have 5 hp. This motor is the most important component of the plant's equipment because any deficiency in its operation alters the normal drying process. The workers must therefore be adequately trained to run it and give it rigorous maintenance.

(A)

(B)

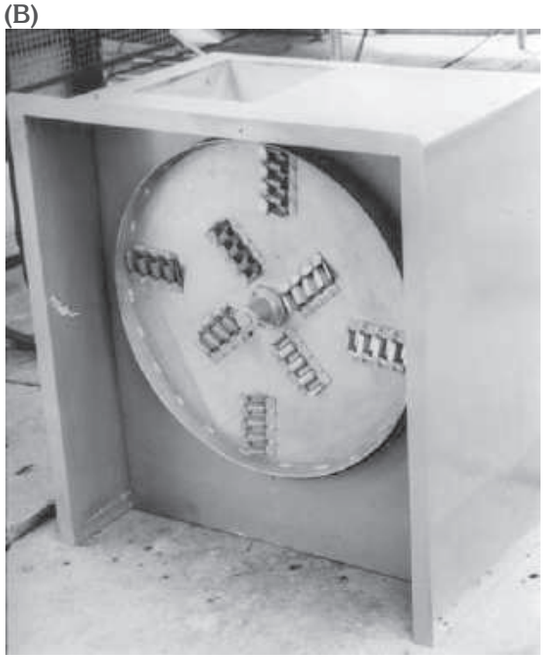


Figure 21-23. Cassava chipping machines, type "Thailand" **(A)** and type "Colombia" **(B)**.

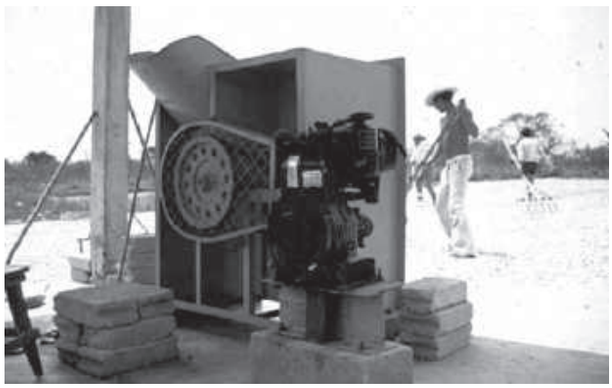


Figure 21-24. An 8-to-10-hp internal combustion motor (gasoline) is needed to operate a cassava chipping machine.

Implements for drying and collecting. The following tools are needed:

- An ordinary *wheelbarrow* with a 50-kg capacity. It is used to distribute cassava chips into heaps on the drying concrete floor at a barrow load per area of 2 × 2 m.
- Several *wooden rakes* to spread and turn over cassava chips. Their form and dimensions are indicated in Figure 21-25A.
- Two types of *shovels* to manage the dried chips. One type is wooden, with the blade being wide, flat, rectangular, and finishing on a fine edge to help pile up the chips (Figure 21-25B). The other type of shovel is the usual metal one. These are used to pick up and pack the chips.
- A sufficient number of *sacks* for both purchasing fresh cassava roots, and for storing and marketing dried chips. The best sacks are those of fique or jute, which have a larger capacity and can be used several times over. Polypropylene sacks have a smaller capacity and last for less time but are less expensive.
- A *plastic cover* to protect cassava chips in the drying concrete floor from unforeseen rains. During winter, the plastic helps dry the chips, albeit on a small scale. For a plant with 500 m^2 of concrete floor, a 250-m^2 plastic cover is sufficient.

Conditions for establishing the natural drying plant

A drying plant will be successful if its management of the production, processing, and marketing of dried chips is well planned and coordinated. Having real data on each stage is therefore indispensable when analyzing the economic feasibility of setting up a plant. The following aspects should be considered:

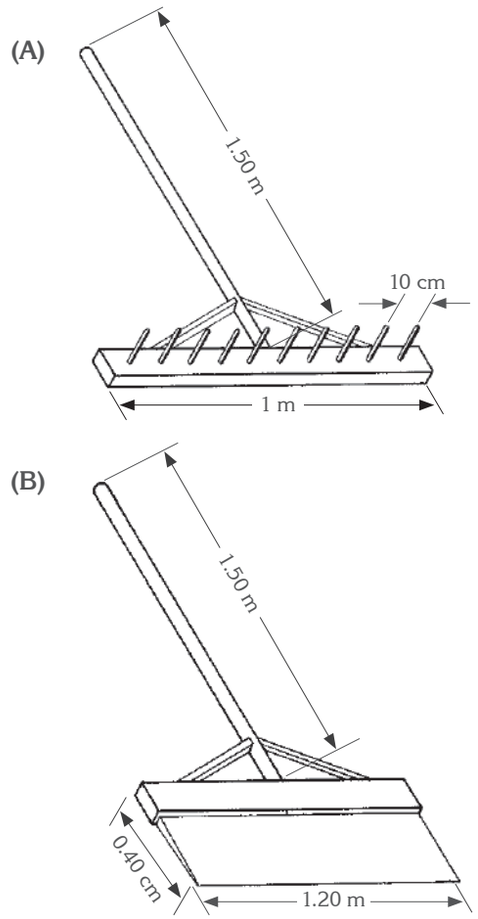


Figure 21-25. Tools for cassava chip drying: **(A)** wooden rake to spread and turn over chips; and **(B)** wooden shovel for piling up dried chips.

- Production of fresh cassava roots in the plant's area of influence
- Plant size and capacity for processing dried chips
- The correct administration and operation of the plant
- The financing required
- Marketing the dried cassava chips

Cassava production in the plant's area of influence. The timely production of fresh cassava roots—the drying plants' raw material—is a significant factor to consider before installing such a plant.

Roots are usually available for processing only when the fresh-cassava market has surpluses, as this

market is, in many places, the principal and almost exclusive channel for marketing cassava. Hence, the offer of raw material for dried chips becomes discontinuous and seasonal. To ensure a continuous and sufficient offer, the cassava crop's productivity must increase considerably. Production costs would therefore be reduced, making root prices more competitive and the cassava-drying agribusiness more profitable.

The organization of farmers in the region into cooperatives or associations that produce and process cassava roots, and receive technical assistance and credit from official entities, is an initiative that would ensure availability of roots for the drying plant. Hence, these groups must incorporate farmers able to obtain good cassava production. Otherwise, the plant would depend on the offer of raw material from farmers outside its area, thus making it dependent and vulnerable as a company. Hence, the socioeconomic profile of a cassava drying plant's potential owners is, perhaps, the most important factor in its establishment and size.

In the Colombian North Coast, cassava-drying companies are constituted by farmers with little capacity to produce cassava. They therefore have difficulties in achieving an acceptable level of profitability. Thus, when a cooperative or association is organized to operate a drying plant, it must establish a suitable procedure for selecting its members to ensure supplies of the raw material needed for the plant's efficient operation.

Plant size and capacity.

Plant size. Feasibility studies and experiences so far obtained indicate that the minimum area for the profitable drying of cassava chips is 500 m^2. To date, plants of 1000 to 2000 m^2 of drying floor have functioned with good results. A new plant should therefore begin with 500 m^2 to expand later when the farmers have completely mastered the drying technique (Ospina and Best, 1984).

To discover the size of the future plant, the area's cassava production must be calculated and the socioeconomic profile of the plant's potential owners described. This information should indicate the probability of obtaining enough raw material and of maintaining the company stable.

The quantity of chips that a plant can dry depends on three factors: the duration of summer, the load of chips that can be dried per square meter, and the drying area's capacity.

Duration of the dry season. Natural drying is based on the use of solar energy. Hence, the summer months of the region where the plant will be established must be known. In the Colombian North Coast, for example, the main dry months are December to March and part of April. A second semester of dry climate is July to September. In total, the region has about 20 weeks during which drying can take place.

Load of fresh chips per square meter. The optimal load of chips (kg) for drying per square meter of floor for 2 days is then determined. Two days is used for calculation because the most efficient advantage is taken of the plant in this time, with three batches of chips being dried per week. In the Colombian North Coast, the optimal chip load is 12.5 kg/m^2. On days of little solar radiation, during climatic transitions, smaller loads are used.

Determining a plant's capacity. A plant's capacity for processing is calculated by using the previous three parameters: plant size, duration of summer, and fresh chip load (Table 21-3).

Amount of fresh chips that can be dried per year. The annual capacity for drying per square meter of concrete floor would be:

$$12\ kg/m^2\ per\ batch \times 3\ batches/week \times 20\ weeks/year = 720\ kg/m^2\ per\ year$$

Hence, on a 500-m^2 floor, 360,000 kg, that is, 360 t, of fresh chips could be dried per year.

Determining the conversion factor (c.f.). The amount of dried chips that can be obtained from a given batch of fresh cassava roots may be discovered by first determining a conversion factor for the cassava variety that was harvested. To calculate it, the cassava's moisture content should be determined, both at the beginning and end of the drying process.

Table 21-3. Value of parameters determining a plant's capacity for processing dried cassava chips in the Colombian North Coast, 2000.

Parameter	Unit
Duration of the dry season	20 weeks
Load of fresh cassava chips	12 kg/m^2
Drying time per batch	2 days
Batches per week	3
Drying area	500 m^2

The c.f. is a parameter that relates directly with the dry matter (DM) content in the cassava being processed. When roots have been attacked by disease or a pest (e.g., cassava hornworm), DM content at harvest may be very low and thus the c.f. would be very high. Climatic conditions (e.g., rain during harvest) may also affect a variety's DM content and therefore its c.f.

Another factor that affects the c.f. is the farmers' management of the drying technology. For example, if they dry the chips too much (i.e., to less than 12%), the c.f. is high.

The c.f. can be calculated, using, for example, 1000 kg of chips from recently harvested fresh cassava roots that had a moisture content of 65%, and were dried on a concrete floor until the final moisture content was 12%. If a sample of 398 kg of chips is then taken, the c.f. would therefore be:

$$\text{c.f.} = 1000/398 = 2.5$$

Note that the DM should be constant. The 1000 kg of roots, which had 65% moisture content, had 650 kg of water and 350 kg of DM. On drying, most of the water was eliminated from the chips, but the DM was conserved. Accordingly, the 398 kg of dried chips at the end of the process should contain 350 kg of DM. The remaining 48 kg would represent the 12% of final moisture content in the chips.

Calculating dried chip production. The c.f. can be used to calculate the quantity of dried chips that the plant can produce per year. If we assume that the 360 t of fresh chips (FC) that a plant of 500 m^2 processes in 1 year will yield 144 t of dried chips (DC), then the c.f. is 2.5:1 (FC to DC), that is:

$$\frac{360 \text{ t FC}}{144 \text{ t DC}} = 2.5 \text{ FC to } 1 \text{ DC}$$

The c.f. of 2.5 can then be used to calculate the likely production of dried chips from different fresh-chip loads of the same variety processed at the same plant.

Table 21-4 shows the quantities of dried chips that are obtained from processing fresh cassava roots according to drying area and period of drying.

Administration and operational organization. A natural cassava drying plant functions correctly if the plant's group of farmer-owners is well organized. The plant should therefore have a manager or administrator, a treasurer, and a production head.

Table 21-4. Quantities of dried cassava chips obtained by plants with different-sized drying areas and summers of different duration.

Drying area (m^2)	Dry climate (weeks/year)	Annual capacity for processing		Required production (ha/year)[b]
		Fresh roots (t)	Dried chips (t)	
500	12	216	87	27
	16	288	115	36
	20	360	144	45
1000	12	432	174	54
	16	576	230	72
	20	720	288	90
2000	12	864	348	108
	16	1152	460	144
	20	1440	576	180

a. Using a conversion factor of 2.5:1, where 2.5 t of fresh cassava roots is processed into 1 t of dried cassava chips.
b. Calculated area, assuming that the cassava variety yields 8 t/ha of fresh cassava roots.

- The *manager* or *administrator* is responsible for the company's general functioning. He or she coordinates all the plant's activities and technical assistance services, and is also the company's legal representative. The manager must therefore be a dynamic person who is respected by the other member farmers.

- The *head of production* is responsible for organizing working groups (groups of members or of contracted personnel) to guarantee timely supplies of raw material. He or she must also verify results of quality control of the end product.

- The *treasurer* is in charge of making payments and collecting debts. Together with the manager, the treasurer is responsible for establishing an accounting system that allows members to know the outcomes of management.

Although these three positions (manager, production head, and treasurer) imply an administrative cost for the drying plant, they help guarantee its good operation.

Natural cassava drying plants also require a certain amount of labor. Each company organizes its work force according to its conditions. Sometimes, members or their families work at the plant but,

usually, the plant becomes a source of employment for its rural hinterland, especially if employment opportunities are limited.

Table 21-5 lists the types of labor needed for the different operations of a drying plant. Note that the 48 working-hours and maximum of six workers required to process 6 t of fresh cassava roots represent one working day (8 working-hours) for each ton processed.

Financing. To construct and initiate a drying plant, investments must be made in three well-defined areas:

Table 21-5. Labor needed to chip and dry one batch of 6 t of fresh cassava roots.

Tasks	Workers (no.)	Hours (no.)	Working hours (total)
Weigh and chip the roots	4	3	12
Spread out the cassava chips	3	3	9
Turn over and mix the cassava chips	3	3	9
Collect, pack, and store the chips	6	3	18
Total			**48**

plant construction, capital for the plant's operation, and production of raw material.

- Plant construction. The construction costs of a drying plant are specific to each region or country, and depend on the availability and price of materials. The values listed in Table 21-6 indicate that a 500-m^2 plant in the Colombian North Coast needs an initial investment of about US$15,680, according to the National Federation of Cassava Producers, Processors, and Traders (FEDEYUCA 2001, pers. comm.).

- Plant operation. The plant needs a working capital to pay labor, acquire raw material and sacks, and pay freight and administrative costs. The working capital must be available when the plant begins processing. Table 21-7 separates the categories comprising the working capital underlying a plant's operation over 30 days (FEDEYUCA 2002, pers. comm.).

- Production of raw material. In most cases, no credit lines exist to finance cassava crops, but

Table 21-6. The investment needed to make a 500 m^2 concrete floor for a natural cassava drying plant, Colombian North Coast, 2001.

Work, tool, or element	Quantity	Unit value (US$/$m^2$)	Total for item (US$)[a]	Total for category (US$)
Installations				**11,500**
Concrete floor (m^2)	500	15	7500	
Storeroom (m^2)	40	70	2800	
Wire mesh (rolls, 1 m wide)	100	2	200	
Roofing for chipping machine (m^2)	25	40	1000	
Equipment				**2,000**
Chipping machine	1	900	900	
5-hp electric motors	2	350	700	
500-kg capacity platform scale	1	400	400	
Tools				**380**
Wheelbarrows	4	30	120	
Metal shovels	6	10	60	
Wooden rakes	10	10	100	
Wooden collectors	10	10	100	
Others				**375**
Polypropylene sacks	300	0.25	75	
Plastic cover (10 × 50 m, caliber 6)	1	300	300	
Subtotal				**14,255**
Unforeseen contingencies (10%)				**1,425**
Working capital[b]				**3,940**
Total investment (US$)				**19,620**

a. Exchange rate, January 2001: US$1 = Col$2200.
b. Table 21-7 presents the distribution of the working capital by category.

Table 21-7. Working capital used for 30 operational days of a drying plant with a 500m^2 concrete floor having a load of 12 kg/m^2 and 12 batches, Colombian North Coast, 2001.

Category or input	Quantity	Unit value (Col$)	Rubric value (Col$)
Fresh cassava roots (t)	72	80,000	5,760,000
Working days (units)	80	15,000	1,200,000
Sacks (units)	700	500	350,000
Freight (t, dried chips)	30	45,000	1,350,000
Total (Col$)			**8,660,000**
Total (US$)[a]			**3,940**

a. Exchange rate, January 2001: US$1 = Col$2200.

acquiring one is a must. Credit should be timely, sufficient, and preferably of an association type, as this will enable all company members to produce cassava and thus guarantee adequate supplies of raw material.

Farmers may go to state entities or cooperatives when searching for financing. To construct the plant, long-term credit lines with promotional interests should be preferred, as the plant's initial period of operation (1 to 2 years) is critical as farmers adapt to the new agroindustrial alternative. Furthermore, farmers need to enjoy lasting institutional support that will guarantee adequate training in the technical and accounting aspects of the company's effective operation.

Marketing dried cassava chips. The principal market of dried chips comprises processing industries for concentrate feeds, especially for poultry and pigs. However, most cassava-producing countries of Latin America import grains to manufacture this feed instead of using dried cassava chips to substitute imported grains. The factor that most influences substitution is the price of dried chips, compared with that of grains such as maize and sorghum. At the time of writing the price of dried chips is 70% or 80% of the grain price.

The price of dried cassava chips depends on processing costs and, mainly, on the cost of raw material (Table 21-8). The next major cost is that of labor (including administration), which represents almost 10% of total costs.

Consequently, all possible effort must be dedicated to increasing the crop's productivity, for example, planting high-yielding varieties and developing best agronomic practices that reduce the costs of root production. If the costs stay down sufficiently, then dried cassava chips can be marketed to give an adequate profit margin (Table 21-9).

Table 21-8. Structure of production costs per ton of dried cassava chips for a cassava drying plant with a 500m^2 drying concrete floor.

Costs (concept or category)	Value (Col$)
Fixed costs	**27,500**
Administration[a]	12,500
Depreciation[b]	15,000
Variable costs	**240,500**
Raw material[c]	200,000
Labor[d]	37,500
Expenses[e]	3,000
Marketing expenditures	**53,000**
Packaging[f]	8,000
Freightg	45,000
Total production cost per ton of dried cassava chips[h]	**321,000**

a. Salaries of the Administrator: Col$450,000 per month, 4 months period (Col$1,800,000). The total production of dry cassava chips during the period is 144 MT.
b. Based on investment costs of US$19,620 and 20 years depreciation period.
c. 2.5 t of fresh cassava roots at Col$80,000/t.
d. 2,5 man/days per MT dry cassava chips (1 man/day= Col$15,000
e. Sacks in fique, cloth, etc.
f. 20 clean fique sacks, each with a 50-kg capacity.
g. Transport from the drying plant to the buyer (concentrate-feed plant), maximum of 150 km.
h. Exchange rate, January 2001: US$1 = Col$2200.

Table 21-9. Calculation of net income per ton of dried cassava chips produced in the previous example.

Concept	Value (Col$)
Costs	
Cassava processing	76,000
Freight[a]	45,000
Raw material (fresh cassava roots)	200,000
Total	**321,000**
Sale price[b]	**335,250**
Net earnings	**14,250**

a. Transport from Sincelejo to Medellín.
b. Product sold in Medellín.

Technology 2:
Drying Cassava Chips on Inclined Trays

Trays

This drying method takes maximum advantage of the drying capacity of wind as it circulates through cassava chips placed on trays. The trays have a wooden framework, and a base of plastic mesh that holds the chips during drying.

Materials. The plastic mesh is strengthened by adding chicken wire netting with 1-inch-diameter holes (Figure 21-26A). The dimensions shown in the figure enable the tray to be handled by two workers. Although the tray's size may vary with the cassava material available in the region, the mesh is standard at 35 perforations per square centimeter, as anything with larger apertures would result in increased losses. With the use of a suitable mesh, losses are less than 3% of dried chips.

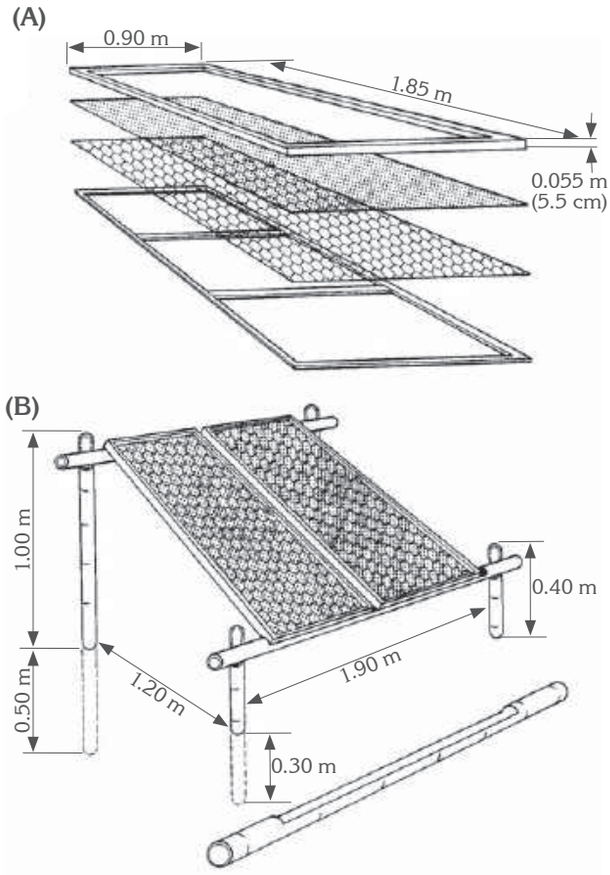


Figure 21-26. **(A)** Dimensions of a tray. **(B)** Placement of tray on supports made from bamboo or building (giant) bamboo. (Adapted from Best 1979.)

Fresh cassava chips are spread over the trays, which are then placed on beams of bamboo or building (giant) bamboo supported by two rows of posts, with the front row being shorter than the back row. The trays thus remain on a slope of 20° to 25° that takes maximum advantage of the direction and strength of the wind (Figure 21-26B).

Management. Once fresh chips are obtained, the trays are filled in at the same site where chipping took place (Figure 21-27) before being taken to the supports.

Another option is to first place the empty trays on the supports (Figure 21-28) and then fill them with

Figure 21-27. A worker fills the trays with fresh cassava chips as a chipping machine operates behind him.

Figure 21-28. Empty trays are placed on their supports.

fresh chips brought by wheelbarrow. The agreed-upon quantity of chips is then placed on each tray and spread over the tray's surface (Figure 21-29).

The weight of cassava chips does not have to be exactly the same for each tray. An average weight is achieved by first measuring a suitable quantity per tray into a container and then spreading the chips over the tray. When shovels are used to directly load the trays (Figure 21-27), the amount of cassava can vary. If trays have different dimensions, the chip load for each is obtained by multiplying the tray's area by the appropriate figure in column 3 of Table 21-10 (tray load in kg/m^2).

The trays can be left on the supports overnight to take advantage of the wind's action. If rain is predicted, the trays should be stacked horizontally (i.e., one above the other) under roofing or outside and protected with a canvas or plastic cover until the next day. The lowest tray of the stack should be sitting on two posts of bamboo (or building bamboo), thus keeping all trays off the ground. The next morning, the trays should be moved back to their supports. Once the chips have attained the appropriate moisture content, they should be collected and packed.

Figure 21-29. Fresh cassava chips are spread over trays already in position.

Table 21-10. Relationship between cassava chip load on inclined trays (L/T) and wind speed.

Wind conditions	Speed (m/s)	L/T (kg/m^2)
Calm, smooth breeze	<1	10
Constant breeze	1–2	10–13
Constant wind	>2	13–16

SOURCE: Best (1979).

The quantity of chips placed on the trays depends largely on wind speed (Table 21-10). The higher the wind speed, the greater will be the quantity of cassava chips that can be dried without needing to turn them over. However, if the load is more than 16 kg/m^2, the chips will need to be turned over.

As illustrated in Figure 21-30, drying in trays is faster than drying on floors for a given load of chips. One reason for this difference is that chips in the trays continue losing moisture during the night, because air circulation does not stop. In contrast, when drying is carried out on concrete floors, chips lose only a small quantity of moisture during the night, as wind speed at floor level is low.

Drying time

Initial stage. Initially, fresh chips lose moisture rapidly and air circulation (wind) is more important than air temperature and humidity. If wind speed is sufficient, this stage can be completed even if the sky is cloudy. Furthermore, drying can be carried out at night. As a result, in dry times, the chips may lose a considerable amount of moisture if left on the trays and their supports during the night. To best take advantage of this period, cassava may be chipped in the afternoon hours. Table 21-11 illustrates the effect of the principal factors of drying time, especially wind speed.

In contrast, fresh chips left spread on concrete floors during the night lose only a small part of their moisture, for the reasons mentioned above: low wind speed at ground level and infrequent turning over.

Final stage. In the final drying stage, when moisture content is about 30%, moisture loss is very slow (Figure 21-31) and the high temperatures at mid-day are needed to complete the process. During this stage, air humidity should be less than 65% so that the chips' final moisture content is suitable for storage. Sometimes, particularly in the rainy season, relative humidity is high; drying should continue until the climate improves.

Several trials were conducted in different sites in Colombia to determine drying times under different climatic conditions (Table 21-12). The following conclusions summarize the work:

- Drying almost always takes more than 10 hours (1 day), but less than 20 hours (2 days). Only under exceptional environmental

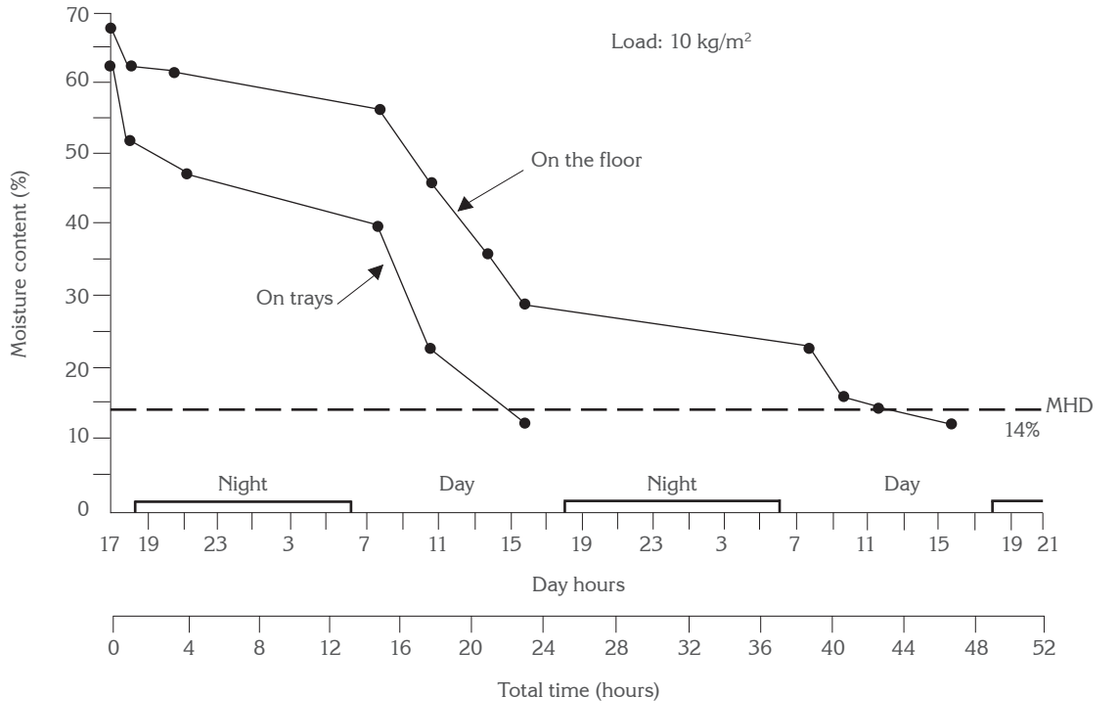


Figure 21-30. Comparison of two drying curves for cassava chips. One curve is for concrete floors and the other is for sloping trays (see text). MHD = maximum level of humidity accepted during drying.

Table 21-11. Drying time for fresh cassava chips cut at different hours of the day.

Site	Average climatic conditions throughout trial					Hours needed to dry to 14% moisture content on:				
	Altitude (m above sea level)	Temp. (°C)	r.h. (%)	Wind (m/s)	Solar radiation (cal/cm^2.s)	Floor (5 kg/m^2) at 8:00[a]	Inclined trays (load of 10 kg/m^2) at:			
							8:00[a]	11:00[a]	14:00[a]	17:00[a]
Sevilla	1250	25	73	1.14	0.74	9	14	10	9	11
Espinal	430	29	60	0.66	0.66	11	13	10	9	6
Palmira	1000	26	68	1.26	0.61	14	12	9	6	8
Caicedonia	1100	26	69	0.90	0.72	14	14	12	11	15 (16%)[b]
El Darién	1450	23	72	1.73	0.70	13	13	12	12	11 (15%)[b]

a. Time at which trial began.
b. Percentages indicate moisture content at that hour.

SOURCE: Best (1979).

conditions will cassava chips dry in less than 1 day. In places where wind speed and solar radiation are low, drying may take as long as 3 days.

- About the same number of hours per square meter is needed for drying, but the weight of chips in trays is almost double that of those on the concrete floor.
- In very moist areas, rapid drying requires a high wind speed (e.g., at Sevilla, Espinal, and El Darién).

Chip size

Chip size influences drying time: the finer a chip is, the shorter the time to release the moisture in its tissues. Table 21-13 shows the range of chip dimensions used

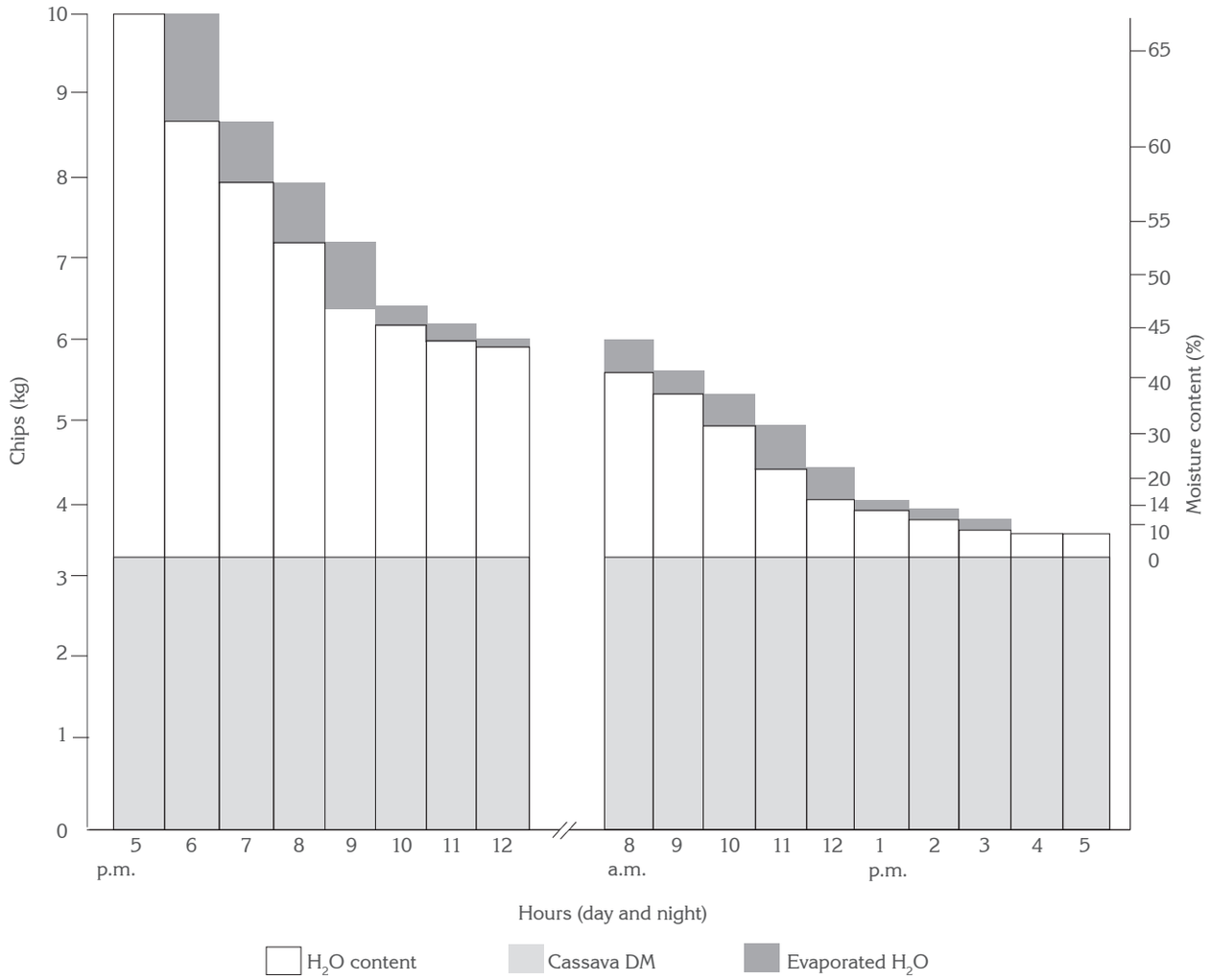


Figure 21-31. Typical drying curve for cassava chips on trays. Note the moisture loss in relation to the hour of the day, starting at 5:00 p.m. and recording during the night (from Best 1979). DM: dry matter.

Table 21-12. Time needed[a] between 8:00 and 18:00 hours to dry fresh cassava chips to 14% moisture content in five different sites.

Site	Climatic conditions of site				Time (hours) on:	
	Altitude (m above sea level)	Temp. (°C)	r.h. (%)	Wind (m/s)	Solar radiation (cal/cm^2.s)	Trays (10 kg/m^2)[b]	Floor (5 kg/m^2)[b]
Sevilla	1250	22	78	1.0	0.71	13	13
Espinal	430	30	64	0.9	0.65	12	10
Palmira	1000	26	66	1.2	0.61	13	15
Caicedonia	1100	26	67	0.8	0.58	19	17
El Darién	1450	24	70	1.9	0.73	12	11

a. Values averaged over three trials.
b. The value in parentheses is the cassava chip load.

SOURCE: Best (1979).

by different chipping machines currently used to process fresh roots. Table 21-14 lists the characteristics of the overall material promade up of typical chips. As can be observed, no machine produced more than 46% of typical chips. Reasons include imperfect adjustment of disks with the front, variation in speed of feed, and diversity of fresh-root size (Castillo and Hernández, 1985).

Net drying times

Figures 21-32 and 21-33 show the net drying times for three types of chips in the concrete-floor systems (10, 12, and 14 kg/m^2) and inclined trays (10, 12, 14, 16, 18, and 20 kg/m^2). Drying was carried out between 8:00 and 18:00 hours every day. The net time does not include the 14 hours of night. Average environmental conditions at CIAT, the site of the trials, were as follows:

- Environmental temperature: 23.5 °C
- Relative humidity: 75%
- Solar radiation: 0.73 cal/cm^2 per min
- Wind speed: 1.12 m/s
- Rainfall: 80 mm/month

For a given load, the difference between the two systems is noticeable. On concrete floors, the chips practically did not differ in drying time. "Malaysia" chips tended to perform better only for loads of 10 and 12 kg/m^2. For drying on inclined trays, no differences were found between the finer "Malaysia" chips and the rectangular "Brazil" or "Colombia" chips. Net drying times for the rougher "Thailand" chips were quicker by 2 or 3 hours than for the other chips. Figures 21-34 and 21-35 show the results in terms of dried chips per day and per each square meter of drying surface. This parameter permitted the selection of the best load for a specific site or region.

Table 21-13. Range of typical sizes (in mm) expected for fresh cassava chips.

Type of chipping machine	Length	Width	Thickness
"Thailand"	60–80	25–30	4–7
"Brazil"	50–70	10	4–6
"Malaysia"	50–80	4–6	4–6

Table 21-14. Percentages of different types of fresh chips produced according to type of chipping machine.

Type of chipping machine	Traditionally cut chips	Thinly cut chips	Finely cut chips
"Thailand"	42	34	24
"Brazil"	46	35	19
"Malaysia"	35	29	36

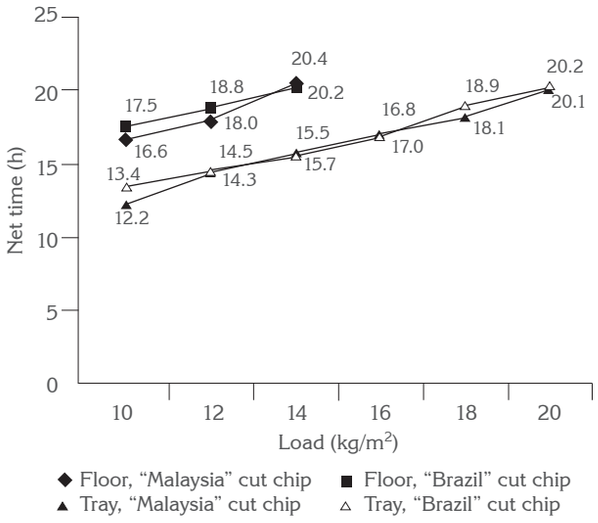


Figure 21-32. Net times for drying "Brazil" and "Malaysia" cut cassava chips, and dried on concrete floors or inclined trays.

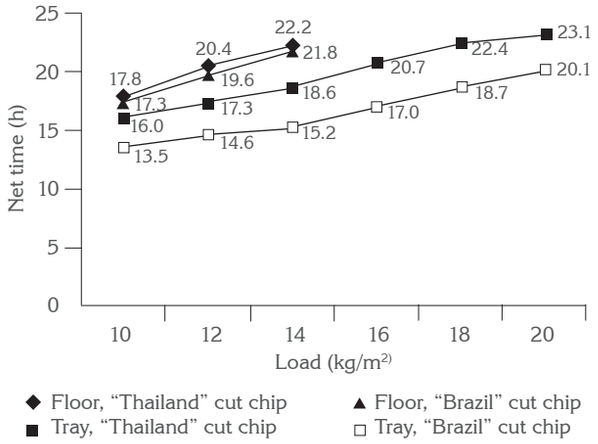


Figure 21-33. Net times of drying "Thailand" and "Brazil" cut cassava chips, and dried on concrete floors or inclined trays.

Costs

Drying on inclined trays is a good alternative for drying fresh chips in places where constructing concrete floors is not possible because of inclined land or insufficient resources. Table 21-15 compares costs of materials for constructing a concrete floor versus trays.

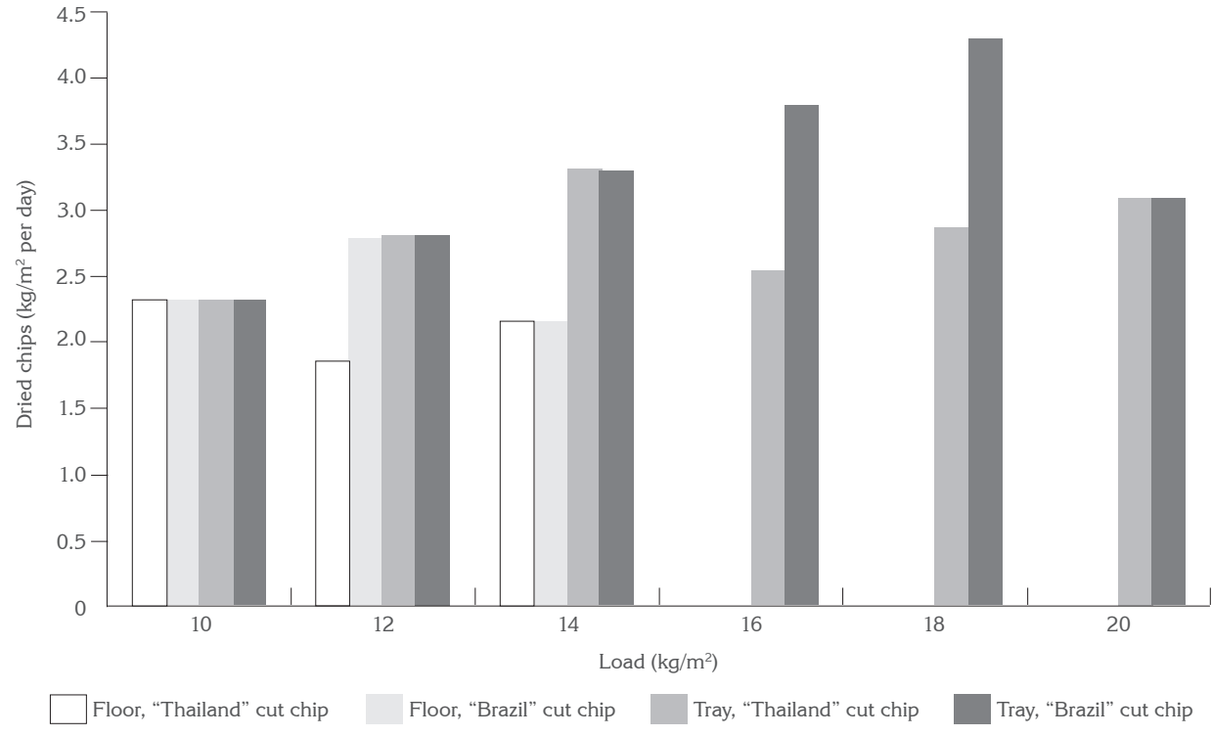


Figure 21-34. Production of "Thailand" and "Brazil" cut cassava chips, dried on concrete floors or inclined trays.

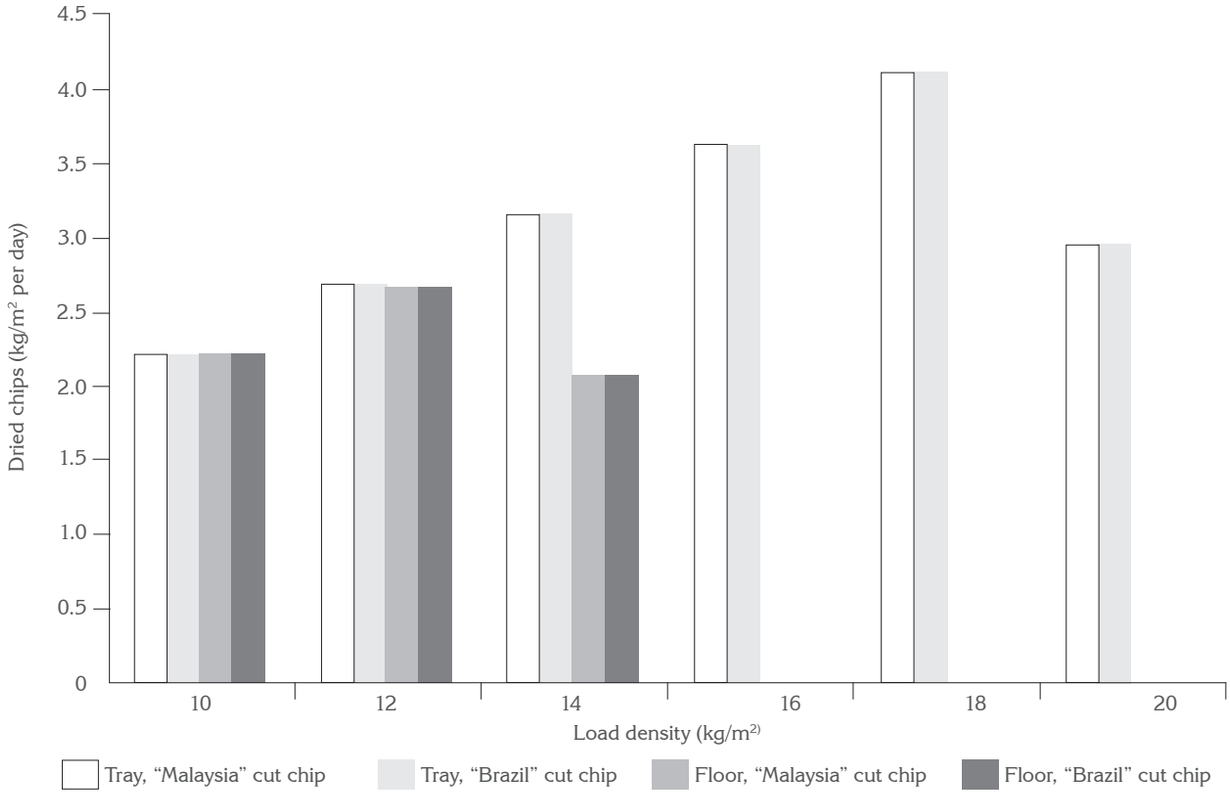


Figure 21-35. Production of "Brazil" and "Malaysia" cut cassava chips, dried on concrete floors or inclined trays.

Table 21-15. Comparison of costs of materials needed for 100 m^2 of drying surface, whether as a concrete floor or as trays, March 2001

Material (unit)	Unit cost (Col$)	Units needed	Total cost (Col$)
Concrete floor			
Cement (50-kg sacks)	13,000	40	520,000
Sand (m^3)	15,000	5	75,000
Gravel (m^3)	30,000	10	300,000
Tar (kg)	4,000	20	80,000
Wooden planks (2.8 × 0.24 × 0.025 m)	8,000	30	240,000
Subtotal			**1,215,000**
Unforeseen contingencies (10%)			130,000
Labor (60%)			805,000
Total			**2,150,000**
Cost per square meter of surface	21,500		
Inclined trays			
Wood (2.8 × 0.24 × 0.025 m)	8,000	42	336,000
Chicken wire netting (roll of 1.2 × 36 m)	39,500	3.2	126,400
Plastic mesh (roll of 0.9 × 30 m)	150,000	3.8	570,000
Nails (kg)	1,500	10	15,000
Frames (3 m × 2 cm × 2 cm)	3,000	100	300,000
Subtotal			**1,347,400**
Unforeseen contingencies (10%)			134,740
Labor (60%)			890,000
Total			**2,372,140**
Cost per square meter of surface	23,700		

SOURCE: Best (1979).

Infrastructure. The cost per square meter of drying surface is larger for trays than for concrete floors. However, if the larger carrying rate of the tray system is taken into account, savings in the total investment would be evident. The trays' maintenance costs and their duration depend on the care with which they are handled. The concrete floor, in contrast, needs little maintenance and is long lasting.

Inclined trays notably simplify the management of cassava chips, as the chips do not need turning over. Moreover, the labor needed for the entire process with trays is about 25% less than that required for a concrete floor (Table 21-16). Table 21-17 presents the flow of activities for three workers who dry 3 t of cassava on 190 m^2 of inclined trays (load = 16 kg/m^2). Total working hours spent was 19.5. If 2.5 is taken as the conversion factor, the working hours needed for producing 1 t of dried cassava would be 16.2 (about 2 working days).

Investment. Table 21-18 details the investments needed to install a plant with 300 m^2 of inclined trays and a capacity to dry 5 t of fresh cassava every 2 days.

Table 21-16. Comparison of the labor needed to chip one ton of cassava roots and dry on either concrete floors or inclined trays.

Activity	Working hours	
	Floor	Trays
Weigh and wash roots	3	3
Chip roots	2	2
Subtotal	**5**	**5**
Spread the chips	2	2
Turn the chips over (4 × a day)	1.5	
Collect and cover chips at night	1	1
Spread out again in the morning	1.5	1
Turn the chips over (4 × a day)	1.5	
Collect and pack chips	2	2
Subtotal	**9.5**	**6**
Total labor	**14.5**	**1**

SOURCE: Best (1979).

This is equivalent to a plant with a 500-m^2 concrete floor. Table 21-19 records the processing costs of a drying plant in the Colombian North Coast. Data were provided by FEDEYUCA in August 2000. The costs

Table 21-17. Timetable of activities to dry 3 t of fresh cassavaa on inclined trays.

Activity	Workers (no.) in hour of the day:													
	6	7	8	9	10	11	12	13	14	15	16	17	18	19
First day														
Weigh and chip roots		2												
Spread out chips			1											
Collect and cover													2	
Second day														
Uncover trays		2												
Collect												3		
Store													3	

a. Drying area = 190 m2; total working hours: 19.5; working hours per ton of cassava: 16.2; conversion factor: 2.5.

Table 21-18. Investment needed for a natural drying plant with a tray area of 300 m^2 and a capacity to dry 5 t of fresh cassava chips every 2 days, February 2001.

Concept	Unit value (US$)[a]	Total value (US$)[a]	Rubric totals (US$)[a]
Installations			**6,280**
Trays (300 m^2)	12/m^2	3,600	
Storeroom (40 m^2)	46.80/m^2	1,872	
Wire mesh (100 m)	1.00/m^2	100	
Roofing for the chipping machine (25 m^2)	28.30/m^2	708	
Equipment			**1,700**
Chipping machine, type "Colombia"	700.00	700	
2 electric motors (5 hp)	300.00	600	
500-kg capacity platform scale	400.00	400	
Tools			**180**
4 wheelbarrows	30.00	120	
6 metal shovels	10.00	60	
Others			**60**
300 sacks	0.20	60	
Subtotal			**8,220**
Unforeseen contingencies (10%)			822
Working capital (30 days)[b]		4,000	4,000
Total			**13,042**

a. Exchange rate, March 2001: US$1 = Col$2300.
b. Calculation table:

Working capital (Col$) needed to operate the plant normally for 30 days	
Fresh cassava roots = 72 t × Col$75,000 per ton	5,400,000
Working days = 80 × Col$12,000 each	960,000
Sacks = 600 × Col$300 each	180,000
Dried cassava chips = 30 t × Col$45,000 (freight per ton)	1,350,000
Total working capital (Col$)	**7,890,000**

Table 21-19. Cost structure of a cassava drying plant with 300 m^2 of inclined trays, Colombian North Coast, August 2000.

Concept or cost	Value (Col$)	Value (%)
Fixed costs		
Administration	3,000	
Depreciation		
Financial costs		
Maintenance	4,500	
Subtotal	**7,500**	**3.5**
Variable costs		
Raw material[a]	187,500	
Labor[b]	24,000	
Expenses	3,000	
Unforeseen contingencies		
Subtotal	**214,500**	**78.0**
Marketing expenses		
Packaging	7,000	
Commission		
Freight[c]	45,000	
Subtotal	**52,000**	**18.5**
Total costs + expenses	**274,500**	**100.0**

a. From 2.5 t of fresh cassava roots, 1 t of dried cassava is obtained.
b. Two working days to produce 1 t of dried cassava.
c. Freight from Sincelejo to Medellín.

include freight from Sincelejo to Medellín. For a typical North Coast plant, processing costs is more than Col$40,000 per ton of dried chips and the profit obtained is about Col$25,000 (Table 21-20).

Table 21-20. Costs of processing 1 t of dried cassava chips and perceived profit[a], Colombian North Coast.

Category	Col$[b]
Raw material	187,500
Processing	42,000
Freight	45,000
Total production costs	274,500
Sale price[c]	300,000
Net earnings	25,500

a. As perceived by the Cooperativa CooproAlgarrobos, Chinú, Department of Córdoba, Colombia, August 2000.
b. Note that the cost data offered by this table must be updated when considering a specific project.
c. At the concentrate-feed plant.

Appendix:

Determining Dry Matter Content of Fresh Roots, using the Specific Gravity Method

Julio César Toro[5] *and Alonso Cañas*[6]

Dry matter (DM) and starch contents, expressed as percentages in cassava roots, are often called quality factors. They vary greatly among different cassava varieties. These factors are closely related to the soil's potassium content, crop's age, and the climate (mainly rainfall and soil moisture). They also depend heavily on the absence or severity of attacks from defoliating pests (e.g., thrips and hornworm) and other defoliating agents such as hail (Celis and Cadavid 1978, pers. comm.).

To calculate the DM yield of roots at harvest from fresh root yield, the following methods are used:

- Conventional *laboratory* techniques that require much work and time.
- A *hydrometer* similar to that used for potato tubers. Apparently, it can be adapted to cassava roots (G Gómez 1977, pers. comm.).
- *Specific gravity* method for roots, which has been applied ever since the relationship between that parameter and DM and starch contents in roots was verified.

Determining specific gravity (SG) is simple, useful, and within the reach of farmers on their farms or of companies processing cassava flour or starch.

Elements for determining specific gravity

The method requires the following elements:

- A beam balance that can weigh gram by gram to 3 kg, and has divisions in decigrams.
- A container that can carry sufficient water to submerge the sample.
- A metal mesh basket, with a square base, and able to carry 3 kg of cassava roots.
- Several bags, either plastic or paper, that can carry 3 kg of cassava.
- Plastic or nylon string or cord, 2 m long.
- An S-shaped hook.
- A plank, 25 × 60 cm, which is large enough to act as a small table for carrying the balance. The plank has a central perforation (Ø at 5 cm) just underneath the balance's weighing plate.
- A four-legged framework for the plank. The framework may be 50 cm wide and 73 cm long.
- A pencil or a permanent ink marker.
- A machete or wooden spatula.

Conducting the specific gravity method

Taking samples. Samples of recently harvested roots should be collected, taking 3 or 4 samples per variety or plot and ensuring they are representative, that is, that they include large and small roots, both thick and thin. Each sample should weigh more than 3 kg. The roots are cleaned with the blunt edge of a machete or wooden spatula and the rootlets and peduncles cut off. They are then packed into previously marked bags and taken to the site where measurements will be made. This site should not be exposed to air currents, as these affect readings from the balance.

Fresh root weight in air (FRWA). Each bagged sample is weighed individually. All samples should have similar FRWA in that the weight is not less than 3.0 kg (Figure 21A-1A). The relative uniformity of the weight helps correct possible erroneous readings, in that if a large difference is seen, then the sample can be re-weighed to immediately verify its weight. If sample weights do not vary, such repetition becomes unnecessary. Once the FRWA is obtained, the sample is re-packed into its bag. The roots in each sample do not have to be entire.

5. Formerly, Head, Agronomy and International Cooperation, Cassava Program, CIAT; now Researcher in fruit trees, Cali, Colombia. E-mail: frutillartor@telesat.com.co
6. Agricultural Technologist, Medellín, Colombia.

Fresh root weight in water (FRWW). The metal mesh basket, tied to a nylon cord, is introduced into a container full of water in such a way that it remains balanced. The other end of the cord is tied to the S hook, which, in its turn, is hung by its upper curl from the lower extremity of the balance's linchpin, which passes downwards through the perforation in the plank (Figure 21A-1B). The basket should remain totally submerged. Neither the basket nor the cord should touch or even brush against any object.

Once assembled, the balance is calibrated to zero to eliminate the weight of the elements described above, and the sample of roots is then placed into the basket (Figure 21A-1C). Figure 21A-1D gives an overall view of the equipment as it weighs the sample in water. The FRWW is noted beside the respective FRWA. Once the weights of all the samples are obtained, the SG is calculated for each case, using the following formula:

$$SG_C = \frac{FRWA}{FRWA - FRWW} \quad (1)$$

The result should have four decimal figures. Table 21A-1 was developed by Wania G. Fukuda (cited in Toro and Cañas 1983) to obtain percentages of DM from cassava roots as derived from specific gravity ("density", in the table). The original table was later expanded with new entries and densities ranging from 1.0200 to 1.1900. The following regression equation led to Table 21A-1.

$$DM\ (\%) = 158.26\ (SG) - 142.05 \quad (2)$$

These tables are applied to cassava varieties harvested 10 to 12 months after planting, under normal cassava production conditions in Colombia (CIAT 1978).

Table 21A-1 was used to prepare another, even shorter, table (Table 21A2) for finding only the most usual DM values (%) for roots (i.e., between 20% and 46%), knowing the corresponding FRWW. This is expressed in grams and takes only one decimal figure. The FRWA of 3.0 kg is taken because the table can then be summarized, and a correct reading of the FRWW is more likely. Cours (1951) verified that a variation of 16.7 g in the FRWW can indeed alter the DM content value by 1%.

Determining DM content (%) in cassava roots through the SG method is an easily adoptable practice that can be very useful for identifying those cassava varieties that have higher DM content.

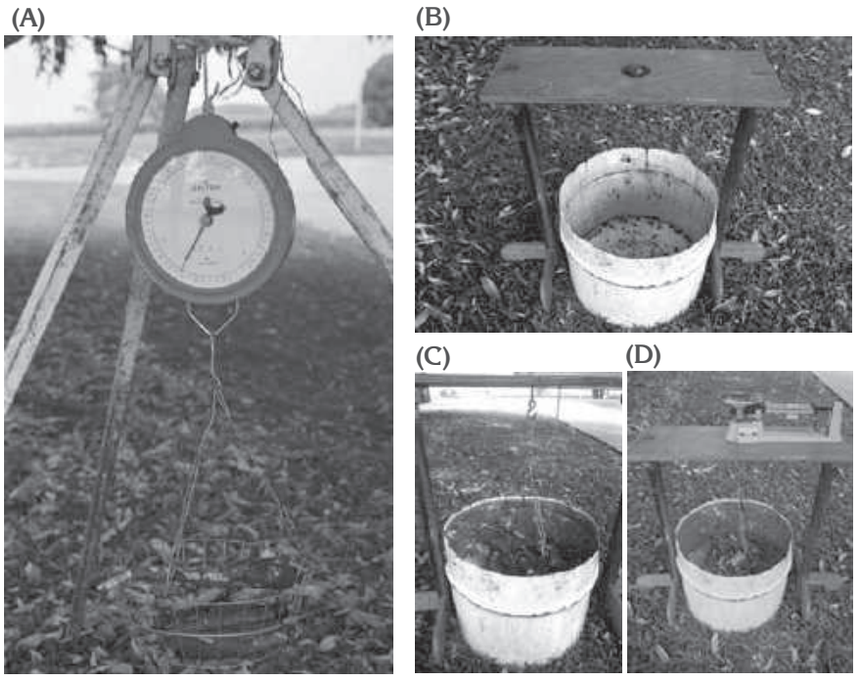


Figure 21A-1. Measuring the values for "weight in air" (FRWA) and "weight in water" (FRWW) of cassava roots. From these data, the specific gravity is calculated and, from a table, the percentage of dry matter in the sample roots is obtained. **(A)** Balance for weighing in air. **(B)** Plank with perforation, its supporting framework, and the water container. **(C)** Balance, cord, S-shaped hook, and metal basket containing cassava roots. **(D)** Overall view of the equipment used for measuring "weight in water".

Table 21A-1. Determining dry matter (DM) content in cassava roots, using the specific gravity (or density) method.

Density (SG)	DM (%)	Density (SG)	DM (%)	Density (SG)	DM (%)
1.0200	19.53	30	23.12	65	26.79
05	19.61	35	23.20	70	26.87
10	19.69	40	23.28	75	26.95
15	19.76	45	23.36	80	27.03
20	19.84	50	23.43	85	27.10
25	19.92	55	23.51	90	27.18
30	20.00	60	23.59	95	27.26
35	20.08	65	23.67	1.0700	27.34
40	20.15	70	23.75	05	27.42
45	20.23	75	23.82	10	27.50
50	20.31	80	23.90	15	27.57
1.0255	20.39	85	23.98	20	27.65
60	20.47	90	24.06	25	27.73
65	20.54	95	24.14	30	27.81
70	20.62	1.0500	24.22	35	27.89
75	20.70	05	24.29	40	27.96
80	20.78	10	24.37	45	28.04
85	20.86	15	24.45	50	28.12
90	20.93	20	24.53	55	28.20
95	21.01	25	24.61	60	28.28
1.0300	21.09	30	24.68	65	28.35
05	21.17	35	24.76	70	28.43
1.0310	21.25	40	24.84	75	28.51
15	21.33	45	24.92	80	28.59
20	21.40	50	25.00	85	28.67
25	21.48	55	25.07	90	28.74
30	21.56	60	25.15	95	28.82
35	21.64	65	25.23	1.0800	28.90
40	21.72	70	25.31	05	28.98
45	21.79	75	25.39	10	29.06
50	21.87	80	25.46	15	29.14
55	21.95	85	25.54	1.0820	29.22
60	22.03	90	25.62	25	29.30
1.0365	22.11	1.0595	25.70	30	29.37
70	22.18	1.0600	25.78	35	29.45
75	22.26	05	25.86	40	29.53
80	22.34	10	25.93	45	29.61
85	22.42	15	26.01	50	29.69
90	22.50	20	26.09	55	29.77
95	22.57	25	26.17	60	29.84
1.0400	22.65	30	26.25	65	29.92
05	22.73	35	26.32	70	30.00
10	22.81	40	26.40	75	30.08
15	22.89	45	26.48	80	30.16
20	22.97	50	26.56	85	30.23
25	23.04	55	26.64	90	30.31
		60	26.71	95	30.39

(Continued)

Table 21A-1. (Continued.)

Density (SG)	DM (%)	Density (SG)	DM (%)	Density (SG)	DM (%)
1.0900	30.47	35	34.14	70	37.80
05	30.55	40	34.22	75	37.88
10	30.62	45	34.29	80	37.96
15	30.70	50	34.37	85	38.04
20	30.78	55	34.45	90	38.12
25	30.86	60	34.53	95	38.19
30	30.94	65	34.61	1.1400	38.27
35	31.01	70	34.69	05	38.35
40	31.09	75	34.76	10	38.43
45	31.17	80	34.84	15	38.51
50	31.25	85	34.92	20	38.59
55	31.33	90	35.00	25	38.66
60	31.41	95	35.08	30	38.74
65	31.48	1.1200	35.15	35	38.82
70	31.56	05	35.23	40	38.90
75	31.64	10	35.31	45	38.98
80	31.72	15	35.39	50	39.05
85	31.80	20	35.46	55	39.13
90	31.87	25	35.54	60	39.21
95	31.95	30	35.62	65	39.29
1.1000	32.03	35	35.70	70	39.37
05	32.11	40	35.77	75	39.44
10	32.19	45	33.85	80	39.52
15	32.26	50	35.93	85	39.60
20	32.34	55	36.01	90	39.68
25	32.42	60	36.09	95	39.76
30	32.50	65	36.16	1.1500	39.84
35	32.58	70	36.24	05	39.91
40	32.65	75	36.32	1.1510	39.99
45	32.73	1.1280	36.40	15	40.07
1.1050	32.81	85	36.48	20	40.15
55	32.89	90	36.55	25	40.23
60	32.97	95	36.63	30	40.30
65	33.05	1.1300	36.71	35	40.38
70	33.12	05	36.79	40	40.46
75	33.20	10	36.87	45	40.54
80	33.28	15	36.95	50	40.62
85	33.36	20	37.02	55	40.69
90	33.44	25	37.10	60	40.77
95	33.51	30	37.18	65	40.85
1.1100	33.59	35	37.26	70	40.93
05	33.67	40	37.34	75	41.01
10	33.75	45	37.41	80	41.08
15	33.83	50	37.49	85	41.16
20	33.90	55	37.57	90	41.24
25	33.98	60	37.65	95	41.32
30	34.06	65	37.73		

(Continued)

Table 21A-1. (Continued.)

Density (SG)	DM (%)	Density (SG)	DM (%)	Density (SG)	DM (%)
1.1600	41.40	10	43.12	15	44.76
05	41.48	15	43.19	20	44.83
10	41.55	20	43.27	25	44.91
15	41.63	25	43.35	30	44.99
20	41.71	30	43.43	35	45.07
25	41.79	35	43.51	40	45.15
30	41.87	1.1740	43.59	45	45.22
35	41.94	45	43.66	1.1850	45.30
40	42.02	50	43.74	55	45.38
45	42.10	55	43.82	60	45.46
50	42.18	60	43.90	65	45.54
55	42.26	65	43.98	70	45.61
60	42.33	70	44.06	75	45.69
65	42.41	75	44.13	80	45.77
70	42.49	80	44.21	85	45.85
75	42.57	85	44.29	90	45.93
80	42.65	90	44.37	95	46.00
85	42.72	1.1795	44.45	1.1900	46.08
90	42.80	1.1800	44.52		
95	42.88	05	44.60		
1.1700	42.96	10	44.68		
05	43.04				

SOURCE: CIAT (1978).

Table 21A-2. Calculation of dry matter (DM) content in cassava roots, using the value "fresh root weight in water" (FRWW)[a].

FRWW	DM (%)	FRWW	DM (%)
58.8	20	296.0	34
77.4	21	311.8	35
95.8	22	327.4	36
112.6	23	342.8	37
130.6	24	359.0	38
148.3	25	371.9	39
165.8	26	386.7	40
183.1	27	401.5	41
198.9	28	416.0	42
215.8	29	430.4	43
232.5	30	443.5	44
248.9	31	457.6	45
265.2	32	471.5	46
280.1	33		

a. Assuming that the "weight in air" (FRWA) of each sample is equal to 3000 g. The specific gravity method is applied indirectly.

SOURCE: CIAT (1979).

References

To save space, the acronym "CIAT" is used instead of "Centro Internacional de Agricultura Tropical".

Best R. 1979. Cassava drying. CIAT, Cali, Colombia. 24 p.

Best R; Gómez G. [1983]. Procesamiento de las raíces de yuca para alimentación animal. In: Domínguez CE, ed. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (UNDP), Cali, Colombia.

Castillo C; Hernández W. 1985. Estudio del secado natural de tres tipos de trozos de yuca. BSc thesis. Faculty of Agronomy, Universidad del Valle, Cali, Colombia. 119 p.

CIAT. 1978. Método para la determinación del contenido de materia seca y almidón en la yuca por el sistema de gravedad específica. In: CIAT. Curso de producción de yuca. Cali, Colombia. Vol 1, p 352–356.

CIAT. 1979. Manual de producción de yuca. Cali, Colombia. (Multicopied.)

Cours G. 1951. Le manioc á Madagascar. Mem Inst Sci Madagascar Ser B 3(2):203–416.

Herrera C, A; Arias CA; Muñoz H. 1983. Guía para la construcción de una trozadora de yuca. CIAT, Cali, Colombia. 35 p.

Ospina Patiño B; Best R. 1984. Manual de construcción y operación de una planta de secado natural de yuca. CIAT, Cali, Colombia. 41 p.

Ospina Patiño B; Gómez G; Best R. 1983. El secado de la yuca para la alimentación animal. CIAT, Cali, Colombia. 12 p.

Toro JC; Cañas A. [1983]. Determinación del contenido de materia seca y almidón en yuca por el sistema de gravedad específica. In: Domínguez CE, ed. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (UNDP), Cali, Colombia.

CHAPTER 22

Artificial Cassava Drying Systems

Lisímaco Alonso[1], Miguel Angel Viera[2], Rupert Best[3], Sonia Gallego[4], and José Alberto García[5]

Introduction

Great potential exists in tropical Latin America for using dried cassava in animal feed. Good prospects also exist for including it in human food as a source of calories in processed foodstuffs, together with other raw materials. Examples include composite flours for soups, beverages, breads, and pastas. These end uses have created a need to develop drying methods that are efficient, reliable in terms of product quality, and technically and economically feasible. These three aspects in the dried cassava production should be considered within the socioeconomic situation of the developing countries that produce cassava.

Among the different drying systems there are two that require relatively low investment and are simple to manage. They therefore create interest, and have been included in CIAT's research programs. The two systems are *natural drying* and *artificial fixed-bed drying*.

Technology 1:

Case Study of Artificial Cassava Drying in the Colombian Atlantic Coast[6]

Lisímaco Alonso, Miguel Angel Viera, and Rupert Best

In the 1970s, CIAT adapted a technology to naturally dry cassava and applied it on a commercial scale in the Colombian Atlantic Coast in a collaborative project with the Fund for Integrated Rural Development (DRI, its Spanish acronym)[7]. The project was directed towards establishing small rural businesses that produced dried cassava for animal feed. In 2000, more than 180 cassava drying plants were established in Colombia.

Natural drying depends completely on climatic conditions, which restricts its use during rainy seasons. Thus, to prolong the drying period and ensure continuous supplies of dried cassava, a fixed-bed dryer with artificial circulation of hot air was chosen. This system was evaluated, using different sources of heat such as diesel, propane gas, coal, and a solar collector.

In this chapter, the results of this evaluation are presented and the usefulness of artificial drying discussed for the current conditions of cassava production and marketing in the Colombian Atlantic Coast. This method is also studied as an alternative in the production of dried cassava for human consumption.

1. Agricultural Engineer, Postharvest Management Systems, CLAYUCA, Cali, Colombia. E-mail: l.alonso@cgiar.org
2. Chemical Engineer, formerly of the Cassava Utilization Section, Cassava Program, CIAT, Cali, Colombia.
3. Chemical Engineer, formerly Leader of the RAD Project, CIAT. E-mail: rupertbest@gmail.com
4. Chemical Engineer, Postharvest Management Systems, CLAYUCA. E-mail: s.gallego@cgiar.org
5. Mechanical Engineer, Postharvest Management Systems, CLAYUCA. E-mail: albertogarcia@mailworks.org
6. The text of this section of the chapter, written by L. Alonso, M.A. Viera, and R. Best, was published in Revista ACOGRANOS (Colombia), no. 3, 1987.
7. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Research history

The most economical drying method that humans have used since remote times is natural drying. This method of drying cassava was studied by several researchers, using both concrete floors and vertical or sloping trays during the 1970s (Roa 1974; Best 1978; Thanh et al. 1979). These studies led to better understanding of the factors most affecting the process such as the size and shape of cassava chips, load density, and environmental conditions.

Despite the best efforts to improve natural drying techniques and the advantages that these offer over artificial drying in terms of investment and operational costs, they cannot be used in regions where environmental conditions are unfavorable. For these areas, the use of batch dryers, involving the circulation of ambient or hot air or a combination of both, directly through a layer or fixed bed carrying the product to be dried. The use of continuous artificial dryers of large capacity is economically the most favorable alternative for Latin America (Crown 1981; Freivalds 1982).

In parallel to research on natural drying, studies on fixed-bed drying were carried out to improve operational parameters, bed height, and air temperature and speed for drying cassava chips.

- Chirife and Cachero (1970) found that beds of up to 12 cm high do not appreciably reduce drying time with air flows at more than 5000 kg/h per m^2. The temperature at which chips are toasted to low moisture content (<35%) is more than 84 °C. These authors also found that constant speed was not present and that the internal movement of moisture within the chips is the mechanism that controls the process from the beginning. These findings were later confirmed by Webb and Gill (1974) and Akhtar (1978).

- On a larger scale, Rossi and Roa (1980) and Ospina (1980) experimented with a dryer that had a 15-m^2 drying area and was coupled to a solar collector with 100 m^2 of absorbent area. The authors used mathematical models to determine the minimum air flow that should be applied as temperature and relative humidity vary. They reported that, for 30-cm-high beds, the applied flow ranged between 47.5 and 102.5 m^3/min per ton of cassava chips, with air temperatures ranging between 20 and 40 °C, and relative humidity between 25% and 55%.

- Toh (1973) studied the drying of grated cassava pulp at several temperatures, air flows, and load densities in a continuous tunnel dryer. Pulp had been dried previously to a moisture content of 50% (wet basis) in a filter press. A kerosene burner was used to heat the air. Fuel consumption varied exponentially with load density, and increased (to a lesser extent) when flow was increased. Toh found that, for the experimental conditions, heating air to temperatures of more than 70 °C was unsuitable because of high fuel consumption.

- With this same material (pressed grated pulp), Seng (1976) evaluated the use of a rotary and continuous dryer. The fuel used accounted for 55% of the operation's total cost. Even so, this system could compete, in terms of costs, with traditional sun drying under Malaysian conditions, where the study was developed.

- A study on the economic feasibility of establishing an artificial drying plant for dried cassava chips was carried out by the National Center for Food Science and Technology (CITA, its Spanish acronym) in 1974, in Costa Rica. The project was found feasible, with returns of 11% on the total investment and 16% on the fixed investment, if the plant was operated at a minimum capacity of 10 t/ha for 20 h per day and 200 days per year. Based on this study, a plant was installed, but it failed because of poor location and the inability of the area to supply the necessary raw material.

The studies mentioned above indicate that, when attempting to minimize operating costs and obtain good quality dried cassava, control parameters are fineness of chipping the material, temperature, and air flow. Furthermore, to ensure the feasibility of the process, a continuous and adequate supply of raw material must be guaranteed.

Research CIAT plan

Our study in Colombia was carried out in two phases:

- *First*, a 6-m^2 dryer, coupled to a flat solar collector with a 30-m^2 surface, was evaluated. The dryer and collector were constructed in the Municipality of San Juan de Betulia, Department of Sucre, in a region known as the Colombian Atlantic Coast.

- *Second*, at CIAT (Palmira, Department of Valle del Cauca, southern Colombia), two dryers were used. One had 2 m^2 of drying area and was coupled to a coal burner. The other dryer had 6 m^2 and was coupled, independently, to two burners, one of propane gas and the other of diesel.

To evaluate the dryers with the three sources of heat, the quantity of chips placed in them was modified to obtain different air flows per ton of fresh cassava chips. Air temperature was reduced to the values obtained with the solar collector and was set at 50 and 60 °C for the two fuels used.

Raw materials

Roots were harvested from cassava (*Manihot esculenta* Crantz) crops that were 8 to 10 months old. The varieties used were, for the first phase, the local 'Venezolana', planted in the Atlantic Coast, and, for the second phase, 'Manihoica P-12', a variety planted at CIAT.

Cassava roots were chipped in a machine prototype, known as "Thailand" type. It consisted of a metal structure with a feed hopper and a vertical turning disk. The disk had six rows of holes with diameters of about 25 mm (Figure 22-1), and sliced the cassava into chips that measured 60 to 80 mm long, 25 to 30 mm wide, and 7 to 10 mm thick. These standard chips were produced at a rate of 42%, together with smaller chips (at 34%), and fine particles (at 24%).

Figure 22-1. Cassava chipping machine of the type "Thailand".

Drying systems

First phase. For trials in the first phase, the system shown in Figure 22-2 was used. It consisted of a 6-m^2 dryer, with a centrifugal fan and a 30-m^2, flat, solar collector. The dryer was a chamber constructed from materials available in the region. It measured 3 m long by 2 m wide. The drying area was a false floor formed of galvanized steel sheets, which were perforated with 3-mm-diameter holes for 3% of their total area. The sheets, measuring 1 × 2 m, were supported 60 cm off the ground by wooden beams.

A Dayton fan (reference no. 3CO73) circulated the air through the system by means of blades that curved backwards. The machine was operated by a 1-hp electric motor.

The solar collector had a 30-m^2 absorbent surface. It was constructed on a 6-cm-thick concrete floor edged with concrete blocks. The medium used for absorbing solar radiation consisted of corrugated zinc sheets painted in matte black. These sheets were placed inside the collector, between the floor and a plastic cover (caliber 6), itself supported by a structure of wood and chicken mesh (Figure 22-2).

Second phase. This phase of the experiment was carried out at CIAT, where two dryers were used. The one with a 2-m^2 drying area was coupled, through a Dayton centrifugal fan (reference no. 3CO73), to a unit comprising a coal burner and heat exchanger (Figure 22-3). The coal burner for the air oven was basically a combustion chamber or housing with a stationary grill. The heat exchanger was a double concentric tube, with longitudinal blades on both sides

Figure 22-2. The solar collector used to heat air for a cassava chip dryer.

Figure 22-3. An artificial fixed-bed dryer that uses a coal burner to heat the air.

of the interior tube by which the combustion gases flowed. The drying air circulated through the annular space formed by the two tubes.

The 6-m^2 dryer was coupled independently to two heating units, one of propane gas and the other of diesel. The diesel unit consisted of a Lister 7.5-hp motor (model LT1), coupled directly to a Lister axial fan. Through a transmission belt, the unit ran a Markon generator, producing an electric current of 1.5 kilovolt-amperes (kVA), which provided the current needed to operate the diesel burner (Nu-way Benson). The propane gas unit (Farm Fans, model 116SH) consisted of an axial fan and gas burner. Figures 22-4 and 22-5 show the heating units (diesel and gas) that were coupled to the dryer.

The coal and diesel burners heated the air indirectly, that is, they did not mix the air with the fuel gases. The burners were connected to the dryers by means of AMCA measuring ducts (Ashrae 1977).

Figure 22-4. A diesel heating system coupled to an artificial fixed-bed dryer.

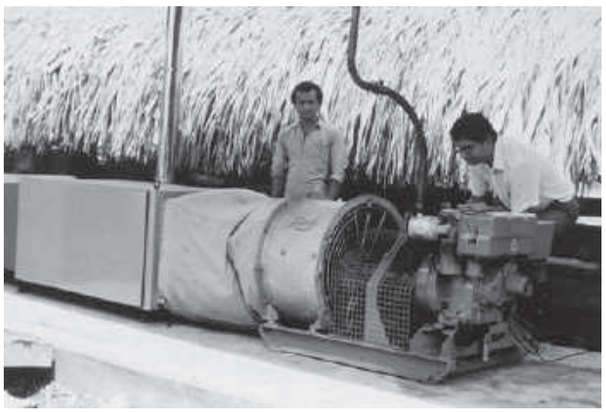


Figure 22-5. A propane gas heating system coupled to an artificial fixed-bed dryer.

Air flow was determined with a blade anemometer, a pitot tube, and an inclined-tube manometer with a scale 0 to 2.4 inches of water and a ±0.02 accuracy. In the dryers' plenum, the air temperature was measured with a mercury thermometer, calibrated from 0 to 120 °C and a ±1 °C accuracy.

Evaluating the artificial drying systems

The solar collector. The solar collector was studied in February and March 1984. Results were classified into two groups: one evaluating the solar collector's performance, and the other the dryer's capacity when the collector was used to heat the air. Results are presented in Table 22-1.

The collector operated daily from 7:00 to 19:00 hours, during which time it heated an air flow of 106 m^3/min at an average temperature of 36 °C. The initial temperature of ambient air averaged 31 °C.

Relative humidity of the air dropped from 62% to 46%. The collector's efficiency was defined as the ratio between the average amount of energy absorbed by the air and the energy of incident solar radiation. The result was 63%, a standard value, according to Rossi and Roa (1980) for this type of collector.

Table 22-2 shows the results obtained when the dryer was coupled to the solar collector. On applying various air flows, different drying times were obtained, which were expressed as net daylight hours between 7:00 and 20:00 hours. Nocturnal hours, during which the process was suspended, were included. The number of batches that could be dried per week, considering drying time, was determined on the basis that new batches were not processed after the one that finished after mid-day.

Table 22-1. Value[a] of parameters by which a flat solar collector with a 30-m^2 absorbent surface[b] operates.

Ambient air		Solar radiation	Air flow	Temperature (°C)		Efficiency
Temp. (°C)	r.h. (%)[c]	(cal/cm^2 per min)	(m^3/min)	Increase	Final	(%)
31	62	0.62	106	5	36	63

a. Average values over 43 days of observations between 7:00 and 19:00 hours.
b. Absorbent surface was constructed with corrugated zinc sheets, painted in matte black and placed under a cover of polyethylene sheeting.
c. r.h. refers to relative humidity.

Table 22-2. Effect of air flow applied over time within an artificial fixed-bed drying system that is coupled to a flat solar collector.[a]

Applied air flow (m^3/min per t)	Drying time		Capacity per week	
	Net[b] (h)	Production[c] (days)	Batches (no.)	Dried chips (kg)
78	41	3.2	1.5	810
88	42	3.3	1.5	720
100	29	2.2	2.0	840
118	26	1.6	3.0	1077
141	20	1.3	3.0	480

a. Average values of three replications by level of applied air flow. General trial conditions were as follows:
   - Moisture content of cassava chips = initial: 64.5% ± 2%; final = 12.3% (interpolated).
   - Air: temperature = 36 ± 2 °C; relative humidity = 43.5% ± 6.5%; flow = 106 m^3/min.
   - Solar radiation (cal/cm^2) = 0.60% ± 10%.
b. Daylight drying period = 7:00 to 20:00 hours.
c. Includes nocturnal hours during which drying was suspended.

This standard was adopted because the product's final quality could not otherwise be guaranteed. The chips deteriorated if their drying was interrupted and their moisture content did not drop below 35% on the first day. If this occurred, the chips appeared yellowish—a general sign of inadequate processing that had left them with a poor appearance. The same thing also happened when drying time continued for more than 2 days.

Although drying can continue after 20:00 hours, this time was not used for reducing moisture content in the chips, because the low temperatures obtained with the collector during those hours did not sufficiently justify expenditure on electric power.

Table 22-2 shows that the largest capacity for drying per week was obtained when an air flow of 118 m^3/min per ton of fresh chips was applied.

Table 22-3 shows the value of investment and production costs of a natural system, compared with those of an artificial system with a solar collector. The artificial system has higher initial costs to pay for the motor-fan unit, and higher production costs to pay for replacing the plastic cover and consuming electric power. As a result, this system does not compete with the natural system, even though this latter system is dependent on environmental conditions.

The use of a solar collector to artificially dry cassava chips, a product whose initial moisture is high (60% to 65%) at relatively low temperatures (34 to 38 °C), requires high air flows. This affects the size of both collector and fan, and limits the system's capacity to 2.5 to 3 t of dried product per batch.

Using three fuels. Table 22-4 gives the results of artificial drying, using three available fuels: coal, propane gas, and diesel. The Table also shows the overall efficiency of the process for different operating conditions and the operating costs generated according to fuel. With the air flows applied and given temperatures, cassava chips can be dried to a moisture content of 12.3% over 5.5 to 10 hours in a normal workday. Fuel consumption was greater for coal than for propane gas. When the temperature or air flow was increased, drying time was reduced but fuel consumption and, therefore costs, were higher.

Propane gas was the most efficient, followed by diesel and coal. Few differences were seen between the latter two fuels. The propane gas's higher efficiency was due to the air being directly heated, as it is mixed with the fuel's gases.

Table 22-3. Costs of investment and production of batch-drying systems with a capacity to produce 2.4 t of dried cassava chips, 1985.

Drying system	Cost of:	
	Investment (US$)[a]	Production (US$/t)
Natural: on concrete floor (500 m^2)	183.6	11.9
Artificial: fixed-bed and solar collector[b]	566.7	12.6
Difference	383.1	0.7[c]

a. US$1.00 = Col$1800 in 2010.
b. Costs of system elements: chamber (30 m^2) = US$111.1; solar collector = US$122.2; motorized fan = US$333.3
c. This difference in production costs is due to the replacement of the plastic cover and consumption of electric power in artificial drying.

Table 22-4. Effect of temperature and air flow on drying time and fuel consumption, and on two parameters (efficiency and costs) of the artificial cassava drying system with three different sources of heat.[a]

Air temp.[b] (°C)	Air flow (m^3/min per t[c])	Net drying time (h)	Fuel consumption[c]			Overall efficiency (%) with:			Cost[d] (US$/t[c])		
			Coal (kg/t)	Propane gas	Diesel (gal/t)	Coal (kg/t)	Propane gas	Diesel	Coal	Propane gas	Diesel
50	130	10.0	250	105	65	38	70	36	1625	3150	7150
	190	7.5	390	110	70	32	72	36	2535	3300	7750
60	130	7.5	300	100		35	65			1950	3000
	190	5.5	350	130		25	54			3575	3900

a. Average of three values per treatment. General trial conditions were as follows:
   - Average temperature of ambient air = 26 °C.
   - Moisture content of cassava chips (%) initial = 61% ± 2%; final = 12% (interpolated).
   - Heat value of fuels (kcal/kg): coal = 6,700; propane gas = 14,000; diesel = 41,000
   - Efficiency of burners: coal = 60% ± 5%; propane gas = 95% ± 2%; diesel = 76% ± 2%.
   - Fuel prices in 1985: coal = US$0.004 per kg; propane gas = US$0.02 per kg; diesel = US$6.1 per gallon.

b. The diesel heating system, on its own, provides a temperature of 50 °C.

c. t refers to tons of fresh cassava chips.

d. US$1.00 = Col$1800 in 2010.

Although drying with coal was the least efficient and consumed the most fuel, operating costs were the lowest because its price per kilogram was relatively low. Higher air flows and temperatures meant higher operating costs. In this regard, the difference between coal and propane gas diminished. Accordingly, choosing between them has to be based on the availability of fuel and costs of combustion and heating equipment. Table 22-5 presents these costs, together with those of the burners, heat exchangers, fans, and controls that form each unit. The end result tends to favor the coal option, which presents lower costs of both investment and operation.

Economic analysis

Burners form the heat transfer equipment in artificial dryers, with coal having advantages over propane gas or diesel. Hence, an economic study of the four alternatives for investment was carried out, using the conditions of production and marketing of dried cassava chips in the Atlantic Coast, where dried cassava technology is supported. Cost data are expressed in American dollar (US$). The principal assumptions of this analysis are presented below:

Table 22-5. Cost of combustion equipment, using diesel, propane gas, or coal, with a capacity of 70,000 kcals per hour, 1985.

System	Investment cost (US$)[a]
Coal	261.1
Diesel	680.6
Propane gas	358.3

a. US$1.00 = Col$1800 in 2010.

- *Production capacity* is determined according to the capacity of a model plant in the Atlantic Coast, and is calculated as 538 t of dried cassava chips per year.

- *Price of raw material* is US$4.44/t of fresh cassava roots, the value reported by drying plants during the operational year 1985.

- *Conversion factor* of fresh roots to dried chips is 2.5. That is, 2.5 t of fresh cassava roots are needed to produce 1 t of dried cassava chips.

- *Sale price* per ton of cassava chips dried to a moisture content of 12.3% was US$15.11. (This is 85% of the price for sorghum in 1985.)

- *Coal consumption* costs US$0.004/kg per 450 kg/t of fresh cassava chips.

- *Workdays* per week: 6.

- *Drying methods*:
  - Natural, on concrete floors
  - Artificial, fixed-bed, with air heated to 60 °C, using coal.

The prices of fresh roots and dried chips can vary over the project's life. For this analysis, the prices are assumed to be in constant currency, that is, they are deflated by the same index. Table 22-6 describes the four investment alternatives:

- *Alternative 1* corresponds to a model plant in the Atlantic Coast. It operates during summer (December to April) over 20 weeks per year.

Table 22-6. Description of four alternative investment structures for drying cassava chips.

Parameter	Alternative			
	1	2	3	4
Drying method	Natural	Natural	Natural/Artificial	Artificial
Annual operational period (no. of weeks)	20	35	20/30	50
Drying system	On 2000 m^2 of concrete floor	On 1300 m^2 of concrete floor	On 1000 m^2 of concrete floor/ 20-m^2 fixed-bed dryer	20-m^2 fixed-bed dryer
MCP[a] by batch (t)	24	13	12/4	4

a. MCP = maximum capacity for processing fresh cassava chips.

- *Alternative 2* is the same as Alternative 1, but operates for an extra 15 weeks, during the transitions from winter to summer and summer to winter, or in regions where summer is longer, as in the northeastern departments of the Atlantic Coast, where warm spells occur.

- *Alternative 3* operates for 50 weeks of the year, with 20 weeks with a natural drying system on concrete floors, and 30 weeks of rainy season with an artificial, fixed-bed, drying system.

- *Alternative 4* also operates for 50 weeks per year, but uses only an artificial drying system.

Table 22-7 shows the investment needed for equipment (chipping machines, dryers, and motors), tools, and working capital (the money needed to buy raw material for 1 month's operation). It varied from plant to plant, because the period of annual operation was different for each, even though their production capacity was the same. Some plants therefore handled larger monthly volumes of fresh cassava than others. Table 22-8 gives the production costs per ton of dried cassava chips. Processing costs includes labor, maintenance, and consumption of electric power and coal.

With data tabulated, the profitability or rate of return was calculated on a personal computer, equalizing income values to payment values. The four alternatives were economically feasible, with their profitability rates at 26.4%, 37%, 12.6%, and 12.4%, respectively. Alternative 2 was the most profitable because it used its installations over a longer period, and had low operating and investment costs. Alternative 4 required the least investment, but had the highest operating costs.

Table 22-7. Value of investment and working capital for the four alternative investment structures for drying cassava chips, 1985.

Parameter	Alternative			
	1	2	3	4
Initial investment (US$)[a]	1,721	1,269	1,946	1,410
Working capital (US$)[a]	1,196	684	478	478

a. US$1.00 = Col$1800 in 2010.

Table 22-8. Production costs (US$) a per ton of dried cassava chipsb according to four alternative investment structures, 1985.

Parameter	Alternative			
	1	2	3	4
Raw material (fresh cassava roots)	11.1	11.1	11.1	11.1
Processing	2.0	2.0	3.0	3.6
Total	13.1	13.1	14.1	14.7

a. US$1.00 = Col$1800 in 2010.
b. Components: moisture content at 13.7%; protein, 3.5%; fat, 0.5%; fiber, 10%; carbohydrates, 78.6%.

The economic data of the analysis were valid for summer, when dried cassava chips were produced. In winter, dried cassava chip production was nil, given that natural drying was being used. Hence, the price increased, reaching US$20.6 per ton or more, especially when sorghum imports were also restricted and scarce on the market.

If the supply of dried cassava chips could be year round, then the price could be expected to stabilize to a balance between supply and demand, or agreements could be made to stabilize it. Hence, the same price was considered for all alternatives, even though they had functioned in different seasons of the year.

However, the price of collecting fresh cassava roots varies with the changeover from dry to rainy seasons; difficulties in harvesting, collection, and transport; or scarcity. Although obtaining raw materials most affects production costs, the same price was also considered for this factor when analyzing the four alternatives because no information was available for predicting a

reliable price during the rainy season. Hence, if a project of dried cassava chip production is to be profitable or to expand its capacity throughout the year, a drying plant must not only be located in a cassava-producing region, but should also develop its infrastructure and grow its own crops. Thus, raw material supplies will be guaranteed and at a stable price.

Conclusions and recommendations

The evaluation of technologies for producing dried cassava chips, by creating an agroindustry in the Colombian Atlantic Coast, led to the introduction of improvements to production. This could not have happened if the work had been at an experimental level. These improvements manifested in reduced production costs and consequent increases in profits for the project.

The production of dried cassava chips and their use as a source of calories to substitute certain grains (especially sorghum) in animal feed has generated a growing demand for this product in the market. To meet this demand, both the production and processing of cassava chips must be developed:

– For *production*, both yield per hectare and area cultivated must be increased. Thus, cassava may be produced for the fresh-root market, which pays higher prices, and for industries using dried cassava chips.

– For *processing*, the use of a natural drying system confines work to dry seasons of the year and thus the processing of the largest volumes of fresh cassava roots to these periods. The product becomes distributed throughout the rest of the year. This increases capital costs as it requires increased capacity and storage.

However, the use of an artificial fixed-bed dryer, with coal as a source of energy, is the best alternative to enable a year-round offer of dried cassava chips. Furthermore, product quality can be improved, an advantage when incentives are paid for quality or the product is marketed for human consumption, thereby achieving better sale prices.

Given the study conditions, the two systems—natural drying (ND) and artificial drying (AD)—are profitable options. ND offers higher profits than AD because of lower investment and operating costs. However, the two operational alternatives can be complemented to increase production capacity.

A solar collector for AD is not feasible because considerable energy is needed to evaporate the large quantity of moisture contained in fresh cassava chips. That energy cannot be provided with the temperatures achieved with this system.

A sensitivity study is recommended to establish the effect of the price of raw material, sale price, conversion factor of fresh to dried cassava chips, and consumption and price of coal on the profitability of a project to produce dried cassava chips that alternatively uses ND or AD.

Technology 2:
Producing Dried Cassava Chips for Human Consumption

Sonia Gallego, Lisímaco Alonso, and José Alberto García

Introduction

For more than four decades, different cassava drying systems have been studied for their efficiency, technical and economical feasibility, and reliability for product quality. However, most of the technologies developed focused on dried cassava chip production for animal feed, overlooking the potential of dried chips as cassava flour for human consumption.

In 2000, when CLAYUCA revisited the theme of producing high-quality cassava flour, evaluations of different artificial cassava drying systems were also started (García et al. 2006). Tools, including mathematical modeling, were used to predict the performance and characteristics of cassava drying under certain operational conditions (Gallego et al. 2003). The objective was to develop a procedure for producing dried cassava chips, using artificial drying methods that would guarantee a permanent offer of the

product at competitive prices and a quality that was safe for human consumption.

The quality of dried cassava chips depends largely on the processing technology used. However, obtaining raw material of excellent quality is also very important. Adequate control must be carried out at all stages of the process to guarantee the acquisition of a product that meets the standards of quality established for raw materials used to prepare foodstuffs.

Thus, according to the evaluations made, a processing prototype was developed for producing dried chips of optimal quality on equipment at CLAYUCA's pilot plant in CIAT's facilities, Palmira, Colombia.

Producing dried cassava chips

The operations required for producing dried chips are described in Figure 22-6. Ideally, all equipment or parts thereof that come into direct contact with cassava chips must be constructed or lined with stainless steel sheets to guarantee the prevention of contamination. Otherwise, washing and continuous disinfection of all equipment, tools, and installations used in the process become indispensable.

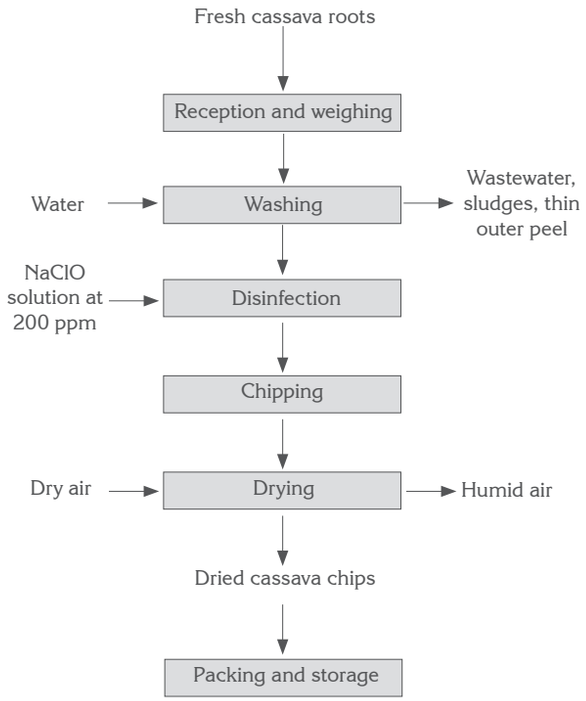


Figure 22-6. Flow chart of dried cassava chips production at the CLAYUCA pilot plant in CIAT.

Reception and weighing. After harvesting, cassava roots are transported, either packed or in bulk, to the drying plant. There, they are unloaded and stored for a maximum of 1 day before processing (Figure 22-7). The cassava is weighed to determine the parameter of yield or the conversion factor of fresh roots to dried chips. The roots should be processed without delay as, within the first 48 h after harvest, symptoms of deterioration develop, principally as color changes in tissues (Figure 22-8).

Figure 22-7. Cassava roots being stored before processing into chips.

Figure 22-8. Typical symptoms of deterioration in cassava roots.

Washing. Harvested cassava roots carry a large quantity of soil and field residues, making their washing before chipping necessary to ensure the dried product's nutritional quality. Washing is carried out in a rotary cylinder, which moves the roots as it washes them with clean pressurized water applied inside the drum. The cylinder walls are perforated to permit the exit of wastewater and residues (mainly the thin outer peel of cassava roots). The equipment also has a loading gate for the length of the cylinder and a feed hopper at one end (Figure 22-9).

About 1 m^3 of potable water is required per ton of fresh cassava roots. For the daily washing of equipment and installations, 2 m^3 are used. Overall, the plant requires 4 m^3 of water per process.

Figure 22-9. Cassava washing machine.

Disinfection. When the roots are clean, they are disinfected, using a diluted solution of sodium hypochlorite (NaClO). This solution is also applied for a few minutes when the roots are in the cylinder.

Chipping. To accelerate the drying rate and thus obtain a good quality product, roots should be cut into small chips of uniform size that increase the surface area exposed to the drying air. Chipping equipment basically consists of a chipping disk assembled vertically onto a structure that supports both the disk's axis and the feed hopper (Figure 22-10). The disk possesses coupled blades that, as the disk spins at 600 rpm, create chips shaped as rectangular bars (Figure 22-11).

Drying. The use of dryers with hot air circulating directly across a fixed bed is the most favorable alternative in terms of quality of end product. Moreover, this method can be used where environmental conditions are not conducive to natural drying.

Artificial drying over a fixed bed consists basically of a uniform flow of hot air passing through a layer, 10 to 30 cm thick, of fresh cassava chips. The dryer is a compartment of simple construction. The product rests on a false floor with perforations, with a fan

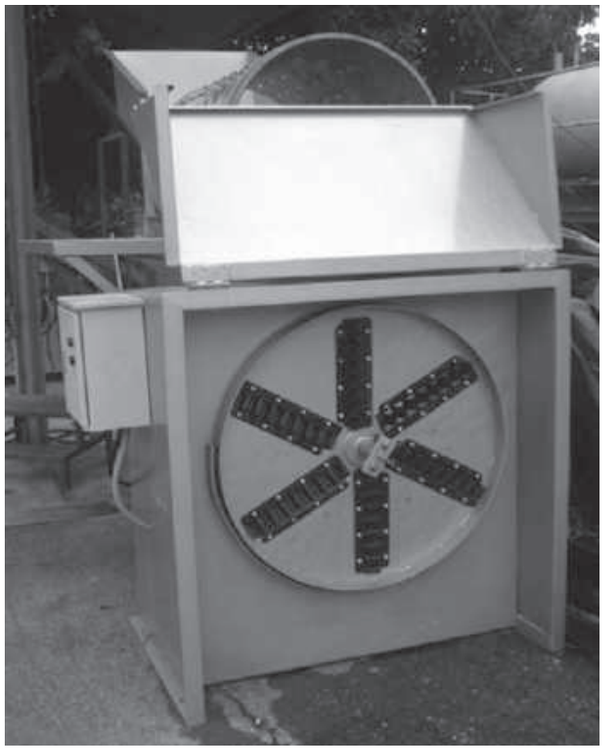


Figure 22-10. Cassava chipping machine.

Figure 22-11. Fresh cassava chips.

forcing the hot air to circulate through the layer of chips. Before it makes contact with the fresh cassava chips, the air is heated in a unit that consists of a burner that is connected to the dryer by ducts. So that drying is uniform, the product must be continually mixed or turned. Although mixing can be manual (Figure 22-12), mechanical mixers are preferable.

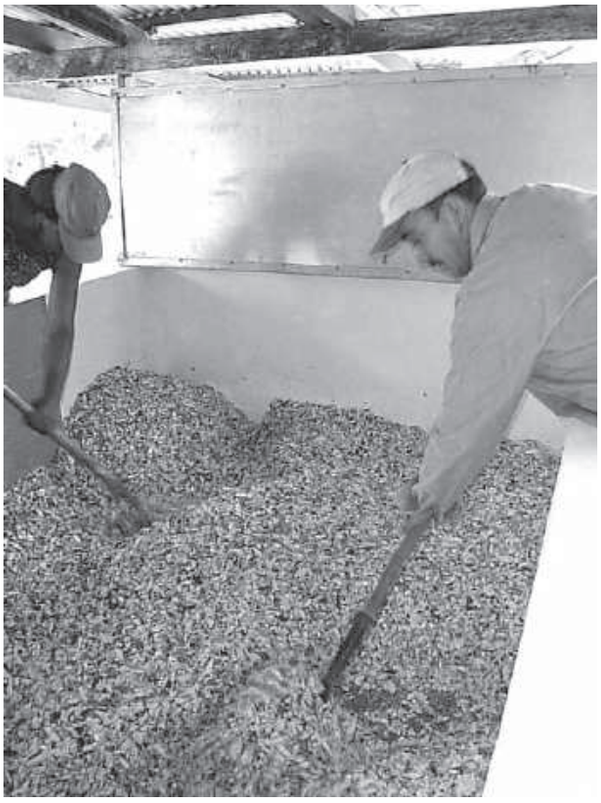


Figure 22-12. Manually mixing cassava chips in the artificial fixed-bed dryer.

For these dryers, the exposed area of the product, temperature, and air flow and humidity must be taken into account, as these variables affect drying times and fuel consumption, themselves significant parameters for determining the process's overall efficiency and operating costs.

Packing and storing. Once the chips have reached a suitable moisture content (10%–12%), they are packed in polypropylene sacks (Figure 22-13). The plant should have a room built for storing dried chips. When storage conditions are adequately controlled, dried cassava chips may be conserved for 6 to 18 months without quality deteriorating. Optimal conditions are achieved if the storage site is kept clean, in good sanitary condition, and free of insect pests.

Evaluating the artificial drying system

Drying is the most important operation in the production of dried chips because of time and fuel requirements, especially as cassava has a high initial moisture content. To evaluate the technical and economic feasibility of the fixed-bed dryer for producing dried chips for human consumption, different trials were carried out to determine the values of the main variables intervening in the process (García et al. 2006).

The equipment used for the evaluation was a fixed-bed dryer with forced circulation of hot air, belonging to CLAYUCA and located at CIAT's facilities in Palmira (Figure 22-14). For the trials, the operation of the equipment and burner was adjusted. Drying curves were established for different loads and operating conditions were determined to obtain a good quality dried product.

Figure 22-13. Dried cassava chips packed in polypropylene sacks.

Figure 22-14. CLAYUCA's artificial fixed-bed dryer at CIAT, Palmira.

Loads ranging between 600 and 1200 kg of fresh chips were managed in one or two 6-m^2 drying chambers. Air flows were heated between 60 and 70 °C, and applied at 115 to 230 m^3/min per ton of fresh cassava chips. The chips' initial moisture content ranged between 58% and 70%.

Table 22-9 shows the average results of the trials carried out with the artificial fixed-bed dryer. According to the initial chip load, various air flows were used and different drying times were obtained for each. Overall, for the different flows applied, drying times ranged from 8 to 18 h.

When air flow was reduced, drying time increased, but fuel consumption (in this case, diesel) was less in terms of quantity of dried chips. Table 22-9 also presents the calculated consumption of natural gas and coal for different air flows, to compare with less expensive fuels in the calculation of the production costs of dried chips. Figure 22-15 illustrates a typical curve for the fixed-bed dryer, for which drying time was about 8 h to reach a moisture content of 12% in the chips.

Table 22-9. Drying times and average fuel consumption for trials carried out with a fixed-bed dryer.[a]

Air flow (m^3/min per ton fresh chips)	Net drying time (h)	Fel consumption		
		Diesel (gal/t dried chips)	Natural gas (m^3/t dried chips)	Coal (kg/t dried chips)
230	8	90	353	602
180	11	88	345	589
150	13	86	340	580
120	18	80	313	535

a. Average ambient temperature = 25 °C.
Average air drying temperature = 65 °C.
Average initial moisture content of chips = 65%.
Average final moisture content of chips = 12%.

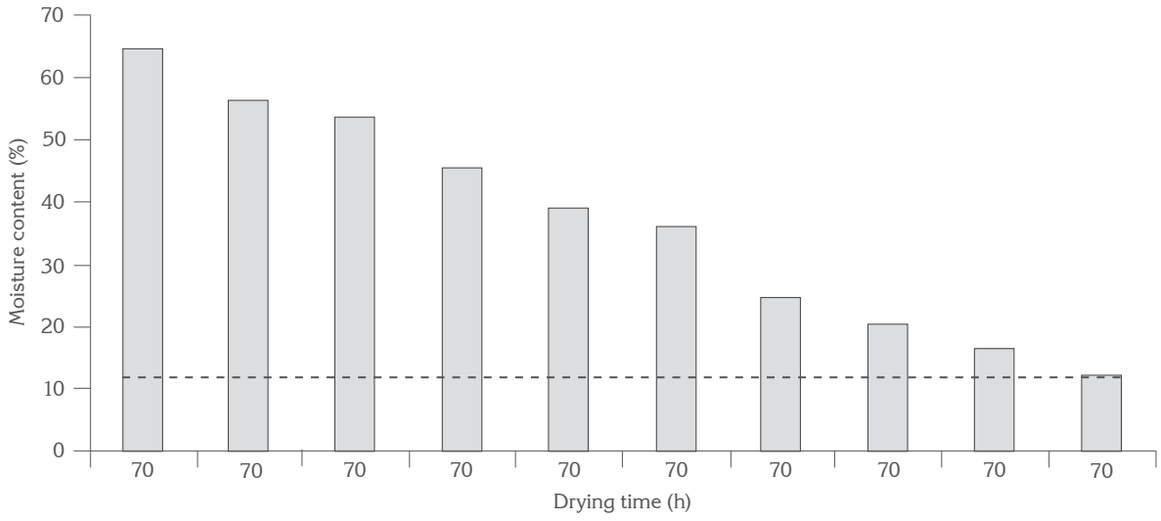


Figure 22-15. Typical curve presented when cassava chips are dried, using an artificial fixed-bed dryer.

The data in Table 22-9 were used to estimate the production costs of dried cassava chips obtained through artificial fixed-bed drying, using natural gas as fuel and an air flow of 120 m^3/min per ton of fresh cassava chips. Table 22-10 shows that the total production costs of 1 t of dried cassava chips, using a fixed-bed dryer with natural gas as fuel, would be US$361.1. However, if coal was used instead as fuel, the cost would be US$299.1, a drop of almost 20%.

In conclusion, if more economical fuels are used for drying, the best quality dried cassava chips can be obtained at low production costs.

Quality of dried cassava chips for human consumption

A product's quality is measured by the way in which its characteristics comply, among other aspects, with:

- Legal health provisions
- Composition
- Taste or acceptability to consumers

A product may comply with legal provisions but nevertheless be rejected by consumers for such attributes as color, flavor, aroma, and chemical composition. Hence, quality control should involve not only compliance with legal provisions but also aspects that determine acceptance by consumers.

With respect to the dried chips' final quality, not only should the raw material be of good quality, but supervision and control should also be carried out at all stages of processing. The difficulty of carrying out such activities in practice means that the finished product, that is, the dried cassava chips, must be continuously and systematically reviewed.

In short, dried cassava chips should comply with given requirements imposed by the market. These characteristics include chemical composition, sanitary condition, physical characteristics (size, rheology, color, and viscosity), and sensory characteristics (aroma and flavor).

Chemical composition. The usual chemical composition of dried cassava chips is presented in Table 22-11. Although composition values are usually constant, ranges are reported, as these values depend largely on factors such as variety, sanitary quality, type of processing, and moisture content of the dried chips (Alonso and Zapata 2005).

Table 22-10. Total production costs of dried cassava chips, using an artificial fixed-bed dryer, Colombia, June 2010.

I. Basic information				
Conversion factor for fresh to dried cassava chips = 2.6:1				
II. Variable costs per ton dried chips	Unit	No. units/t dried chips	Unit value (US$)[a]	Cost/t (US$)[a]
Inputs				
Raw material[b]	t	2.6	55.55	144.4
Fuel (natural gas)	gal	313.0	0.39	122.1
Energy for process	kWh	218.0	0.11	24.0
Washing water	m^3	2.5	0.49	1.2
Sacks	unit	25.0	0.37	9.2
Labor[c]	workday	2.0	13.89	27.8
Total variable costs				328.7
III. Fixed costs/ton dried chips				Cost/t (US$)
Depreciation and maintenance[d]				32.4
Total fixed costs				32.4
Total production costs/ton dried chips[e] (US$)				361.1

a. US$1.00 = Col$1800 in 2010.
b. Price of fresh cassava roots as delivered to plant.
c. Assuming a workday of 8 h.
d. Depreciation over 10 years; maintenance at 4% annually; initial investment at US$27,778.
e. Production costs obtained for the conditions and equipment at CLAYUCA (fixed-bed dryer).

Table 22-11. Average values for chemical constituents of dried cassava chips destined for human consumption.

Parameter	Range
Moisture content (% wb)[a]	10–13
Starch (%)	60–85
Protein (%)	1–3
Crude fiber (%)	1–4
Ether extract (%)	1–2
Ashes (%)	1–3
Total sugars (%)	2–5
Total cyanide (ppm)	10–30

a. wb refers to wet basis.

Overall, dried cassava chips are characterized by their low contents of protein, fiber, and ether extract (fat), but high levels of carbohydrates, which comprise mainly of starch and small amounts of sugars. The peel or cortex represents 15% to 20% of the cassava root's total weight, with the pulp or parenchyma amounting to 80%–85% (Alonso and Zapata 2005).

To produce refined flour, dried cassava chips are ground and sieved, removing most of the peel, thin outer peel, and fiber as a solid waste byproduct. Most of the protein, fat, fiber, and ashes are located in the cortex, the principal component of the solid waste, whereas the carbohydrates are located in the parenchyma, the principal component of refined flour.

The standard used for quality in Colombia for dried cassava chips destined for human consumption is the Colombian Technical Standard NTC 2716, issued by the Colombian Institute of Technical Standards and Certification (ICONTEC, its Spanish acronym). At world level, the quality standard is the CODEX STAN 176-1989 for "edible cassava flour", developed by the Codex Alimentarius Commission for cassava flour obtained from dried cassava chips.

Microbiological quality. Apart from the average characteristics of size, presentation, and chemical composition, dried cassava chips for human consumption must also meet the microbiological requirements called for by the Ministry of Health in each nation. Table 22-12 shows the maximum values permitted by the Colombian Government, according to Standard NTC 2716. In short, the product must be free of microorganisms and parasites, and must not contain any substance derived from microorganisms in quantities that may endanger health.

Table 22-12. Microbiological requirements for dried cassava chips destined for human consumption.

Analysis	Maximum limit
Total count of aerobic mesophiles (cfu/g)	200,000
Count of total coliforms (cfu/g)	150
Count of *Escherichia coli* (cfu/g)	3
Count of *Staphylococcus aureus* (cfu/g)	100
Count of fungi and yeasts (cfu/g)	2,000
Detection of *Salmonella* spp. in 25 g	Absent
Count of *Bacillus cereus* (cfu/g)	1,000

Uses of dried cassava chips

The production of dried cassava chips to obtain refined flour destined for human consumption is of great importance at national and international levels, as they may constitute a raw material of special interest for numerous food-processing industries.

Dried cassava chips used to produce high-quality refined flour may partially substitute not only wheat flours, but also flours of other grains such as maize and rice, in food formulations, including for breads, pastas, pie mixtures, confectionery, flour mixtures for beverages and soups, extruded products or snacks, and processed meats (Ospina et al. 2009).

Even with partial substitution of other flours with cassava flour, food-processing companies can save costs as, in most cases, cassava flour can be obtained at lower prices than the other flours.

Finally, so that an agroindustry of this type is sustainable over time, the following aspects should be considered: a guaranteed supply of quality cassava roots at adequate volumes and stable prices; an efficient, economic, and reliable technology in terms of the end product's quality; and support from food-processing industries that identify cassava flour as a suitable raw material that will, on the one hand, bring economic benefits to their business and, on the other hand, contribute to the cassava crop's agroindustrial development and promotion in their region.

References

Akhtar J. 1978. Drying of cassava with heated air. MSc thesis. Asian Institute of Technology (AIT), Bangkok, Thailand. 47 p.

Alonso L; Zapata, V. 2005. Manual de producción de trozos secos de yuca para la alimentación animal. CIAT; CLAYUCA; World Vision International, Palmira, Colombia.

Alonso L; Viera MA; Best R. 1987. La investigación en el secado artificial de yuca como apoyo al desarrollo agroindustrial de la Costa Atlántica de Colombia. Revista ACOGRANOS 3:24–32.

Ashrae H. 1977. Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, USA.

Best R. 1978. Cassava processing for animal feed. In: Weber EJ; Cock JH; Chouinard A, eds. Cassava harvesting and processing—Proc workshop held in Cali, Colombia, April 1978. International Development Research Centre (IDRC), Ottawa, Canada. p 12–20.

Chirife J; Cachero RA. 1970. Through-circulation drying of tapioca root. J Food Sci 35(4):364–368.

CITA (Centro Nacional de Ciencia y Tecnología de Alimentos). 1974. Estudio de factibilidad agrícola e industrial para el establecimiento de una planta de chips secos de yuca en San Carlos. San José, Costa Rica.

Crown F. 1981. White elephant tales: Venezuela's cassava processing plants. Agribusiness Worldwide 2(1):24–29.

Freivalds J. 1982. Farm fiction: the feasibility studies for cassava production and processing in Espírito Santo, Brazil. Agribusiness Worldwide 3(6):10–13.

Gallego S; Tobar LM; Marriaga N. 2003. Evaluación técnica del primer secador de la planta piloto de secado artificial continuo de yuca, CLAYUCA–Protón. BSc thesis in Chemical Engineering. Universidad del Valle, Cali, Colombia. (Also available in: CLAYUCA/ CIAT. Informe anual de actividades. Palmira, Colombia.)

García JA; Gallego S; Alonso L. 2006. Establecimiento de una planta piloto para la producción continua de harina refinada de yuca. In: Informe de proyecto. CLAYUCA, Palmira, Colombia.

Ospina JE. 1980. Quantificação da deterioraçâo de mandioca durante a secagem em barcaça por convecção forçada de ar aquecido com coletor solar. MSc thesis. Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil. 100 p.

Ospina B; Alonso L; Gallego S; García JA. 2009. Tecnologías para el manejo poscosecha del cultivo de la yuca—Proc Reunión Anual de Socios. CLAYUCA/ CIAT, Palmira, Colombia.

Roa G. 1974. Natural drying of cassava. Dissertation. Department of Agricultural Engineering, Michigan State University (MSU), USA. 234 p.

Rossi SJ; Roa G. 1980. Secagem e armazenamento de productos agropecuários com uso de energia solar e ar natural. Secretaria da Indústria, Comércio, Ciência e Tecnologia; Academia de Ciências do Estado de Sâo Paulo (ACIESP), Sâo Paulo, Brazil. 295 p.

Seng YY. 1976. Development of a drying system for cassava using a high temperature rotary drier. Thesis. University of Malaysia, Kuala Lumpur, Malaysia. 219 p.

Thanh R; Muttamara S; Lohani BN; Rao BV; Burintratikul S. 1979. Optimization of drying and pelleting techniques for tapioca root. J Food Sci 35(4):364–368.

Toh KB. 1973. An investigation into the techniques of dehydration of tapioca by mechanical and artificial heat drying. BSc thesis. University of Malaysia, Kuala Lumpur, Malaysia. 120 p.

Webb BH; Gill KS. 1974. Artificial heat drying of tapioca chips. Malays Agric Res 3:67–76.

CHAPTER 23

Production and Uses of Refined Cassava Flour

Contributors, in order of appearance, to different sections of this chapter:

José Alberto García[1], Lisímaco Alonso[2], Sonia Gallego[3], Johanna A. Aristizábal[4], Sergio Henao[5], Ana Milena Bonilla[6], and Andrés Giraldo[7]

Introduction

Rapid urban growth in Latin American and Caribbean (LAC)[3] countries has increased demand for processed food, opening opportunities whereby the cassava crop can acquire higher added value. In Colombia, public and private entities are highly interested in the potential prospects of increasing the consumption of cassava and its derived products. Accordingly, several agroindustrial projects on cassava are being promoted in various parts of the country. One dynamic market is animal feed, where cassava flour or dried chips can be used as an energy source in balanced feed formulas.

However, to be viable, agroindustrial cassava projects need other alternative marketing options for using cassava, for example, as a partial substitute of other products such as wheat, maize, and rice flours, and even sweet cassava starch. Thus, cassava can participate in food-processing and industrial markets, for which products of higher added value can be developed.

CIAT has conducted projects to expand the production of cassava flour and its use, thus promoting the opening of new markets and establishing rural agribusinesses that offer small farmers opportunities for increasing their income.

In 2006, CLAYUCA, with financial support from the Ministry of Agriculture and Rural Development of Colombia (MADR, its Spanish acronym), implemented the project *Establishing a pilot plant for the continuous production of refined cassava flour*. The aim was to develop a technology to extract, on an ongoing basis, refined cassava flour with high starch contents and low contents of fiber, ash, and protein (García et al. 2006).

A modular pilot plant was therefore established to continuously produce refined cassava flour. Mechanical means (mill sieves) and pneumatic classification (cyclones) were used to obtain granules as fine as those of starch. Specifically, flour was refined to a maximum fineness, where particles were less than 50 μm in particle size.

The project was based on the problems industry has with cassava starch such as the generation of large amounts of wastewater to obtain native starch. Studies were initiated, with the collaboration of Universidad del Valle (Colombia), to obtain flours based on dried cassava chips, using a minimum quantity of water (Barona and Isaza 2003).

The pilot plant

Dried cassava chips can be ground into high-quality flour for use as a partial substitute for wheat, maize, rice, and other flours in foodstuffs such as breads; pastas; flour mixtures for pies, beverages, and soups; extruded products; and processed meats. Cassava flour can also be used as raw material in the production of glues for corrugated cardboard boxes, biodegradable plastics, beer, and ethanol.

1. Mechanical Engineer, Postharvest Management Systems, CLAYUCA, Cali, Colombia. E-mail: albertogarcia@mailworks.org
2. Agricultural Engineer, Postharvest Management Systems, CLAYUCA. E-mail: l.alonso@cgiar.org
3. Chemical Engineer, Postharvest Management Systems, CLAYUCA. E-mail: s.gallego@cgiar.org
4. Formerly Chemical Engineer, Postharvest Management Systems, CLAYUCA.
5. Agroindustrial Engineer, UN–Palmira.
6. Agroindustrial Engineer, Universidad de San Buenaventura, Cali, Colombia.
7. Agroindustrial Engineer, Universidad del Cauca, Popayán, Colombia.
8. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Figure 23-1 shows the pilot plant for the continuous production of refined cassava flour located in the facilities of CIAT, Palmira, Colombia. The plant processes 300 kg/h of dried cassava chips. The design took into account the different issues determining the functionality of processing dried chips into refined flour. A simple technology was used, in which elements were easy to manage and accessible for maintenance. The technology was simple enough for anyone person with minimal training to carry out. Furthermore, the plant permitted variation in operating conditions, according to the desired refining requirements such as refined flour or a much finer flour. The pilot plant was used:

Figure 23-1. The CLAYUCA modular pilot plant for producing refined flour from dried cassava chips, Palmira.

- To generate materials or raw materials for the research and development of new products
- For the technical training of functionaries
- To manage actual costs of operation and profitability
- To disseminate a new technology to cassava-processing companies interested in products of higher added value, and to companies wanting to enter new markets, using cassava flour in their processes.

Principal components

Figure 23-2 details the basic procedures for extracting refined cassava flour. It shows a screw conveyor for feeding raw material (dried cassava chips) to the mill sieves, three cylindrical mill-sieves with three shafts and three cylindrical sieves (screens), three fans, and five cyclones for pneumatic classification and flour collection.

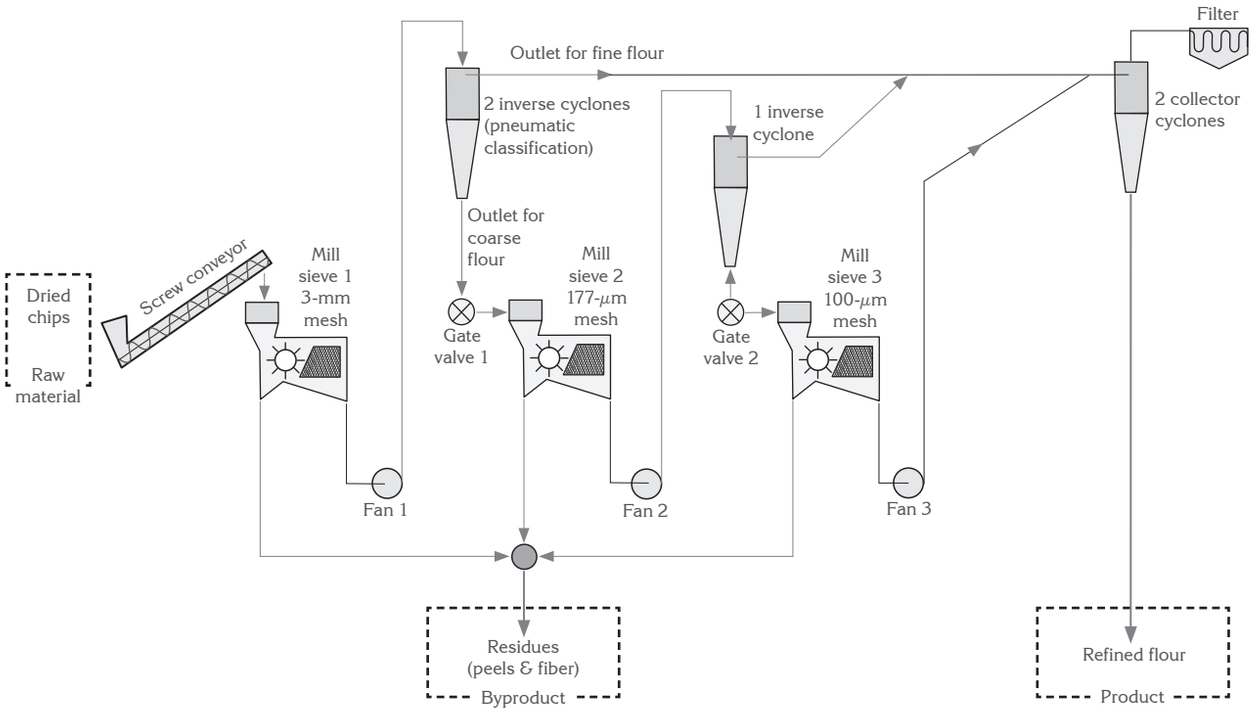


Figure 23-2. Diagram showing basic procedures for extracting refined cassava flour at the CLAYUCA pilot plant, Palmira.

Screw conveyor. The feeder or screw conveyor consists of a receiving hopper with a capacity of 300 kg/h of dried cassava chips (Figure 23-3). The chips are deposited into the hopper and conveyed by the screw to the first mill sieve for processing. At its largest, the screw's diameter is 6 inches. The shaft diameter is 2 inches, and the space between the blades is 4.5 inches.

Cylindrical mill-sieves. Each mill sieve—a fundamental part of the plant—consists of a feed hopper, a cylindrical estructure or body where the sieve and shaft are located, and a discharge hopper with a cylindrical outlet that couples to a fan (Figure 23-4).

Mill shafts. Each of the three shafts measures 1½ inches diameter, 170 cm length and possesses an endless screw at one end to feed dried cassava chips into the sieve. It also transmits energy for the blades striking the chips. The four stainless steel blades are joined to the shaft and are located at 90° to each other. They are designed to strike the chips over the mesh, exercising sufficient strength to mill them and separate the peels from the flour (Figure 23-5).

Figure 23-3. Screw conveyor-feeder.

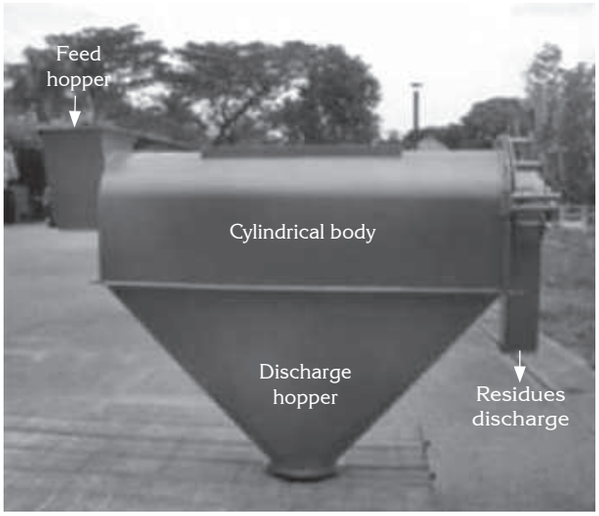


Figure 23-4. Mill-sieve.

Cylindrical sieves. The sieves are built with an expanded mesh of ⅛ inch to form the structure of the screen, with stainless steel rings coupled to its ends, comprising a cylinder of 29.5-cm diameter and 120.5-cm length. The screens are covered with mesh of 3 mm for grinding and 177- or 100-μm for classification of the particles (Figure 23-6).

Fans. The fans transport fine flour from the mill sieves' outlets to the collector cyclones. The pilot plant has three centrifugal fans with radial blades and a 12-inch-diameter rotor (Figure 23-7).

Collector cyclones. The pilot plant has five cyclones, two of which collect fine particles, in this case, of refined cassava flour. The other three classify the particles. The basic structure of a collector cyclone

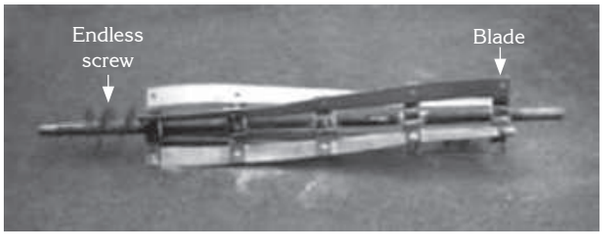


Figure 23-5. A mill shaft.

Figure 23-6. Sieves for milling and classification, with mesh openings of, from left to right, 3 mm, 177 μm, and 100 μm

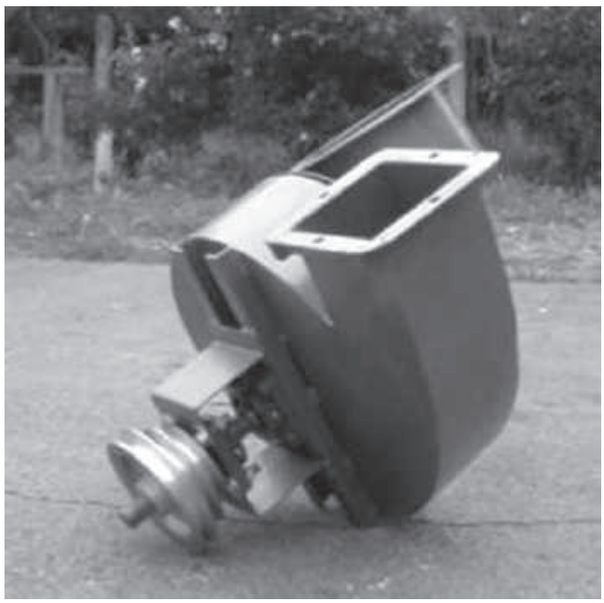


Figure 23-7. Centrifugal fan.

comprises a vertical cylinder with a conical base. It is provided with a tangential inlet, normally rectangular, and a circular discharge for clean air in its upper parts. This equipment is designed to separate particles from a fluid current, with high efficiencies for particles larger than 20 μm.

The cyclone's tangential inlet creates centrifugal forces that tend to push particles towards the equipment's periphery, away from the inlet of the air, thus increasing sedimentation and making collection more effective (Figure 23-8).

Classifier cyclones. These are used to separate fine from coarser particles. It is characterized by an inverse feed (central axial) that differs from that used in conventional cyclones. Studies by CLAYUCA (García 2006; Herrera et al. 2007) determined that, as air loaded with particles flowed into the equipment, in an axially central direction, it moved in different directions in three areas inside the cyclone (Figure 23-9).

- The first area, marked as A in Figure 23-9, constitutes the entire periphery of the cylinder's conical part. The larger particles decant parallel to the axial feed, losing speed and becoming deposited into the cyclone's bottom.

- In area B, a back pressure is formed, which helps disperse the particles entering the cylinder's upper part.

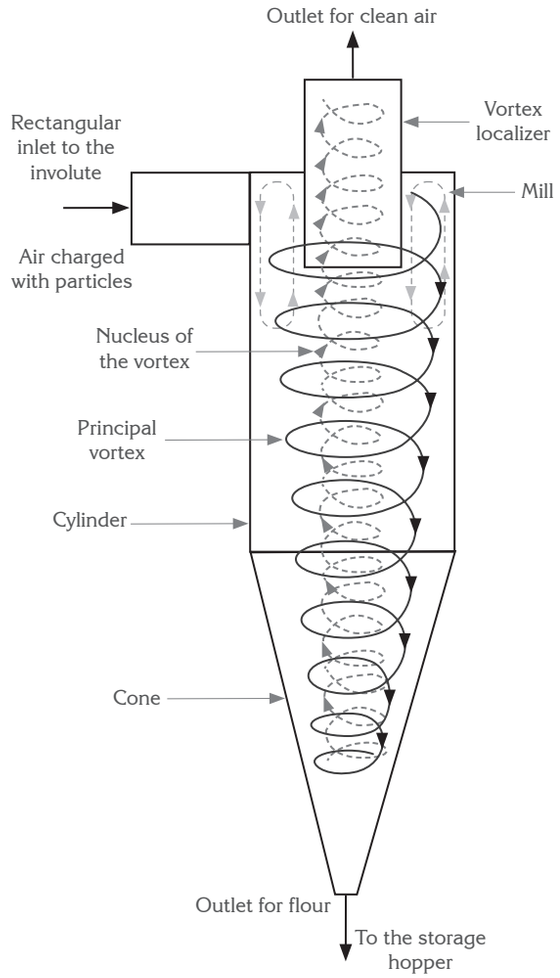


Figure 23-8. Collector cyclone.

- Area C lies in the cyclone's cylindrical part where the air, loaded with particles, flows inside, in an axially central direction. Meeting the back pressure from area B, this air forms considerable turbulence, which lifts the finest particles and forces them to leave the cyclone by a duct connected tangentially to the collector cyclone.

Refined cassava flour production

The stages of refined cassava flour production in the pilot plant are shown in Figure 23-10. The basic stages are feeding dried cassava chips for mill-sieving in mill 1. The resulting coarse flour is then mill-sieved in mill 2 to create an intermediate flour that is then mill-sieved in mill 3. The flour is classified in the three classifier cyclones and the final refined flour is then collected by the two collector cyclones.

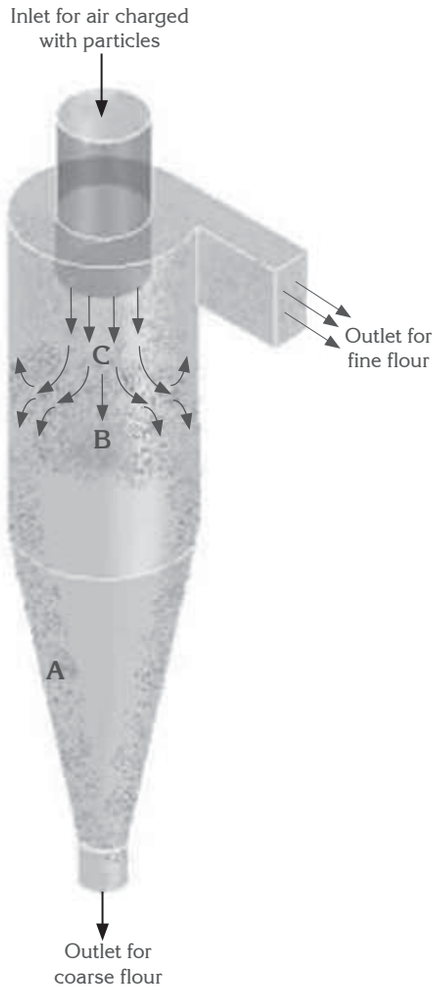


Figure 23-9. Classifier cyclone.

Feeding the dried cassava chips. Unpeeled dried cassava chips with a moisture content between 10% and 12% are deposited in the hopper by a screw conveyor to feed the first mill sieve. The feed capacity is 300 kg/h of dried chips, which are, ideally, free of peduncles.

First mill-sieving. Dried cassava chips are fed to the first mill sieve, which has an expanded mesh with 3-mm openings. The chips are reduced in size and, according to the mesh's openings, separated into small pieces of peel, thin outer peel, and fiber that comprise the residues. These are extracted as byproducts that are usually converted into animal feed. Material that succeeds in passing through the mesh is extracted by fan 1, which transports it to the classifier cyclones. After pneumatic separation, the flour produced by mill sieve 1 is divided into two types: fine flour that rises directly to the collector cyclones, and coarse flour that is decanted through a gate valve and automatically becomes the raw material for the next stage.

Second mill-sieving. In this stage, the coarse flour from the first mill sieve becomes the raw material for mill sieve 2, which has a mesh with 177-μm openings. In this mill, the flour is again reduced in size, and new residue is generated. Flour that passes through the mesh is extracted by fan 2 and separated into two new flours within the classifier cyclone, that is, intermediate flour that is decanted and becomes the raw material for the third mill sieve, and fine flour that is directly collected.

Third mill-sieving. As with the previous stages, intermediate flour from the second mill sieve enters the last stage of milling and refining in mill sieve 3. This mill has a mesh with 100-μm openings. The refined flour is extracted by fan 3 and transported to collection. Again, new residue is generated.

Pneumatically classifying the flour. Classification is carried out during the intermediate stages of mill-sieving. Conventional cyclones are used, that is, those that are normally used to collect processed products. As they already meet the requirements for classifying particles, the cyclones are being used as pneumatic classifiers.

An air current, loaded with flour, is fed inversely into the cyclone, making possible the decanting of coarse particles (>100 μm) towards the mill sieve for further milling. The fine particles, however, leave the cyclone by its tangential outlet to be later collected. They thus avoid being re-milled.

Collecting the refined flour. The refined flour is collected by two cyclones with tangential feed inlets that are connected in parallel for greater flour capture. The two cyclones are coupled to a cone that discharges the end product into packing bags.

Conversion factors

The CLAYUCA pilot plant obtained an average conversion factor of 1.3:1. That is, for every 1.3 kg of dried chips (12% moisture content) that entered the equipment, 1 kg of refined flour was extracted, and 0.3 kg was either byproduct or residues.

If refined-flour production from fresh roots is considered, the conversion factor would range between 3.6:1 and 4:1, depending on the cassava roots' dry matter content. That is, for every 3.6 or 4 kg of fresh cassava, 1 kg of refined flour is extracted.

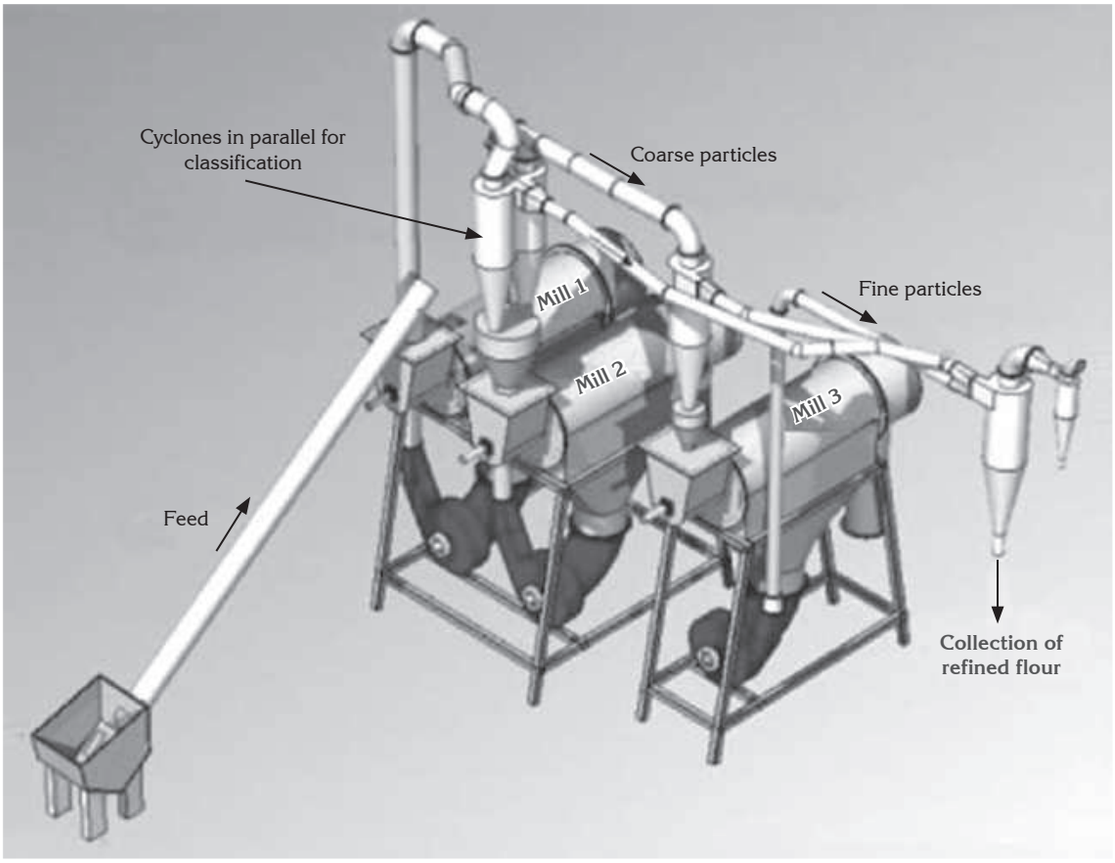


Figure 23-10. Production of refined cassava flour at the CLAYUCA pilot plant, Palmira, Colombia.

Physicochemical description of refined cassava flour

Granule analysis. As mentioned earlier, two types of products are extracted from each mill sieve in the pilot plant: refined flour as the principal product and three types of residues, which form the byproduct. These materials are separated out in the equipment, eliminating any peel that was left over from the manual peeling of cassava roots for dried chip production. This was one of the pilot plant's most valuable contributions to refining, because it eliminated the need for labor (and therefore costs) to peel roots destined for processing into flour for human consumption.

Table 23-1 lists the overall results of several granule analyses of the refined flour obtained at the CLAYUCA pilot plant. The refined flour had a high percentage of impalpable particles (90% at less than 50 μm). Even so, in this same equipment and using only the first two stages of mill-sieving, flour of bread-making quality could be obtained. This flour had the following characteristics: 70%–75% of particles at less than 50 μm and 20%–25% of particles at less than 177-μm. Although less refined, the flour has important applications in the baking, brewing, meat-processing, and ethanol-producing industries.

Table 23-1. Granulometric analysis of the refined cassava flour produced by the CLAYUCA pilot plant.

Mesh openings (μm)	Fraction retained (%)
150	2
106	3
50	5
<50	90

Chemical composition. Table 23-2 shows the average composition of materials present in the production of refined cassava flour from dried chips. The composition of native starch is provided for comparison. The table shows that processing dried cassava chips in the pilot plant leads to reductions by

Table 23-2. Typical composition of materials present in the production of refined cassava flour. The composition of native starch from the same cassava variety is also included.

Materials	Crude protein (%)	Ash (%)	Crude fiber (%)	Ether extract (%)	Starch (%)
Dried cassava chips	3.0	3.5	4.0	0.8	77.0
Refined cassava flour	1.4	1.3	1.9	0.6	85.0
Residues	5.5	6.5	52.0	1.0	24.0
Native starch	0.1	0.1	0.3	0.1	91.0

more than 50% in values for crude protein, ash, and crude fiber. The values for native starch (extracted from the same cassava variety) show significant differences with those of the refined flour, affecting various properties, as described below.

Rheological properties. The rheological characteristics of refined cassava flour were evaluated, using amylographs or profiles of flour slurries, in which changes in the viscosity of a suspension of flour and water are recorded during heating and cooling (Rodríguez et al. 2006). Figure 23-11 shows the viscosity curves, as generated by a viscograph, of refined flours from cassava varieties M Col 1505, M Per 183, and HMC-1, and a commercial cassava starch.

The viscosity curves show that, compared with the commercial starch, all the refined flours presented lower gelatinization temperatures and lower maximum viscosities. Moreover, the maximum viscosity peaks for the flours were not reached as rapidly. This indicates that the commercial starch is easier to cook and requires less energy for cooking. Table 23-3 also presents the results for the following parameters: ease

Table 23-3. Viscosity profiles of refined flour and native starch, both obtained from cassava variety HMC-1. Evaluations on were carried out with a viscoamylograph RVA series 4.

Parameter[a]	Refined flour	Native starch
Gelatinization temperature (°C)	63	65
Maximum viscosity (RVA units)	146	478
Ease of cooking (min)	4.4	1.6
Gel stability (RVA units)	72	332
Gelatinization index (RVA units)	14	54

a. RVA units measure viscosity according to the Rapid Visco Analyzer.

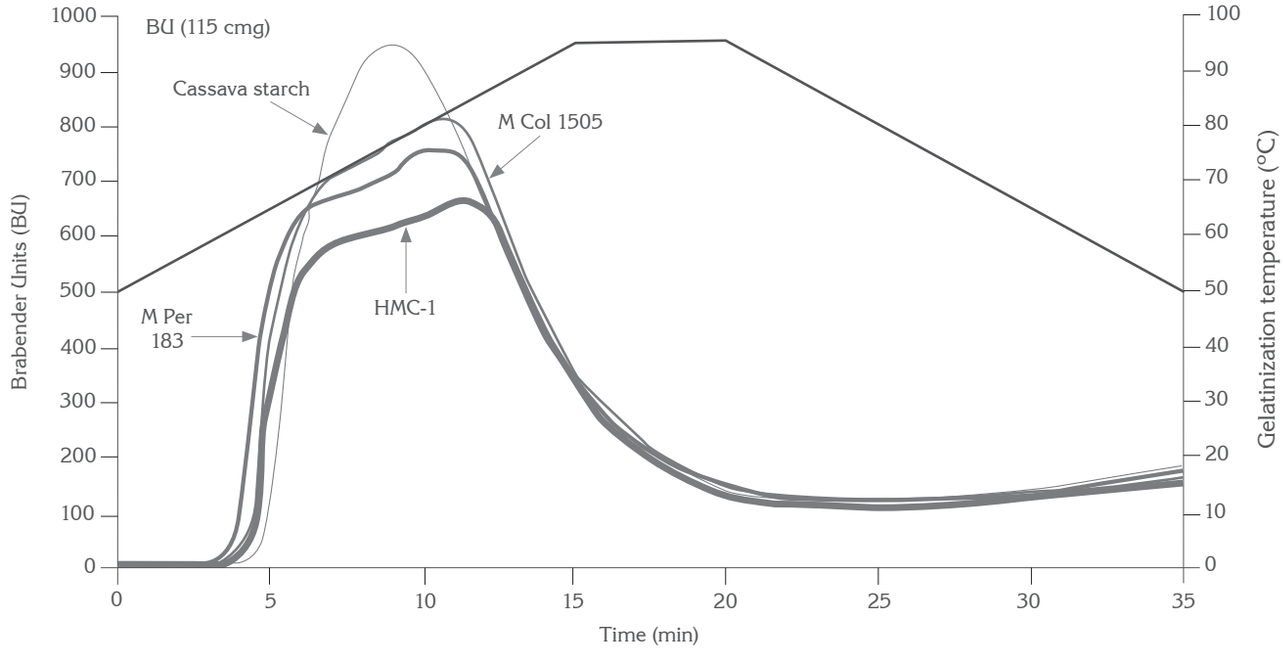


Figure 23-11. Micro-viscoamylograph (MVAG) profiles for flours from different cassava varieties, compared with commercial cassava starch.

of cooking, gel stability, and gelatinization index or gelling for both the refined flour and the native starch extracted from the same cassava variety (HMC-1).

Flour was easier to cook than starch, as confirmed by a slower swelling rate of granules for the refined flour. With regard to gel stability (which is related to the fragility and solubility of swollen starch granules), the native starch presented a value of 332 RVA units, suggesting that the refined flour tended to form more stable gels than did the native starch. Finally, during testing in the RVA viscoamylograph, the value for the gelatinization index of the refined flour indicated that pastes formed with cassava flour are stable, with little tendency towards retrogradation.

Uses of refined cassava flour

Table 23-4 presents possible applications of refined cassava flour in different food products and industrial use, as determined by recent research carried out by CLAYUCA. These studies showed that bread prepared with refined cassava flour, using 5% and 10% levels of substitution, performs well in tests for specific volume and presents high values of water absorption. No significant differences were found for acceptance by consumers, compared with pure wheat bread (Aristizábal and Henao 2004). Partial substitution of cassava flour also enabled bakers to save on production costs, as cassava flour can be obtained at lower prices than wheat flour.

Because of its starch's capacity to thicken during final preparation, refined cassava flour is an excellent raw material for beverage and soup preparation. This characteristic also allows cassava flour to be used as an ingredient in meat processing, as it improves water retention and bite characteristics. Refined flour can also be used in extrusion to produce dietary pastes, snacks, and breakfast cereals (flakes).

All types of composite flours can be used to prepare instantaneous beverages and infants' beverages (Ospina et al. 2009). Tests also confirmed that cassava flour can replace or complement the various raw materials used in extruded products, widely used in human food.

For industrial use, refined cassava flour is an appropriate raw material in the manufacture of glues for affixing corrugated cardboard boxes, even though levels of fiber, ash, and protein are not as low as those of native starch. Refined flour nevertheless also has potential because it has characteristics similar to those of pearl maize starch (Bonilla and Alonso 2002).

In 2006, CLAYUCA analyzed the technical viability of including refined cassava flour as a brewing additive. Results indicated that refined cassava flour is a technically viable alternative for maltose as a raw material in beer production (Ospina and Aristizábal 2006).

Finally, in collaboration with the Universities of Cauca and Valle, research has been carried out on the production of thermoplastic biopolymers from cassava flour. These polymers can be used as precursors in the manufacture of biodegradable plastics (e.g., bags, linings, and disposable utensils). The largest difference between the plastics currently produced (based on petroleum derivatives) and those based on cassava flour is that the latter is completely biodegradable. This means that its usability as packaging, from its production, is no more than 1 year (Villada and Acosta 2003).

Table 23-4. Applications of refined cassava flour.

Market	Product	The raw material replaced	Percentage of substitution	Advantages of cassava flour
Foodstuffs	Bread	Wheat flour	5–20	Lower cost
	Mixtures for beverages and soups	Flours from wheat, rice, maize, and plantain	10–40	Increased yield
	Processed meats	Wheat flour, starches	50	Better quality
	Snacks	Wheat, rice, and maize flours	100	Lower cost
	Beer	Maize starch, rice flour, maltose syrup	50–100	Lower cost
Industrial uses	Glues	Maize and potato starches	30–100	Lower cost
	Biodegradable plastics	Maize and potato starches	70	Better structural stability

References

Aristizábal J; Henao S. 2004. Adaptación y validación de tecnología para utilización de harina de yuca en panificación. In: Informe de proyecto. CLAYUCA, Palmira, Colombia.

Barona SM; Isaza LE. 2003. Estudios para el desarrollo de un proceso de extracción de almidón a partir de trozos secos de yuca (*Manihot esculenta* Crantz) con mínima utilización de agua. BSc thesis in Agricultural Engineering. Universidad del Valle, Cali, Colombia. (Also available in: CLAYUCA. Informe anual de actividades. Palmira, Colombia.)

Bonilla AM; Alonso L. 2002. Estudio de la viabilidad técnica, económica y comercial de la obtención de adhesivos para uso en la industria de cartón corrugado, a partir de almidón de yuca extraído por vía seca. In: CLAYUCA. Informe anual de actividades. Palmira, Colombia.

García JA. 2006. Evaluación de ciclones en la clasificación de partículas refinadas de yuca. BSc thesis in Mechanical Engineering. Universidad del Valle, Cali, Colombia.

García JA; Gallego S; Alonso L. 2006. Establecimiento de una planta piloto para la producción continúa de harina refinada de yuca. In: Informe de proyecto. CLAYUCA, Palmira, Colombia.

Herrera CA; Rosillo ME; García JA. 2007. Cassava flour separation using inverse cyclone. Rev Bras Eng Agríc Ambient 11(5):515–520.

Ospina B; Aristizábal J. 2006. Investigación para la evaluación técnica del uso de la harina de yuca como adjunto cervecero. In: Informe de proyecto. CLAYUCA, Palmira, Colombia.

Ospina B; Nutti M; Gallego S; Carvalho JL; Ascheri JL. 2009. Fichas técnicas: Productos alimenticios. In: Proc of an international course on "Tecnologías para la elaboración de productos alimenticios a partir de cultivos con alto contenido nutricional", held in Palmira, Colombia. CLAYUCA; Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Palmira, Colombia. 115 p.

Rodríguez E; Fernández A; Alonso L; Ospina B. 2006. Reología de suspensiones preparadas con harina precocida de yuca. Ingeniería y Desarrollo. 19:17–30.

Villada HS; Acosta H. 2003. Proyectos de desarrollo de materiales poliméricos biodegradables usando extrusión simple. In: CLAYUCA Informe anual de actividades. Palmira, Colombia. p 212–222.

Technological Study of Cassava Flour in Bread-Making

Johanna A. Aristizábal and Sergio Henao

Introduction

In Colombia, as in many South American countries, an acute imbalance is growing between the production and demand for wheat to supply domestic needs for bread flour. Among the factors causing this imbalance are lack of land suitable for growing the cereal, relatively low yields, population growth, and increasing per capita consumption of wheat and its derivatives. This imbalance has been compensated only through importing large quantities of the cereal at increasingly higher prices, thus generating an expensive outflow of foreign exchange from the country.

To help resolve this situation, much effort has been focused on the partial substitution of wheat flour with indigenous crop flours. Solutions towards incorporating raw materials of local origin (cassava, rice, maize, sorghum, and millet) into popular foods such as bread and pastas have been studied. Several studies examined the use of cassava flour as a wheat flour substitute in bread-making. In Colombia, such studies have shown promising results. From a technical viewpoint, breads comparable with those of traditional wheat breads and substituting as much as 15% with cassava flours can be produced (Aristizábal and Henao 2004; Henao and Aristizábal 2009).

The Government's strategy of promoting the cassava crop, complemented with efforts to link farmers to new markets for cassava, will help promote the sustainable cultivation of the crop. Thus, new employment opportunities in rural areas will be created, benefiting cassava flour producers, increasing the offer of this product, and reducing wheat flour imports. Furthermore, bread-makers will have a more economical substitute for the traditional raw material. About 60% of wheat flour is destined for bread-making. Hence, if 10% were replaced with cassava flour, imports would be reduced by about 75,000 t of wheat flour per year.

Although cassava flour contains a low percentage of protein (~2%), one of its important contributions is its higher fiber content (>3%), compared with wheat flour with less than 1%. Cassava flours, which can provide a bread with a high fiber content, are convenient for bread-making in a society concerned with good health and nutrition.

Bread-making tests

Three processing variables were defined: cassava variety, percentage of substitution, and bread type, with three levels for each. The cassava varieties—CMC-40, M Col 1505, and HMC-1—were selected for their availability, average yield of dry matter in roots, dry matter content, and HCN content. The percentages selected for substituting wheat flour with cassava flour were 5%, 10%, and 15% (w/w ratio, based on quantity of wheat flour). These values were chosen from the literature, which reported that values of more than 15% affected the bread's final quality. White bread types selected were *rolls, sandwich,* and *hamburger*, the selection being based on previous studies, which had selected the most used bread types—rolls and sandwich—for evaluation.

The bread-making trials were based on the typical formulas used for rolls, sandwich, and hamburger breads by the bakery "La Estrella" located in Palmira, Colombia. To avoid modifying the preparation protocols that its workers followed daily, only the percentages of substitution by cassava flour were included in the traditional mixture. For each trial, 1 kg of wheat flour was used with its respective percentage of substitution according to cassava variety and bread type, and always preparing a 100%-wheat bread as control. The stages of bread manufacture are illustrated in Figure 23-12.

The bread types were prepared according to the proportions of components in the formula, fermentation time, and baking temperature and time. Thus, bread rolls was divided mechanically for later shaping. This type of bread required a fermentation chamber with a constant feed of steam at 30 °C for 1.5 h. The bread was then baked at 200 °C for 25 min.

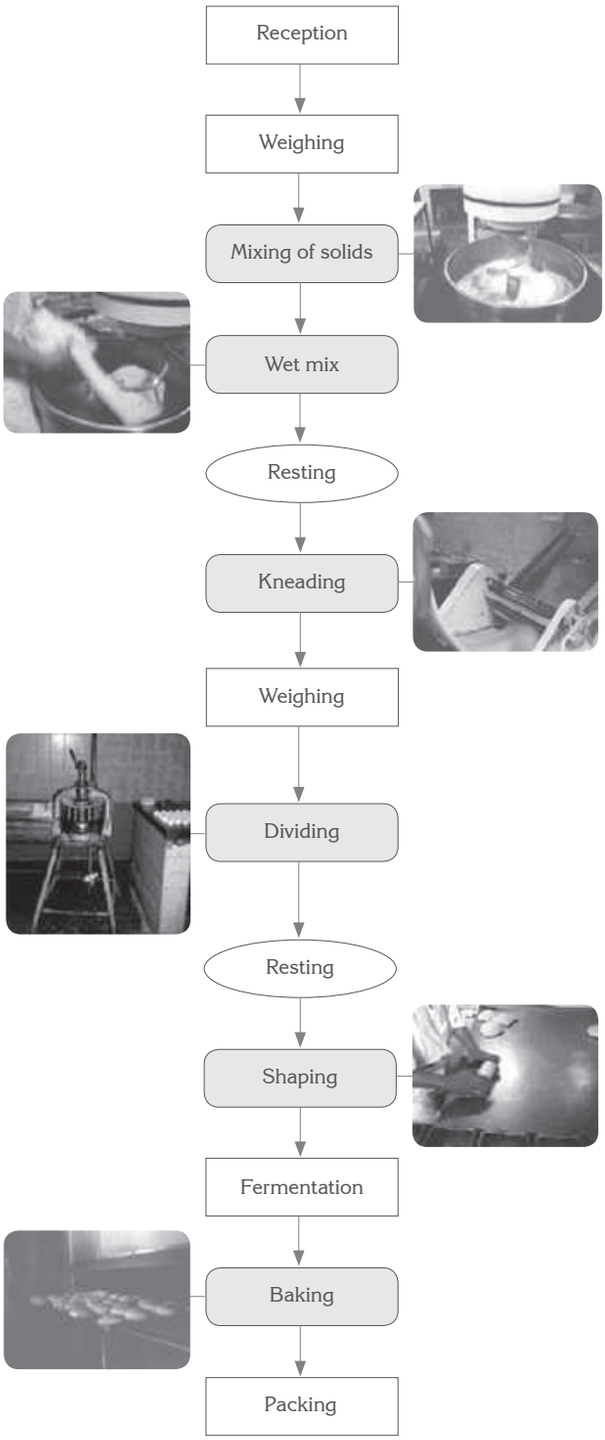


Figure 23-12. Flow chart for bread production at a large bakery in Palmira.

Sandwich bread was also divided, but manually, and the dough then shaped and introduced into rectangular molds that gave the breads their characteristic form. Fermentation was carried out in closed molds at room temperature, not in the fermentation chamber. The bread was then baked at 190 °C for 45 min.

Hamburger bread was divided mechanically before the dough was fermented in the chamber. The dough was then rested for about 20 min to soften before being kneaded to facilitate shaping. The hamburger breads were baked at 200 °C for 25 min.

The formulas used to prepare rolls, sandwich, and hamburger bread are listed in Table 23-5.

Analyzing cassava flour

Cassava flours obtained at the CLAYUCA pilot plant were evaluated, using microbiological, granulometric, and physicochemical analyses (Table 23-6). The cassava flours obtained met microbiological requirements and possessed the granule size required by the Colombian Technical Standard for wheat flour (NTC no. 267, as established by ICONTEC). More than 98% of particles passed through the mesh with 212-μm openings.

The water-absorption index for cassava flours was higher than for wheat flours. This factor favors the former's use in bread-making, as increased water absorption means that more bread will be obtained for the same quantity of flour. The water-solubility index was also higher for wheat flour, which was expected, as wheat flour presents a higher content of soluble proteins in water.

Table 23-5. Formulas for rolls, sandwich, and hamburger breads at a large bakery in Palmira.

Component	Percentage[a]		
	Bread rolls	Sandwich bread	Hamburger bread
Wheat flour	85–100	85–100	85–100
Cassava flour	5–15	5–15	5–15
Yeast	4	4	6
Sugar	12	8	12
Salt	2	2.5	2
Margarine	12	6	6
Water	50–60	50–60	50–60

a. Percentages given, assuming 100% as flour.

Table 23-6. Physicochemical characteristics of wheat and cassava flours.

Analysis[a]	Flours from cassava variety:			
	CMC-40	M Col 1505	HMC-1	Wheat
Dry matter (%, wb)	89.20	92.03	91.61	89.02
Moisture (%, wb)	10.80	7.97	8.39	10.98
Protein (%, db)	1.78	2.32	1.34	14.01
Crude fiber (%, db)	3.45	3.21	2.96	0.84
Starch content (%, db)	86.00	87.00	88.25	69.00
Ash (%, db)	2.06	1.26	2.25	0.72
Cyanide, total (ppm)	6.58	9.30	13.00	—
Cyanide, free (ppm)	0.58	1.15	0.58	—
Reducing sugars (%, db)	1.73	2.30	1.37	0.94
Amylose (%, db)	12.02	12.15	12.31	13.87
Amylopectin (%, db)	87.98	87.85	87.69	86.13
WAI (g of gel/g of flour)	4.35	4.73	4.15	3.11
WSI (%)	7.01	7.43	8.79	13.26

a. Abbreviations wb refers to wet basis; db, dry basis; WAI, water-absorption index; WSI, water-solubility index.

Rheological analyses of wheat-cassava composite flours

Doughs made from wheat-cassava composite flours, using three substitution percentages, were evaluated. Testing involved a farinograph (Table 23-7), alveograph, amylograph, falling number test (Table 23-8), mechanical work, and water absorption during the process.

Except for flours made from variety HMC-1, water absorption by all composite wheat-cassava flours was, on average, 1% more than water absorption by wheat flour. The growth period for wheat flour is almost double that of wheat-cassava composite flours. This factor indicates that dough prepared from wheat-cassava composite flours reaches consistency in less time.

Results for flour stability presented major differences between varieties, showing a ratio that is inversely proportional to the percentage of substitution. Composite flours with a 15% substitution showed less tolerance of kneading.

The degree of decay of composite flours is higher than that of wheat flour. In contrast, the time to breakage for all composite flours was shorter than for wheat flour. This was expected, as this period indicates the strength of gluten in bread flours. Wheat flour therefore presents the highest resistance to breakage.

Table 23-7. Characteristics of composite flours according to a farinograph.

Composite flour[a]	Water absorption[b]	Dough peak time (min)	Stability (min)	Degree of decay (FU)[c]	Break-down time (min)
Wheat only (control)	63.8	3.9	17.1	11.0	18.0
Wheat+CMC-40 (5%)	64.4	2.3	16.7	23.0	10.3
Wheat+CMC-40 (10%)	64.5	2.0	10.5	39.0	4.5
Wheat+CMC-40 (15%)	64.5	2.2	9.4	48.0	3.6
Wheat+M Col 1505 (5%)	64.3	2.7	9.3	37.0	6.0
Wheat+M Col 1505 (10%)	64.7	1.9	3.0	60.0	2.9
Wheat+M Col 1505 (15%)	64.6	1.9	3.3	47.0	2.8
Wheat+HMC-1 (5%)	63.1	2.9	17.4	25.0	12.1
Wheat+HMC-1 (10%)	63.4	2.0	14.0	37.0	4.8
Wheat+HMC-1 (15%)	62.9	1.7	3.7	53.0	2.8

a. Percentages indicate levels of substitution of wheat flour with cassava flour.
b. In mL/100 g of flour.
c. FU refers to farinograph units.

Table 23-8. Characteristics of composite flours in terms of an alveograph, falling number test, and amylograph.

Composite flour[a]	Strength (joules)	Tenacity[b]	Extensibility (mm)	Balance	Falling number (sec)	Tgel (°C)	Vmax (cP)
Wheat only (control)	381.87	147.40	60.80	2.42	353	59	77.40
Wheat+CMC-40 (5%)	400.96	152.90	56.00	2.73	360	66	77.45
Wheat+CMC-40 (10%)	280.30	152.90	41.49	3.69	354	68	76.90
Wheat+CMC-40 (15%)	339.55	152.90	48.20	3.17	354	68	77.90
Wheat+M Col 1505 (5%)	295.28	154.00	50.70	3.04	343	61	77.65
Wheat+M Col 1505 (10%)	335.63	151.47	45.05	3.36	349	63	77.35
Wheat+M Col 1505 (15%)	284.49	151.80	39.77	3.82	329	68	76.90
Wheat+HMC-1 (5%)	372.98	152.90	54.00	2.83	349	70	76.92
Wheat+HMC-1 (10%)	301.03	152.90	43.20	3.54	324	74	77.85
Wheat+HMC-1 (15%)	272.13	143.66	46.30	3.10	325	74	76.95

a. Percentages indicate levels of substitution of wheat flour with cassava flour.
b. In water (mm).

The values of strength in flours made from variety HMC-1 tended to be inversely proportional to the percentage of substitution. However, composite flour with 5% substitution of flour from variety CMC-40 had a higher strength value than wheat flour. The tenacity values for all composite flours were similar to each other and surpassed, by a low percentage, that for wheat flour. This datum reflects what was observed during the process, that the tenacity of doughs made with composite flours was greater. Extensibility of doughs made with composite flours were less than that of wheat flour.

The balance of doughs from wheat-cassava composite flours presented values that were higher than those of the control and showed differences between themselves. In the bread-making tests, problems occurred during kneading and in the bread's final appearance for flours from varieties HMC-1 (10%), M Col 1505 (15%), and CMC-40 (10%), when these were prepared as sandwich bread, as the composite flours presented the highest balance values.

The "falling number" values obtained for all composite flours presented acceptable values, falling into the requisite range of 250 to 400 seconds. Bread flours should not present values of more than 400 seconds, as they would require the addition of enzymes, thus inducing prolonged fermentation times and creating breads with pale crumbs.

Gelatinization temperatures (Tgel) of composite flours are higher than for wheat flour. Starch granule size affects Tgel. In wheat flour, this ranges between 2 and 38 μm, whereas, in cassava flour, it ranges between 5 and 35 μm. Hence, wheat flour presenting smaller granules may reach Tgel in less time.

Wheat flour presents constant viscosity over time once it reaches maximum viscosity. In contrast, cassava flours tend to continue increasing in viscosity over time after reaching maximum viscosity, thus demonstrating higher instability, compared with wheat flour. Composite flours tend to form more stable gels, whereas cassava flour of the same variety, after being gelatinized and reaching maximum viscosity, tends to continue increasing in viscosity over time.

Composite flours need to absorb more water during processing, the need increasing as the percentage of substitution increases. This fact is verified by the higher value of water absorption that composite flours presented during the farinograph test (Table 23-7). Composite flour made from variety M Col 1505 required the largest volume of water.

Analyzing prepared breads

Prepared breads (Figure 23-13) were evaluated for their specific volume, shelf life, and sensory tests of acceptance (aroma, crumb texture, flavor, and acceptability).

To evaluate the presence of mold, four samples of each treatment were stored in individual polyethylene bags, under the same conditions (away from direct light, moisture, and sources of contamination) and at room temperature. While the breads did not harden, most samples showed mold 7 to 9 days after preparation. These values were closely similar to those obtained for wheat bread, which showed mold after 9 days.

Results also indicated that an inverse ratio exists between the percentage of substitution of wheat flour and specific volume. The specific volumes of breads prepared from composite flours with substitutions of 5% and 10% were higher than that of wheat bread. All breads prepared with 15% of substitution presented lower specific volumes than wheat bread. Flour from variety M Col 1505 performed best in the specific volume tests.

The sensory tests included 50 surveys (hedonic test) to evaluate four samples (the three percentages of substitution and the control) from each variety. The surveys were directed at people who regularly consumed bread. They ranged in age from 14 to 70 and in social strata from 2 to 6. The people surveyed only made one evaluation, so that panelists were not repeated in the evaluation.

Results suggested that bread prepared from composite wheat-cassava flour from variety M Col 1505 did not present differences in acceptability to consumers, whether for aroma, flavor, crumb texture, and general acceptability. As a result, this variety produced flour with the best baking quality of the three varieties evaluated. The 5% substitution was the most acceptable overall, presenting an equal scoring or higher than the control. The 15% substitution presented the lowest values for most of the tests.

Bread rolls performed best in the acceptability tests as, according to the consumers, it presented minimal or no differences to wheat bread, probably because this type of bread had the highest amounts of fat and sugar in its formula. These factors helped mask the effects of including cassava flour. The lowest values were for the hamburger bread, where flours from most of the varieties did not please the respondents. This bread had the fewest ingredients in its formula, which meant that the effects of adding cassava flour were more noticeable.

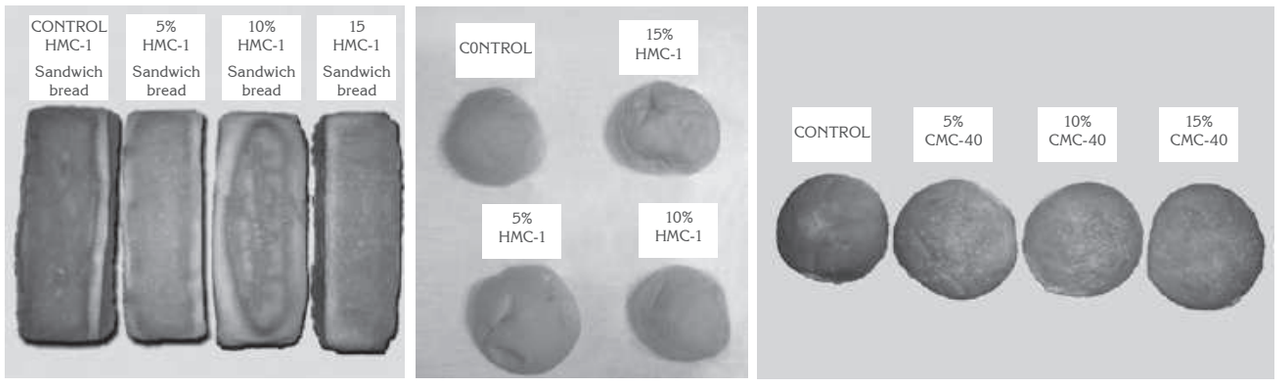


Figure 23-13. Samples of sandwich, rolls, and hamburger breads prepared with composite flours, substituting 5%, 10%, and 15% of wheat flour with cassava flour.

Conclusions

The microbiological quality of cassava flour can be improved by ensuring prior cleaning of the washing and chipping equipment and drying trays. This should be followed by efficiently washing cassava roots, immersing them for 20 min in tanks containing sodium hypochlorite at 20 ppm.

From a technical viewpoint, the use of wheat-cassava composite flours at 5% and 10% substitution is feasible and advantageous, as these present characteristics that are indistinguishable from those of wheat bread.

Of the cassava varieties used to manufacture bread from wheat-cassava composite flour, M Col 1505 performed best in the specific volume tests, had the highest water absorption values, and did not present differences of acceptability to consumers in terms of aroma, flavor, crumb texture, and overall acceptability. As a result, flour from this variety presents the best baking quality of the three varieties evaluated, particularly when a 5% substitution is used.

Economic indicators determined that, for the processing conditions of a large bakery such as the one in which the experiment was developed, savings obtained by using a 10% substitution were about US$8,055 per year (US$1.00 = Col$1800 in 2010).

References

Aristizábal J; Henao S. 2004. Adaptación y validación de tecnología para utilización de harina de yuca en panificación. In: Informe de proyecto. CLAYUCA, Palmira, Colombia.

Henao S; Aristizábal J. 2009. Influencia de la variedad de yuca y nivel de sustitución de harinas compuestas sobre el comportamiento reológico en panificación. Revista Ingeniería o Investigación 29(1):39–46.

Glues from Dry-Extracted Cassava Starch for Use with Corrugated Cardboard

Ana Milena Bonilla and Lisímaco Alonso

To identify new products and options for marketing cassava, and as part of CLAYUCA's research and development activities, research was developed to analyze the technical and economic viability of producing glues from refined cassava flour and thus replace certain starches used in the glue industry.

Cassava starch is traditionally extracted by means of a "wet" process (Chuzel 1991), where polluting effluents are generated that are mostly discharged into rivers and other sources of water for the rural areas where starch-extraction agribusinesses are located. Moreover, in most of these regions, water is limited and does not have the quality needed for preparing a quality product.

A "dry" process needs to be found for obtaining cassava starch without generating polluting effluents (Garcia 2006; Garcia et al. 2006; Herrera et al. 2007; Barona and Isaza 2003) while producing a quality product that is competitive in price for use in glue manufacture. Such a process would help reduce negative environmental effects; and give industries another source of raw material for their products, thus helping them to reduce costs of importing raw materials. In particular, the "dry" process would help strengthen the role of the cassava crop as a source of employment, foreign exchange, and income for the country's cassava-producing sector.

This feasibility study handled issues such as extraction of refined flour and production of ultra-refined flour, which is known as "dry" starch (testing five selected cassava varieties). Several formulas for making two types of glues were also evaluated and compared with commercial glues (Bonilla and Alonso 2002).

Preselecting cassava varieties

To produce ultra-refined flour (with <100-μm diameter particles), five cassava varieties were preselected from the elite clones group in the germplasm bank held at CIAT (Improved Cassava Project). Criteria were amylose content, viscosity, high field production, and high starch yield. The varieties were HMC-1 (ICA P-13),

CM 6740-7 (Reina), M Per 183 (Peruana), CM 523-7, and M Col 1522 (Venezolana). Table 23-9 provides the values of these varieties' principal characteristics.

High amylose content generates an effective glue as an end product. As the glue dries, the amylose aligns, forming a rigid layer. Furthermore, it permits rapid evaporation of water on union, thus producing faster drying, that is, the amylose molecules tend to reassociate. Fast drying is an important characteristic for glues used to seal cardboard boxes.

Amylose also fulfills a very important task in the glue's penetration into the paper or cardboard (Skeist 1977). Amylose is a polymer, able to recrystallize the starch after gelatinization, a process known as retrogradation. This is significant for the end product's stability and conservation.

Table 23-10 records data from amylographs of native or raw starches extracted from the previously selected varieties.

As this project began, Cartón de Colombia showed interest and offered a sample of maize pearl starch, a raw material used to make glues for different applications. This starch was characterized in terms of its proximal composition and was compared with different cassava flour samples. Table 23-11 lists the compositions of the different ultra-refined flours and maize pearl starch in terms of percentages of protein, crude fiber, fat, ash, moisture content, and starch.

Table 23-9. Characteristics of cassava varieties preselected for the production of "dry" cassava starch.

Variety	Yield (t/ha)	Dry matter (%)	Amylose (%)
HMC-1	20–22	34	24
CM 6740-7	20–28	36	15
M Per 183	25–40	32	22
CM 523-7	18–26	36	21
M Col 1522	10–25	29	23

Table 23-11. Proximal analyses of ultra-refined cassava flours, types 1 and 2, and maize pearl starch.

Identification	Protein (%)	Crude fiber (%)	Fat (%)	Ash (%)	Moisture (%)	Starch (%)
Flour type 1						
HMC-1	4.6	4.5	0.7	3.3	10	78
CM 6740-7	3.6	4.1	0.8	2.4	9	83
M Per 183	3.7	3.2	0.6	3.1	11	83
Flour type 2						
HMC-1	3.9	2.7	0.7	2.5	9	85
CM 6740-7	3.1	2.6	0.7	2.2	10	85
M Per 183	2.3	2.2	0.9	2.7	10	86
Maize pearl starch[a]	0.6	0.3	0.7	0.1	12	87

a. Sample provided by Cartón de Colombia.

The ultra-refined cassava flours were obtained by classifying wholemeal flour, using meshes with 100-μm openings. In this study, two types of ultra-refined flours were handled: type 1, which came from either the total disintegration or grating of roots before drying in a continuous artificial system; and type 2, which was obtained by milling chips that were dehydrated in a batch or fixed-bed dryer.

This study also compared the rheological patterns of maize pearl starch with those of the ultra-refined flours of the three cassava varieties that were finally selected. The patterns for refined cassava flours were significantly different to those of the native starches of these same three cassava varieties.

The refined flour samples, without taking into account variety, presented a slight increase in viscosity during cooling, in contrast to the native or pure cassava starches, thus showing higher product stability

Table 23-10. Characteristics ascertained by amylographsa of native starches extracted from previously selected cassava varieties.

Variety	Tgel (°C)	Vmax (BU)	V 90 (BU)	V 90/20 (BU)	V 50 (BU)	tcook (min)	Gel instability (BU)	Gel index (BU)
HMC-1	25	507	420	280	380	13	227	40
CM 6740-7	26	420	400	241	380	15	179	20
M Per 183	25	420	400	250	320	13	170	80
CM 523-7	23	410	340	218	350	11.5	192	20
M Col 1522	20	500	420	260	345	15	240	75

a. Abbreviations Tgel refers to gelatinization temperature; Vmax, maximum viscosity; V 90, viscosity at 90 °C; V 90/20, viscosity at 90 °C after 20 minutes; V 50, viscosity at 50 °C; tcook, cooking time; Gel index, gelation index.

over time. Stability is higher in maize pearl starch (possibly a modified starch but information not supplied by the company). When the varieties were compared for viscosity (Table 23-12), the performance found to most resemble that of pearl starch was that of variety HMC-1 for both types 1 and 2 of ultra-refined flour. Gelatinization temperatures were between 65 and 82 °C, and maximum peak viscosity was between 100 and 120 BU.

Gelatinization temperature is a very important factor in starch used as raw material for glues. It varies with different starches, and is indispensable for applying the enzyme, enabling it to act effectively in starch hydrolysis. Furthermore, the lower the gelatinization temperature, the less energy is consumed in manufacturing glues.

The viscosity curve of maize pearl starch showed great stability over time to temperature changes and also resistance to shearing stress over time. Similar characteristics also appeared in samples of ultra-refined flour (types 1 and 2) from variety HMC-1. Stability is important in most products containing starch, as it helps their conservation and good appearance.

Adjusting two selected formulas for glues

Initially, to select the glue formulas for this study, several adjustment tests were carried out, taking into account solid contents, additives in the formula, effects of different reagents used, temperature, and agitation times. The first formulation for glue, using enzymes, was as follows:

Refined cassava flour	25%
Water	75%
Calcium chloride	0.1%
alpha-amylose	0.027% (temperature between 70 and 80 °C)
Hydrochloric acid	0.47%
Anti-foam	0.47%
Sodium hydroxide	0.70%
Talcum	5.88%
Formol	4.7%

The second formula, using chemicals, involved the application of magnetic and manual agitation in the laboratory. This conditioned the cassava flour with 10% solids. Borax may be added to stop the sodium hydroxide reaction, and the anti-foam prevents froth from forming through agitation. The formula for this glue was as follows:

Refined cassava flour	10%
Water	90%
Anti-foam	1.5%
Sodium hydroxide	1.5%

A general conclusion of this part of the study was that the ultra-refined flours (with <100-μm-diameter particles) from the three cassava varieties selected were suitable as raw materials for glue manufacture, using either the chemical or enzymatic method. The glues obtained were suitable for sealing cardboard boxes and had characteristics that complied with the requirements set by the standard sample.

With the enzymatic formula, glues achieved short fixing times because of the high solid contents, which

Table 23-12. Data from amylographs[a] of ultra-refined flours from three selected cassava varieties and maize pearl starch.

Identification	Tgel (°C)	Vmax (BU)	V 90 (BU)	V 90/20 (BU)	V 50 (BU)	tcook (min)	Gel instability (BU)	Gel. index (BU)
Flour type 1								
HMC-1	82	100	90	95	100	9	5	5
CM 6740-7	80.5	95	60	90	100	11	5	10
M Per 183	67	140	140	110	140	15	30	30
Flour type 2								
HMC-1	65.5	120	120	100	120	27	20	20
CM 6740-7	58	160	160	160	180	15	0	20
M Per 183	70	200	175	145	210	16	55	65
Maize pearl starch[b]	79	120	110	125	120	11	5	-5

a. Abbreviations Tgel refers to gelatinization temperature; Vmax, maximum viscosity; V 90, viscosity at 90 °C; V 90/20, viscosity at 90 °C after 20 minutes; V 50, viscosity at 50 °C; tcook, cooking time; Gel index, gelation index.
b. Sample provided by Cartón de Colombia.

generated certain advantages. These glues could therefore be used for boxes with a heavy carrying capacity (10–20 kg). In contrast, the chemical formula, involving low solid contents, created a glue with longer fixing times (1 hour) and which was more suitable for boxes with a light carrying capacity (7 kg) and not requiring immediate shipping.

Table 23-13 summarizes the principal characteristics of the two formulas (enzymatic and chemical), and compares them with the standard glue, that is, glue 002 made by Almidones Nacionales. Table 23-14 records the relative sale prices of several glues found on the market and used in the industry to seal cardboard boxes, and compares them with the glues made from refined cassava flour. The value of the enzymatic glue was US$0.06 per kilogram. The estimated sale price of glues in this phase of the project showed that incorporating cassava flour in the formula was advantageous.

Additional activities were carried out informally to strengthen the potential of cassava flour for use in the glue industry, and consider related possible research topics. However, a glue manufacturer evaluated the glues and found that, overall, apparent stability was good and the glue was moderately dark in color. Fixing tests were carried out for paper on paper, kraft paper on kraft paper, and kraft paper on cardboard and on glass. Results showed excellent adhesion. A glue with such characteristics could be used to manufacture kraft paper bags and seal cardboard boxes.

In addition to manufacturing glues for sealing cardboard boxes, the possibility of entering the agglomerate wood market (plywoods), replacing wheat flour, was proposed. In this industrial application, glues must unite two faces of timber to form an agglomerate.

Table 23-14. Relative sale prices compared for different glues used to seal cardboard boxes, Colombia, May 2002.

Glue	Sale price (US$[a]/kg)
Enzymatic formula (CLAYUCA)	0.06
Chemical formula (CLAYUCA)	0.02
Polyvinyl acetate (PVA)	0.28
Hot-melt adhesive (HMA)	0.69
Pegol 015[b]	0.09

a. US$1.00 = Col$1800 in 2010.
b. Supplied by Industrias del Maíz S.A.

Traditionally, the glue was based on phenol formaldehyde, a formulation that involves a high percentage of wheat flour to help adhesion by increasing the quantity of solids in the formula.

Laboratory tests showed that 50% of wheat flour could be replaced by cassava flour. A 100% substitution was not possible as cassava flour reduces viscosity by 20%, compared with wheat flour. Nevertheless, cassava flour is a new alternative for reducing the costs of glue in the manufacture of plywoods. At the time of writing, cassava flour cost US$0.31 per kilogram, while wheat flour cost US$0.56 per kilogram.

References

Barona SM; Isaza LE. 2003. Estudios para el desarrollo de un proceso de extracción de almidón a partir de trozos secos de yuca (*Manihot esculenta* Crantz) con mínima utilización de agua. BSc thesis in Agricultural Engineering. Universidad del Valle, Cali, Colombia. (Also available in: CLAYUCA. Informe anual de actividades. Palmira, Colombia.)

Table 23-13. Characteristics of glues made from refined cassava flour compared with those of a standard glue (glue 002, Almidones Nacionales, Colombia).

Variable	Enzymatic glue	Chemical glue	Standard[a] glue
Solid contents (%)	25%	10%	23%
Viscosity (cP)	8000–12000	10000–18000	6000–12000
pH	7–9	10	8–9
Adhesion	Good	Good	Good
(% of scraped area)	(100 s)	(3600 s)	(100 s)
Adhesive tack	Excellent	Good	Excellent
Stability (days)	30 days	15 days	30 days

a. Glue 002, made by Almidones Nacionales S.A., Yumbo, Colombia.

Bonilla AM; Alonso L. 2002. Estudio de la viabilidad técnica, económica y comercial de la obtención de adhesivos para uso en la industria de cartón corrugado, a partir de almidón de yuca extraído por vía seca. In: CLAYUCA. Informe anual de actividades. Palmira, Colombia.

Chuzel G. 1991. Almidón de yuca, uso actual y potencial. In: Yuca: Boletín Informativo. CIAT, Palmira, Colombia. 15(1):9–11.

García JA. 2006. Evaluación de ciclones en la clasificación de partículas refinadas de yuca. BSc thesis in Mechanical Engineering. Universidad del Valle, Cali, Colombia.

García JA; Gallego S; Alonso L. 2006. Establecimiento de una planta piloto para la producción continúa de harina refinada de yuca. In: Informe de proyecto. CLAYUCA, Palmira, Colombia.

Herrera CA; Rosillo ME; García JA. 2007. Cassava flour separation using inverse cyclone. Rev Bras Eng Agríc Ambient 11(5):515–520.

Skeist I. 1977. Handbook of adhesives. 2ed. Van Nostrand Reinhold, New York. p 192–211.

Cassava Leaf Flour for Human Consumption

Johanna A. Aristizábal and Andrés Giraldo

Introduction

Leaves of cassava (*Manihot esculenta* Crantz) contain, on a wet basis, 77% water, 8.2% crude protein, 13.3% soluble carbohydrates, 1.2% fat, and 2.2% crude fiber. Cassava leaves are regarded as a green vegetable with a high protein concentration. They also contain minerals such as iron, calcium, potassium, phosphorus, magnesium, copper, and zinc, which are significant in human nutrition. Cassava leaves also have high contents of vitamins, particularly beta-carotenes and vitamins A, B1, B2, B6, B12, and C; and of other vitamins, including niacin, which is a depurative and powerful detoxicant; folic acid, which is a powerful anti-anemic vitamin; and pantothenic acid, which prevents deterioration in skin tissues (Guillén 2004).

Table 23-15 shows that beef surpasses cassava leaves for protein content. However, for many other nutrients such as calcium and certain vitamins, cassava leaves surpass both beef and cow's milk by large margins.

The nutritional composition of cassava foliage varies in quality and quantity, according to cultivar, time of cutting, planting density, and the proportion of leaves (leaf blades + petioles) and stems. The part of the plant used also determines nutritional composition, for example, if only leaf blades are used, protein content would be 23% to 28% (dry basis). But, if petioles and apical green branches are also included, protein content would be reduced to 18% to 21%. An inverse relationship occurs for fiber content, which tends to be about 9% for leaf blades, but increases to 20% to 25% when the entire upper part of the plant is incorporated (Domínguez [1983]). Some authors therefore consider that cassava leaves to have high potential as animal feed and human food. Petioles and, consequently, leaves, from the nutritional viewpoint, are valuable.

Table 23-15. Nutritional value of cassava leaves, beef, and cow's milk in accordance for a person's Daily Reference Values (DRV).

Nutrient	DRVs	Cassava leaves (100 g)	Beef (100 g)	Cow's milk (100 g)
Calories (%)	2000 cal	4.0	7.0	3.0
Protein (%)	50.0 g	13.0	41.0	6.0
Iron (mg)	18.0 mg	42.0	18.0	0.6
Calcium (mg)	1000.0 mg	67.0	3.0	25.0
Niacin (mg)	20.0 mg	17.0	36.0	1.0
Vitamin A (mg)	750.0 mg	261.0	0.5	5.0
Vitamin B (mg)	10.9 mg	28.0	10.0	4.0
Vitamin C (mg)	60.0 mg	1036.0	0.0	0.0

Most research on the use of cassava leaves for human consumption has been conducted in Brazil. Much of the research evaluated this product incorporated into dietary mixtures that were consumed by people with nutritional deficiencies or with health

problems because of low levels of vitamins and minerals (Brandão and Brandão 1991).

Although the principal disadvantage of cassava leaves is their HCN content, these levels can be reduced by efficient flour preparation. In countries such as Indonesia and Tanzania, cassava leaves are consumed fresh, like any other vegetable, after first cooking. In Peru, cassava leaves are consumed in capsules or tablets as nutritional supplements.

The use of cassava leaf flour for human consumption is not promoted or commercially supported in the way it should be. Not only could it be as a dietary alternative, providing nutritional benefits, but it could also, as a byproduct, be an option for adding aggregate value to the cassava crop. The inclusion of cassava leaf flour for human consumption is a food alternative. Hence, methods and processes for producing high-quality flour should be established for its use as a raw material in the preparation of foodstuffs such as soups, pies, and extruded products. Giraldo and Aristizábal (2006) therefore studied the process of obtaining cassava leaf flour for human consumption. They proposed alternative uses according to end-product quality and determined the technical and economic indicators for the flour's production.

Preparing flour from cassava leaves

In preparing cassava leaf flour, the various stages of operation were evaluated for the most suitable conditions for obtaining a quality product. Similarly, evaluations and analyses were conducted to calculate how to eliminate HCN during flour production.

Selecting varieties. Cassava varieties HMC-1 and M Col 1505 were selected on the following criteria:

- *Availability*, whereby typical cassava varieties planted near CIAT were chosen, and
- *Variety.* To guarantee low HCN contents in the end product, sweet varieties with HCN contents of about 180 ppm and planted in inter-Andean valleys were chosen.

Harvesting, selecting, and adapting the raw material. Two harvests of cassava leaves were carried out, one at 3 months and the other at 5 months, to compare the composition (e.g., protein, fiber, and HCN) of cassava leaves at harvest. Harvest was carried out by cutting the plant at a height of 30 to 40 cm above ground level to guarantee that the plant would re-sprout for a future harvest.

The harvested plants comprised leaves (i.e., leaf blades and petioles) and stems. However, only leaf blades were needed for the process. During selection, only those leaves that presented the characteristic green color of the cassava leaf were taken. Those leaves that had yellow or coffee-colored leaf blades, or showed spots were rejected. In preparing the raw material, both stems and petioles were removed manually, so to obtain only leaf blades.

Washing and disinfection. Cleaning ensured that the end product presented adequate microbiological and commercially acceptable characteristics according to Colombian Technical Standard NTC no. 267. This standard is used to obtain flour suitable for human consumption. Adequate washing reduced the microbial population present in the raw material, thus obtaining an aseptic product.

To wash, drinking water in a container was used. The leaves were submerged for 15 min, thus removing impurities such as earth, insects, and larvae, and residues of insecticides or pesticides. The leaves were then removed from the water and disinfected with an aqueous solution of sodium hypochlorite at a concentration of 20 ppm. The leaves remained in the solution for 10 min, the maximum time possible before leaf color was affected. The equipment had also been previously washed and disinfected with a hypochlorite solution at 50 ppm.

Reducing leaf size. Leaf blades were obtained in their entirety, which meant that they had to be treated to help eliminate HCN contents. Leaf blades were therefore chopped into smaller pieces, using an industrial mill that possessed appropriate cutting blades. The chopping broke up the leaf tissues, releasing HCN, and thus ensuring that HCN levels in the end product were lower than in the initial raw material. Different types of cuts were evaluated; the more finely the leaf blades were cut, the more efficient was the release of HCN.

Drying. Drying was carried out in two ways—solar and artificial drying (in a tray dryer)—to determine which was the better method. Solar drying was carried out on inclined trays, placing an average of 2 kg of leaf blades per tray. The blades remained exposed to the sun for 24 hours or more, depending on climatic conditions. Solar drying was considered to be inefficient and, microbiologically, the product could not be guaranteed to be aseptic. Artificial drying was

carried out in a tray dryer with air circulation, using temperatures of 40, 50, and 60 °C.

After leaf blades were dried by the two methods, samples were collected from each test for HCN analysis to determine the temperature at which the enzyme linamarase acted most efficiently on cyanogenic glucosides (linamarin and lotaustralin) to release HCN.

To determine HCN contents, a protocol was established that included NaCl and activated carbon during extraction to ensure that the spectrophotometer readings were clear, as leaf chlorophyll colors samples. Results indicated that artificial drying at 60 °C eliminates most of the HCN (Figure 23-14).

Milling. The dried leaf blades were milled into small pieces, comparing three types of mills: blade mill, hammer mill, and mill sieve. For each, efficiency was evaluated according to the amount of flour and granulometry obtained.

Granulometry of cassava leaf flour was determined, using sieves of different mesh numbers: 50 (300-μm openings), 70 (212 μm), 100 (150 μm), 140 (106 μm), 270 (53 μm), and bottom. The best granulometry was obtained with the mill sieve, for which almost 95% of flour passed through the no. 70 mesh (212 μm).

Analyzing cassava leaf flours

Once cassava leaf flour was obtained, tests were carried out to evaluate the digestibility of protein, dry matter, and fiber in diets. That is, for the tests, diets were prepared, based on cassava leaf flour. For comparative purposes, the control diet was based on casein, a protein that has an almost 89% absorption rate in the human organism.

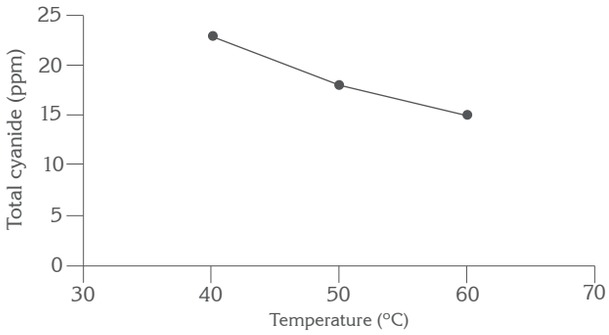


Figure 23-14. Final total cyanide of dried cassava leaves at three drying temperatures.

All the diets were formulated as isoproteic and isoenergetic. The control diet was prepared with 12% protein (casein), 10% sugar, 6% oil, 60% maize starch, 6% fibers, and 6% of a premixture of vitamins and minerals. For the diets with cassava leaves, the casein was replaced with cassava leaf flour at the established percentages of 10% and 20%.

Tests were carried out with laboratory mice that were distributed at random in metabolic cages that were designed especially to provide food to the animals and collect their excreta. The animals were fed the diets over an experimental period of 15 days. For the first 7 days, the mice were habituated to the diets. Over the next 8 days, samples were collected.

During the experiment, three treatments were evaluated: 10% cassava leaf flour, 20% cassava leaf flour, and the control, each having three replications. The three diets were analyzed for contents of dry matter, protein, neutral detergent fiber, and ash; and for energy. The excreta were tested for digestibility of dry matter, protein, and neutral detergent fiber; and for energy.

Habituation was necessary to ensure that the animals' digestive tracts were cleaned out and accustomed to the treatment or diet that would be fed to them. During habituation, the animals received the food but neither the residues nor the excreta were weighed. From the eighth day onwards, excreta from each mouse were taken, and the quantities of food provided and the amount left by each mouse were calculated.

The excreta, collected after habituation, were sampled and cleaned to remove hairs and food particles. They were then weighed and the data recorded. The excreta were kept in a freezer, in bottles that were duly marked with the corresponding mouse's number and diet. After the samples were collected, each bottle of excreta was lyophilized to obtain dry and solid samples for analyses on the digestibility of each diet supplied to the mice.

Data on the digestibility of dry matter and protein (Figure 23-15) suggested that the diet with 10% leaf flour is the most suitable for incorporation into a product for human consumption. The level of digestibility could be improved by mixing the leaves with food rich in methionine, which, in this case, is the limiting amino acid (Lancaster and Brooks 1983).

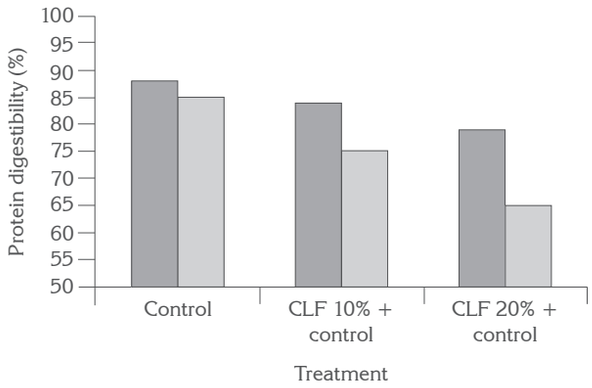


Figure 23-15. Dry matter (■) and protein (□) digestibility of diets evaluated in mice (CLF n% refers to cassava leaf flour at the percentage of substitution).

Conclusions

Any cassava variety, either sweet or bitter, can be used to obtain cassava leaf flour because the stages of chopping and drying guarantee an efficient elimination of HCN, the contents of which are low in the end product.

Efficient washing of leaves and their later immersion in sodium hypochlorite solution, together with a prior washing and disinfection of equipment used in the process, will ensure that the flour obtained from cassava leaves is of acceptable microbiological quality.

The release of HCN is favored by the leaves being finely chopped and exposed to long drying times at a temperature of 60 °C in a dryer with forced hot-air circulation.

From the nutritional viewpoint, the recommended rate of including cassava leaf flour is 10%, as being the most digestible.

To guarantee cassava leaf flour for human consumption that is competitive on the market, artificial drying systems must be used. Good manufacturing practices must also be implemented throughout production to minimize risks of contamination and ensure high levels of safety and quality for the end product.

References

Brandão CT; Brandão RF. 1991. Alimentação alternativa. Pastoral da Criança, CNBB (Conferência Nacional de Bispos do Brasil), Brasília, Brazil.

Domínguez CE, Ed. [1983]. Yuca: Investigación, producción y utilización. Centro Internacional de Agricultura Tropical (CIAT). United Development Programme (UNDP), Cali, Colombia. 656 p.

Giraldo A; Aristizábal JA. 2006. Estudio de la obtención de harina de hojas de yuca (*Manihot esculenta* Crantz) para consumo humano. BSc thesis in Agroindustrial Engineering. Universidad del Cauca, Popayán, Colombia.

Guillén V. 2004. Maravillas curativas de las hojas de yuca. Revista Interamericana Ambiente y Saneamiento A&S. Lima, Peru. p 32–36.

Lancaster PA; Brooks JE. 1983. Cassava leaves as human food. Econ Bot 37(3):341–348.

CHAPTER 24

Producing Hydrated Bioethanol from Cassava

Bernardo Ospina[1], Sonia Gallego[2], Harold Patiño[3], and Jorge Luis Gil[4]

Introduction

Bioenergy, and biofuels in particular, have become priority topics on the research and development agenda of world agriculture. Their significance lies in their enormous potential towards overcoming problems related to using the world's oil reserves such as shrinking volumes, growing use, price increases, and increasing emissions of greenhouse gases with resultant climate change. Bioenergy can also help answer the growing urgency to promote sustainable socioeconomic development. In particular, it can provide farmers with additional employment and incomes opportunities.

The world is demanding economic and social sustainability from the various biofuel production systems currently operating. Although the technology for producing bioethanol has partially met these expectations, the same cannot be said of other components of biofuel production systems. Most ethanol-producing systems are characteristically based on monocultures (e.g., sugarcane and maize), which create serious environmental problems in terms of biodiversity loss, excessive use of water, and generation of considerable quantities of effluents with high potential for contamination. Furthermore, to implement these systems, large investments are required, thus preventing rural communities of few resources from participating and benefiting from these technologies. Indeed, such communities, usually found in developing countries, suffer severe increases in food prices that put them at risk of reduced food security and increased poverty.

A major reason for giving priority to the generation of bioenergy and the use of biofuels on the global agricultural development agenda is the possibility that these technologies can become strategies for reducing poverty and overcoming the social inequalities that exist in many developing countries. More than 2000 million people around the world are estimated to lack access to any modern energy source (UNDP 2004). Hence, production technologies, and the use and marketing of biofuels, must be designed and implemented to help rural communities of few resources minimize their dependence on fossil energy, and permit a more equitable distribution of the benefits available along the entire agricultural production chain for biofuels.

Rural Social Biorefineries: An Approach to Small-Scale Biofuel Production

Since 2006, CLAYUCA has been implementing a research and development project to establish a technological platform for processing hydrated ethanol at the level of small rural communities. The raw materials used were cass ava (*Manihot esculenta* Crantz), sweet potato (*Ipomoea batatas* (L.) Lam.), and sweet sorghum (*Sorghum bicolor* (L.) Moench).

This initiative, called Rural Social Biorefineries (RUSBI)[5], seeks to promote the development of rural communities of few resources and located in the marginal regions of Latin America and the Caribbean (LAC). The idea is to produce and use a biofuel—

1. Executive Director, CLAYUCA, Cali, Colombia. E-mail: b.ospina@cgiar.org
2. Chemical Engineer and Specialist in Postharvest Management Systems, CLAYUCA. E-mail: s.gallego@cgiar.org
3. Zootechnologist, Lecturer in Postgraduate Program in Zootechnics, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil. E-mail: harold.patino@ufrgs.br
4. Zootechnologist and Specialist in the Use of Cassava in Animal Feed, CLAYUCA. E-mail: j.l.gil@cgiar.org

5. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

hydrated ethanol—as the starting point for establishing a level of agroindustrial development that will have a social impact on these regions. That is, it will help farmers stimulate the economies of their regions, create productive employment and opportunities for income, increase security of energy, food, agriculture, and improve their families' quality of life (CIAT 2011).

The local production and use of hydrated ethanol is the principal focus of the RUSBI approach. It involves five technological components (Figure 24-1), and integrates modern concepts of agronomic management, processing engineering, and effluent management. The strategy is to promote, in marginal regions, self-sufficiency in energy, agricultural development, and food security (Figure 24-1).

The CLAYUCA research on bioethanol production from cassava began in 2006 with a project financed by the Ministry of Agriculture and Rural Development (MADR, its Spanish acronym) of Colombia. The MADR's support enabled the construction and operation of a prototype processing plant for hydrated ethanol. In this project, evaluations were also carried out to assess the potential of different cassava varieties as raw materials for ethanol processing.

Several private- and public-sector groups showed interest in bioethanol production from cassava, including farmers, businesses, universities, and research centers, both national and international. They were given firsthand access to the technologies developed (Ospina et al. 2008).

Based on preliminary results, a small biorefinery was established in 2009 at CIAT's facilities in Palmira, Colombia. Technological support was received from Usinas Sociais Inteligentes (USI, a Brazilian private enterprise) and the Universidade Federal do Rio Grande do Sul (UFRGS, Brazil) (Patino et al. 2009). Figure 24-2 shows the equipment used in the rural social biorefinery, including (1) a plant to dry and refine the flours of cassava and sweet potato, and a plant to mill sweet sorghum; (2) a pilot plant to produce hydrated ethanol (96%) at a capacity of 10 to 20 L/h; and (3) a plant to treat effluents. Other equipment used in the biorefinery included a stationary plant to generate bioelectricity from hydrated ethanol and an ethanol-fueled stove for cooking (Figure 24-3).

The small-scale operational prototype for processing hydrated ethanol was inexpensive to construct, operate, and maintain. It is based on the use of saccharine (e.g., sweet sorghum) and/or amylaceous (e.g., cassava and

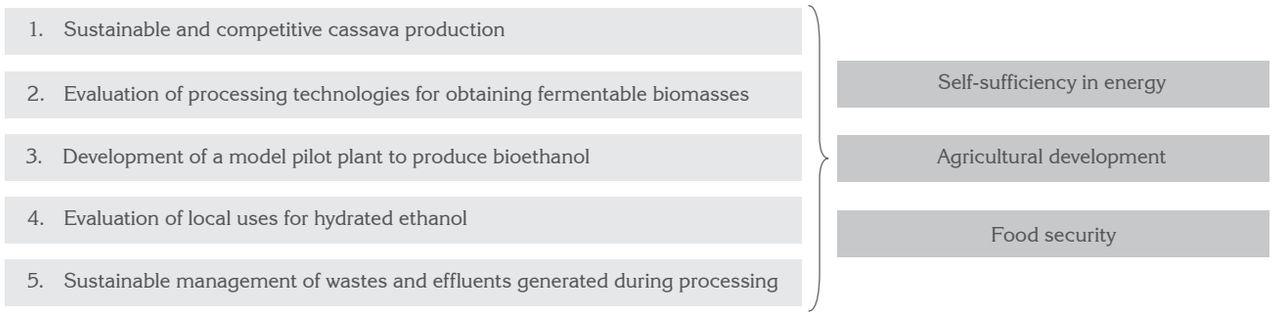


Figure 24-1. Technological components of the Rural Social Biorefinery (RUSBI) approach.

Figure 24-2. Equipment used in the Rural Social Biorefinery (RUSBI) established at CLAYUCA.

"Clean-cook" stove

Energy generator

Flex tek kit

Vehicle powered by ethanol from cassava

Figure 24-3. Validated uses of hydrated ethanol biofuel.

sweet potato) bioenergy crops as sources of substrata. During 2009–2011, the prototype was evaluated, its operation validated, and adjustments made to perfect the process.

CLAYUCA is now attempting to disseminate the model to rural communities that have limited access to electrical power, are highly dependent on fossil fuels, and, usually, depend entirely on agriculture for subsistence and income. The pilot plant's installations can be used for demonstrations and training activities for groups of farmers and technicians from Colombia and other countries in LAC, as well as other regions in the world facing similar problems.

The RUSBI approach (Figure 24-4) could have high impact on LAC's marginal regions. Biofuel production from energy crops would provide access to electrical power and thus open up opportunities for establishing value-added processing of crops such as flour and starch products for human and animal consumption or industrial use, and organo-mineral fertilizers for restoring soils and improving crop yields.

Producing Bioethanol

Figure 24-5 illustrates how hydrated ethanol is produced from cassava, using the RUSBI methodology. The cassava crop is among the richest sources of fermentable substrata for ethanol production, having high starch content (between 70% and 85%, dry basis).

To produce bioethanol, cassava roots are first converted into flour, after which, during biomass pretreatment, water is added. The resulting liquid biomass is known as starch milk. At this stage, incubation environmental conditions (pH and temperature) must be adjusted for the next stages: hydrolysis and fermentation. This stage can also be carried out with fresh cassava roots, which are very finely grated to facilitate the later stages of hydrolysis and fermentation. When fresh cassava roots are used, less water is needed, as root water content is used. However, the mash obtained after fermentation must be filtered, as it has high fiber content. Also, when cassava flour is used instead of fresh roots, drying leads to two byproducts that can be sold for use in animal feed, thus helping to reduce the additional costs for the energy needed to convert roots into flour.

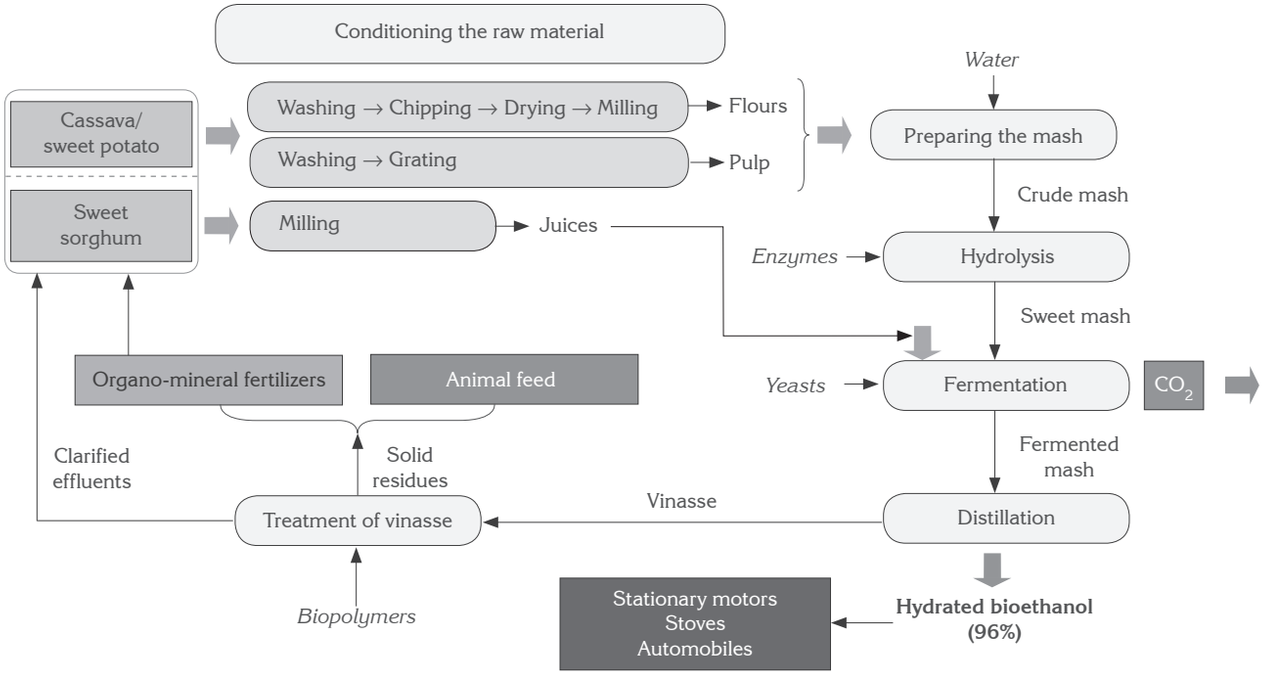


Figure 24-4. Schematic concept of the RUSBI approach, showing procedures, inputs, and products.

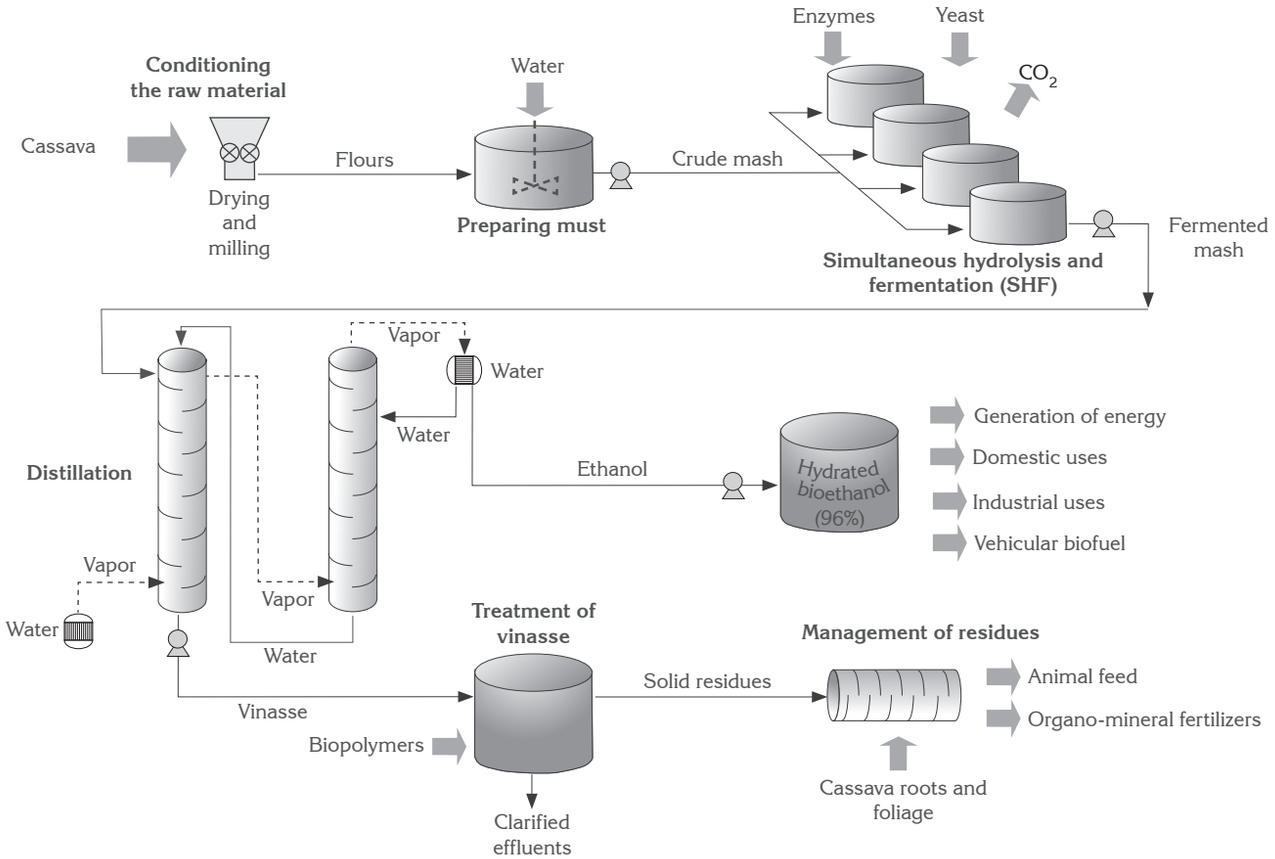


Figure 24-5. Flow chart for the production of hydrated ethanol from cassava.

Hydrolysis is a significant phase in the process. It transforms starches into fermentable sugars, which are then metabolized and assimilated by yeasts during fermentation, thus generating ethanol. Enzymatic hydrolysis, or saccharification, breaks up the large starch molecules to obtain units of glucose. Glucose syrups or sweet mash are obtained from starch through the liquefaction and later saccharification of starch. Two methods of hydrolyzing starch can be used:

1. *Liquefaction, saccharification, and conventional fermentation (LSF)*. The starch is first liquefied, then converted into glucose (i.e., saccharified), and, finally, fermented, using the yeast *Saccharomyces cerevisiae* (Figure 24-6).

   Heat-stable enzymes used for liquefaction and saccharification are, respectively, alpha-amylose and glucoamylase. Table 24-1 describes the

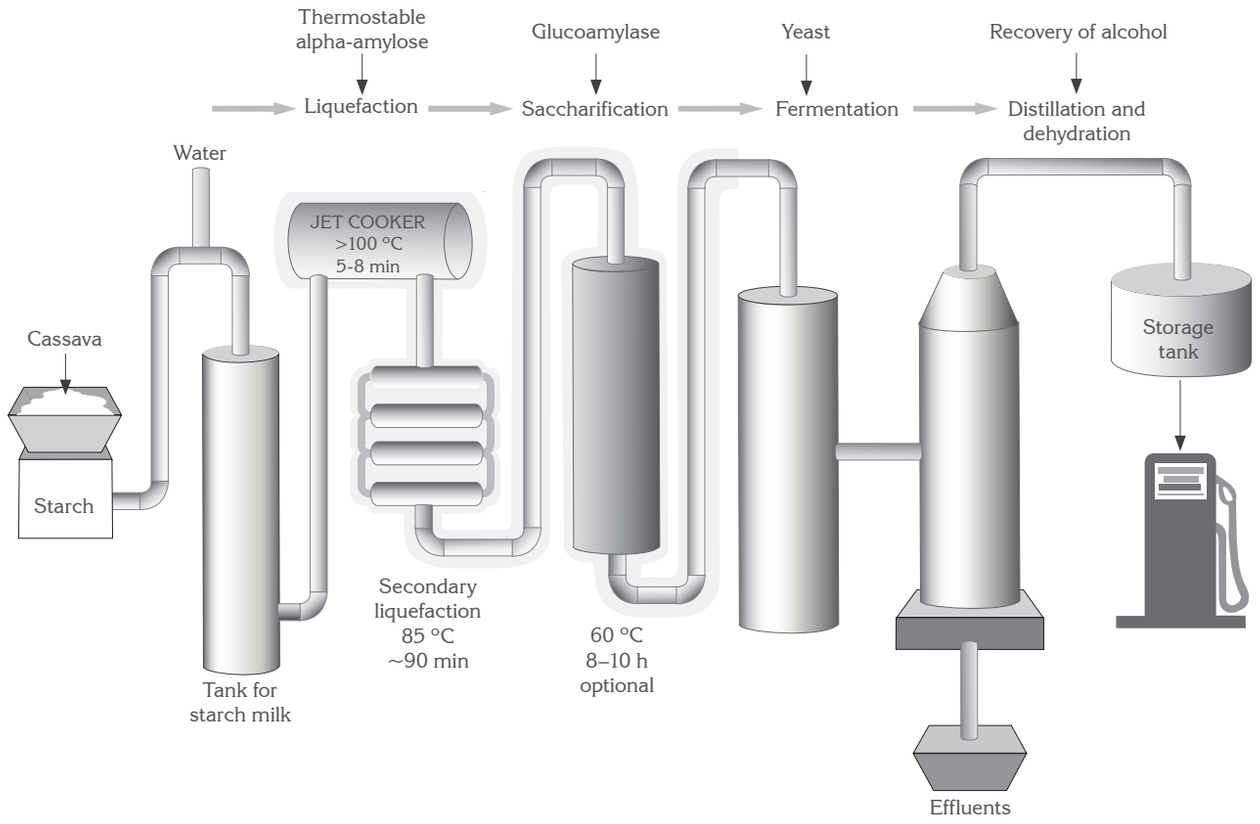


Figure 24-6. Conventional process for producing bioethanol from cassava (from Genencor International, a Danisco company; see www.genencor.com).

Table 24-1. Operating conditions for the hydrolysis and fermentation of organic biomass in conventional processing and simultaneous hydrolysis and fermentation (SHF) processing.

Conventional processing:			
Condition	Hydrolysis (liquefaction, followed by saccharification)		Fermentation
T (°C)	82–86	65–70	32
pH	5.7–6.0	4.3	4.5
SHF processing:			
Condition	Hydrolysis (liquefaction + saccharification)		Fermentation
T (°C)	30–33		30–33
pH	4.0–4.5		4.5

operating conditions conventionally used with this method.

2. *Simultaneous hydrolysis and fermentation (SHF)*. A mixture of enzymes allows the saccharification and liquefaction processes to occur simultaneously (Figure 24-7).

   This method uses STARGEN™ enzymes (which enable hydrolysis at low temperatures) and combines saccharification and fermentation within a single stage, because the enzymes function under the same conditions of temperature and pH as does the yeast (i.e., *S. cerevisiae*). Table 24-1 indicates the operating conditions used with this method.

In the RUSBI methodology to produce bioethanol, CLAYUCA used the SHF method to reduce processing time, energy consumption, and installation costs (i.e., no need to install a heating system for the mash). The end product of the SHF process—fermented mash—was distilled at 78 °C, and its steam—ethanol—captured and condensed. The distillation products were therefore ethanol at 96% purity and an organic liquid byproduct known as vinasse. Finally, the hydrated ethanol was evaluated as a biofuel in suitably adapted equipment, selected for being commonly used by rural communities such as kitchen stoves, electrical power generators, and other motors (Figure 24-3).

The validated uses of hydrated ethanol as a biofuel produced from the cassava crop will help rural communities have access to electrical power, enabling them to establish processing enterprises to add value to their crops, and thus link with markets that will afford them higher incomes and improved food security and quality of life.

Bioethanol Production Trials

The preliminary results obtained by CLAYUCA for cassava variety evaluation in ethanol production showed that enormous potential exists to exploit the crop's genetic diversity and improve the processing of cassava biomass into ethanol. Considering the average value of starch found in the varieties analyzed, we could estimate a theoretical value of 220 L/t and determine an experimental value of 118 L/t to convert biomass into ethanol. This means that real processing efficiency represented only 54% of the theoretical potential (Table 24-2; Arriaga 2008).

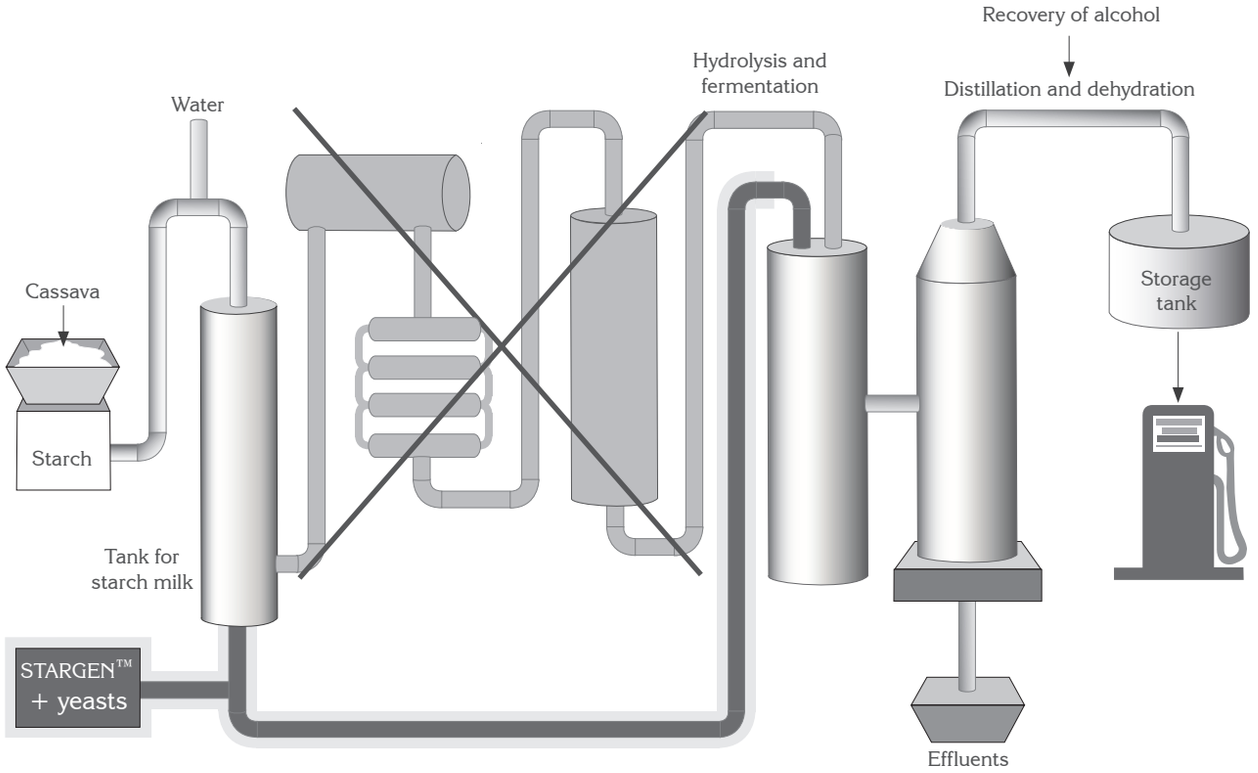


Figure 24-7. Simultaneous hydrolysis and fermentation (SHF) (from Genencor International, a Danisco company; see www.genencor.com).

Table 24-2. Comparing cassava varieties for ethanol production.

Variety	Production (t/ha)	Starch (%)	Theoretical conversion (L/t)	Real conversion (L/t)	Efficiency (%)	Ethanol production (L/ha)
CM 4574-7	25	32.3	230.6	118 .0	51	2950
CM 6438-14	26	33.3	237.8	129.8	55	3374
M TAI 8	29	31.6	225.6	129.1	57	3743
Verónica	29	29. 0	207.1	99.9	48	2897
Ginés	27	27.9	199.2	114. 7	58	3096
Average	27 ± 1. 8	31 ± 2. 3	220 ± 16. 3	118 ± 12.2	54 ± 4.2	3212 ± 350

More recent work carried out on the CLAYUCA biorefinery model aimed to optimize the enzymatic hydrolysis of the starch present in cassava (Cajamarca 2009). The efficiency of bioethanol production from cassava flour was also estimated at a pilot scale by calculating the balances of materials and energy in the process (Martínez 2009). Table 24-3 presents trials carried out with cassava flour in the pilot plant, using the SHF method at room temperature.

According to the results shown Table 24-3, the best results were for Trial 3. Yields were 372.5 L of ethanol per ton of flour, and 106.4 L per ton of fresh roots. These values are slightly lower than those reported in the literature (Vinh 2003; Atthasampunna et al. 1990). A relatively low value (61%) was also obtained for the efficiency of the process in terms of real ethanol production versus the theoretical conversion. This implies the presence of polluting agents, especially during fermentation, which either reduced or limited the fermentative glycolysis of ethanol.

Table 24-4 shows the results of two trials with fresh cassava roots, using the same conditions of simultaneous hydrolysis and fermentation at room temperature.

Initially, in the real results of hydrated ethanol production from fresh cassava roots, no notable

Table 24-3. Results of three trials for producing hydrated bioethanol from cassava flour at the CLAYUCA pilot plan.

	Trial		
	1	2	3
Raw materials			
Refined flour (kg)	75	86	120
Enzymes (STARGEN™) (kg)	0.375	0.428	0.600
Yeast (Ethanol Red®) (kg)	0.250	0.286	0.400
Urea (kg)	0.175	0.200	0.300
Water (kg)	400	400	400
Generated product			
Hydrated ethanol at 96%, v/v (L)	21.8	27.3	44.7
Quantitative analyses[a]			
Total production (liters of ETOH)	21.8	27.3	44.7
Yield (L ETOH per ton of flour)	290.7	317.4	372.5
Yield (L ETOH per ton of roots)[b]	83.1	90.7	106.4
Yield (L ETOH per hectare)[c]	2076.4	2267.4	2660.0
Efficiency in production of ETOH[d]	48%	52%	61%
Ratio of vinasse to ethanol (v/v)	25.3	19.81	14.1

a. ETOH refers to hydrated ethanol at 96% (v/v).
b. Conversion factor for fresh cassava roots to refined flour is 3.5:1.
c. Average yield of cassava roots is 25 t/ha.
d. Calculated as the ratio of real production to theoretical conversion.

Table 24-4. Results of two trials on hydrated bioethanol production from fresh cassava roots at the CLAYUCA pilot plant.

	Trial 1	Trial 2
Raw materials		
Fresh cassava roots (kg)	300	300
Enzymes (STARGEN™) (kg)	0.380	0.380
Yeast (Ethanol Red®) (kg)	0.500	0.500
Urea (kg)	0.300	0.300
Water (kg)	300	450
Generated product		
Hydrated ethanol at 96%, v/v (L)	48	48
Quantitative analyses[a]		
Total production (liters of ETOH)	48	48
Yield (L ETOH per ton of roots)	160	160
Yield (L ETOH per hectare)[b]	4000	4000
Efficiency in production of ETOH[c]	89%	89%
Ratio of vinasse to ethanol (v/v)	13.6	16.7

a. ETOH refers to hydrated ethanol at 96% (v/v).
b. Average yield of cassava roots is 25 t/ha.
c. Calculated as the ratio of real production to theoretical conversion.

variation is observed for the treatments tested, resulting in a production of 160 L for 1 t of fresh roots. For Trial 1, 13.6 L of vinasse were obtained per liter of ethanol, indicating that the quantity of effluents produced per liter of ethanol was reduced. This aspect is of utmost importance, as the disposal or management of these effluents is critical in ethanol production.

Furthermore, Del Ré et al. (2010) conducted an experiment at CLAYUCA/CIAT to evaluate the effect of the amount of water used to produce ethanol and effluents. Six fermentation tanks, each having a capacity of 1000 L, were used in a randomized complete block experiment design replicated over time, with four replications per treatment. Results showed a 37.5% reduction in the amount of water used (i.e., from 800 to 500 L), a 107% increase of ethanol production (i.e., from 21.75 to 44.94 L), and a 33% increase in processing yield (i.e., from 268.8 to 357.5 L/t) (Table 24-5).

Results for processing yield, using less water in the fermentation tanks, were 62% higher than the theoretical value estimated for the evaluation of cassava varieties (357 versus 220 L/t). They were very close to the values used internationally to evaluate ethanol production from cereal grains (400 L/t) (Jansson et al. 2009).

The 37.5% drop in the amount of water used reduced the ratio of vinasse to ethanol by 44% (25.34 versus 14.09 L/L) ($P < 0.05$) (Table 24-5). These results are highly significant as the competitiveness of the biofuel chain in small agribusinesses is highly sensitive to the management of generated effluents, as additional resources must be used to manage them according to the environmental standards in force.

Analyses of the hydrated bioethanol produced (Table 24-6) demonstrated that this is a crude redistilled alcohol of industrial use. It can be easily converted into a neutral rectified alcohol that meets technical standards for pharmaceutical and potable use.

Table 24-5. Production of ethanol (L), yield of ethanol (L/t of dry matter), and quantity of vinasse generated per liter of produced bioethanol.

	Treatment[a]		
	1	2	3
Raw materials			
Refined flour (kg)	150	150	150
Enzymes (STARGEN™) (kg)	0.714	0.714	0.714
Yeast (Ethanol Red®) (kg)	0.500	0.500	0.500
Urea (kg)	0.350	0.350	0.350
Water (kg)	800	700	500
Generated product			
Hydrated ethanol at 96%, v/v (L)	21.75 b	27. 28 b	44.94 a
Quantitative analyses[b]			
Total production (liters of ETOH)	21.75 b	27.28 b	44.94 a
Yield (L ETOH per ton of flour)	268.80 b	306.60 ab	357.50 a
Ratio of vinasse to ethanol (v/v)	25.34 b	19.81 ab	14.09 a

a. Values in the same row with different letters are significantly different, Tukey's at 5%.
b. ETOH refers to hydrated ethanol at 96% (v/v).

Table 24-6. Characteristics of hydrated bioethanol produced in the CLAYUCA pilot plant.

Characteristic	Unit	Specification ANP[a]	Result
Aspect	—	Clear[b]	Clear
Color	—	Colorless to yellow	Colorless
Total acidity (e.g., acetic acid), max.	mg/L	30.0	17.0
Alcoholic percentage	% (v/v)	93.2 ± 0.4	91.3
pH	—	6.0 to 8.0	
Aldehydes (e.g., acetaldehyde), max.	mg/L	60	29
Esters (e.g., ethyl acetate), max.	mg/L	100	47.3
Methanol, max.	mg/L	500	No data
Higher alcohols, max.	mg/L	500	163.8

a. National Petroleum Agency (ANP, its Portuguese acronym).
b. Clear in color and free of water or materials in suspension.

Energy Balance

Figure 24-8 shows the energy balance for producing 250 L of hydrated ethanol. The electrical power consumed by equipment is recorded according to operating time for producing cassava flour and ethanol, and the thermal energy required for the boiler to generate steam.

Total energy consumption indicates that the consumption of electrical power was 95.3 kWh or 342.9 MJ (1 kWh = 3,600,000 joules = 3.6 MJ), while thermal energy consumption, as according to the wood consumed, was 3932.5 MJ. In short, total energy consumption (electrical + thermal) to produce 250 L of hydrated ethanol was 4275.4 MJ. Consequently, energy consumption for processing 1 L of ethanol at the biorefinery is 17.1 MJ/L.

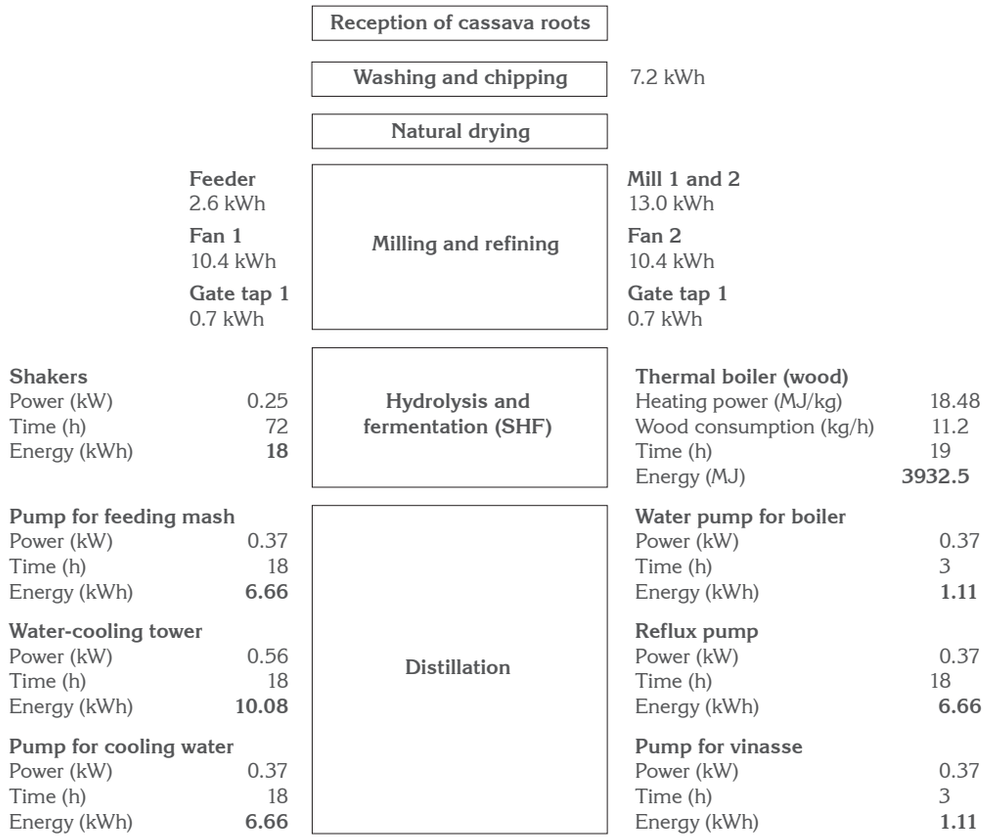


Figure 24-8. Energy balance for producing 250 liters of hydrated bioethanol at the CLAYUCA biorefinery.

If we assume a value of 1.54 MJ/L for the principal agronomic operations to produce 1 L of ethanol from cassava (Assis 2008), a total value (i.e., agronomic + industrial consumption) of 18.64 MJ/L is reached. This indicates that if we obtain 23.375 MJ from 1 L of ethanol, then the rate of return for energy is positive at 1.25.

Costs of Producing Hydrated Bioethanol

Based on the data obtained for the CLAYUCA biorefinery model (500 L/day), total production costs for hydrated ethanol (96%, v/v) was US$1.34/L. This includes the costs of raw materials, processing, depreciation, and maintenance, as well as the possible profits derived from the sale of byproducts (Table 24-7).

Finally, Gomes (2010) evaluated the technical and economic viability of implementing a biorefinery (500 L/day) in three rural areas of Colombia with problems of self-sufficiency and/or high energy costs: Puerto Carreño, La Macarena, and Leticia. The study concluded that the project was not viable in Puerto Carreño and Leticia, as production costs of ethanol were not competitive with the prices of local fuels brought in at low cost from Venezuela and Brazil, respectively. In contrast, in La Macarena, the project could indeed be viable, depending on the cost of gasoline and the possibility of tax exemption (Table 24-8). Moreover, the study concluded that if a biorefinery were implemented in La Macarena, it would provide 0.5% of the rural population with access to electrical power and that 7.3% of the volume of gasoline currently sold in the rural area could be mixed at 30% with ethanol.

The study also recommended that, to improve the project's efficiency, improved cassava varieties must be introduced and technological improvements in converting cassava into ethanol must be identified. Also, farmers should receive training and support, and their associations or small groups should be promoted.

Table 24-7. Estimate of the costs of producing hydrated bioethanol from cassava at the CLAYUCA pilot plant.

Item	Cost (US$)[a]	
	(per liter)	(%)
Raw materials		
Cassava roots (US$0.055/g)	0.51	38.0
Flour production		
Electricity	0.02	1.5
Labor	0.06	4.5
Ethanol production		
Water	0.01	0.7
Electricity	0.02	1.5
Wood	0.04	3.0
Reagents	0.41	30.6
Labor	0.06	4.5
Subtotal for process	**1.13**	
Sale of byproducts[b]	-0.08	
Depreciation, maintenance[c]	0.29	15.7
Total production costs	**1.34**	100.0

a. US$1.00 = Col$ 1800 in 2010.
b. Cost recovery through sale of byproducts (375 kg at US$0.11/kg).
c. Depreciation: 5 years at 250 days/year; maintenance: annual at 4.

Managing Effluents

When hydrated ethanol is being produced as a biofuel from cassava, one aspect of considerable environmental and energy sensitivity is the huge quantity of effluents resulting from the process. On average, for every liter of ethanol obtained, 10 to 15 L are generated of an effluent, known as vinasse. As described previously, vinasse is the organic liquid byproducts resulting from the fermentation of carbohydrates (e.g., sugarcane juice and molasses or cassava starch milk) and later distillation of the fermented mash. The composition of vinasse is variable and depends on the characteristics of the raw materials (e.g., cassava flour or fresh cassava roots) used to produce the alcohol, and on the type and efficiency of fermentation and distillation (CIAT 2011).

Vinasse is usually made up of water, mineral salts, organic matter, residual yeast, and non-fermentable constituents. Table 24-9 presents the bromatological composition, *in vitro* dry matter digestibility, organic matter content, and starch content of vinasse obtained from fermenting fresh cassava roots. Table 24-10 indicates the mineral concentration (dry basis).

Table 24-8. Data for current gasoline prices, potential market, and costs of biofuel for each of three regions in Colombia.

Site	Potential market (L/year)	Current gasoline price (US$/L)	Cost of ethanol (US$/L)
Puerto Carreño	1,364,000	0.92	1.14
La Macarena	4,548,000	1.41	1.19
Leticia	6,503,640	1.17	1.21

Table 24-9. Bromatological composition (%) of vinasse produced during the processing of cassava into bioethanol.

Crude protein	Ash	Ether extract	Crude fiber	Moisture	IVDMD[a]	OM[b]	Starch
11.60	5.23	4.86	60.35	8.49	64.70	93.52	0.74

a. IVDMD refers to *in vitro* dry matter digestibility.
b. OM refers to organic matter.

Table 24-10. Mineral contents present in vinasse produced during the processing of cassava into bioethanol.

P	K	Ca	Mg	S	Zn	B	Mn	Fe	Cu	Al	Na
		(%)						(ppm)			
1.42	1.49	5.38	0.40	0.48	40.4	15.5	104.5	3305.1	14.2	3120.6	38,398.2

Mineral concentrations in vinasse from cassava processing are low except for Ca (5.38%), limiting their use as an individual product. García and Rojas (2006) reported that these effluents are deficient in elements, implying low fertilizer power. To supply crop needs, large quantities must therefore be applied. However, they are extremely acid and have a high electrolytic concentration, which may favor their use over other byproducts.

Most of the chemical components of vinasse are chelants, enabling the formation of organic complexes with nitrogen and other minerals of greater bioavailability for animal nutrition. However, vinasse also contain typical chemical components, including soluble inorganic substances (particularly ions of K, Ca, and SO_4), dead yeast cells, organic substances resulting from the metabolic processes of yeasts and polluting microorganisms, alcohol and residual sugars, insoluble organic substances, and volatile organic substances.

Vinasse is one of the most polluting organic wastes for the planet's flora and fauna, as they present high organic matter contents, which are measured in terms of chemical oxygen demand (COD) and biological oxygen demand (BOD). Values range from 24,635 to 65,457 and 26,500 to 33,600 mg of O_2 per liter, respectively. Effluents also contain high concentrations of fixed soluble solids (1400 to 2000 mg/L), low electrical conductivity (2.6 to 4.2 mS/cm), very low pH (3.6 to 3.8), high concentrations of phenols (478 to 541 mg gallic acid equivalents/L), absence of a buffer capacity because of low pH, and contents of phosphates and sulfates that range between 290 and 1705 mg/L, and 308 and 946 mg/L, respectively (Robles and Villalobos n.d.).

The principal problems are that, for each hectoliter (hL) of ethanol produced, about 15 hL of vinasse are obtained as residues (Lezcano and Mora 2008). Because of its high production, storing this byproduct is not easy. Hence, in many places, the effluents are poured directly on to the soil and/or into water sources without treatment, polluting large extents of surface and ground water and heavily affecting the environment.

With the growth in the production and use of biofuels, the search for methods to treat and use vinasse has increased. This means that technologies for their use are available, such as fertilizer applications; production of biogas, compost, unicellular protein (i.e., SCP), and animal feed; energy generation; brick production; concrete reinforcement; and production of chemical compounds. Technologies for managing vinasse include recirculation to reduce volumes to 2 L of effluents per liter of ethanol, with 60% total solids content, thus facilitating transport, storage, and use.

Concentrating vinasse by evaporation has high energy cost and requires chemical compounds to periodically wash the system to eliminate deposits of non soluble salts in the evaporation tubes. Another technology for treating vinasse is methanization or anaerobic degradation, which not only removes more than 90% of the BOD and 70% of the COD, but also generates methane gas, which can be used as fuel. A further alternative is composting for use as fertilizer. This use, despite being more environmentally friendly, demands high levels of capital, area, and time to operate.

To treat and use effluents generated in ethanol production, no simple techniques of bioremediation (filtration) are available that comply with environmental standards, as the particle sizes of most of the solids found in solution are extremely fine. In the RUSBI methodology, vinasse is treated with biopolymers. These electrically charged chemical compounds are prepared from starch, and are used to guarantee the

controlled release of nutrients from fertilizers, reduce erosion, increase the penetration of water into soil, and improve the germination rate of seeds.

When biopolymers come into contact with solutions carrying high loads of ionic solids and basic pH, they foster flocculation and later coagulation of these loads. After the organic matter in the effluents flocculates and coagulates and the resulting sludge is removed, the clarified liquids may be used for other activities in the distillery or irrigation.

To flocculate and coagulate vinasse, the biopolymers used are prepared to a concentration of 1000 ppm and added to the effluents, generating clarification. The products obtained are called clarified vinasse and clarified sludge. Figure 24-9 illustrates the decanting of solids from the effluents, and Table 24-11 lists the nutrient contents present in each clarified product, from sugarcane biofuel processing (Patino et al. 2007).

CLAYUCA in collaboration with Soil Net–Polymer Solutions (a private U.S. company in Madison, WI, USA; www.soilnetllc.com) and the Universidade Federal do Rio Grande do Sul (UFRGS, Porto Alegre, Brazil),

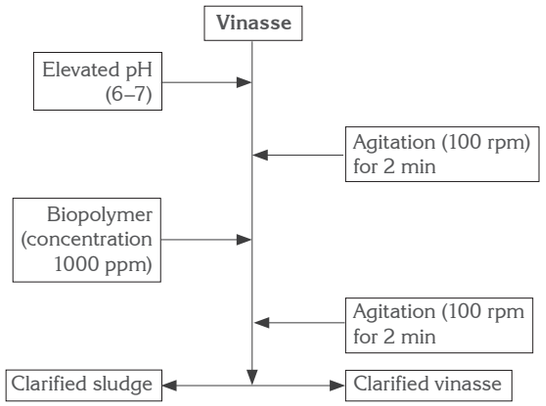


Figure 24-9. Sequence of clarification of vinasse, using biopolymers.

generated new ecological alternatives for managing wastes generated by alcohol distilleries at the national level. One was to process cassava products (i.e., roots and foliage) on an industrial level, together with vinasse. That is, they are incorporated into protein and energy supplements for ruminants, or are prepared fertilizers from agroindustrial residues of cassava production. The effluents and substrate wastes can therefore be used for irrigation and soil fertilizer applications, and the production of compost, biogas, yeasts, and animal feed (Figure 24-10).

The first efforts were directed towards preparing solid organo-mineral fertilizers (Tables 24-12 and 24-13 and Figure 24-11). Table 24-13 shows the values, obtained in laboratory, for the chemical composition of organo-mineral fertilizers prepared from vinasse produced during cassava processing, plus the addition of minerals, cassava wastes, and polymers. Because

Table 24-12. Experimental formula of an organo–mineral fertilizer based on vinasse produced during the processing of cassava into bioethanol.

Raw material	Inclusion (%)	Contribution (%) of:		
		N	P_2O_5	K_2O
Vinasse	15.80	0.27	0.51	0.80
Cassava wastes	25.00	0.10	—	—
Urea	20.00	9.20	—	—
KCl	19.00	—	—	9.50
Triple superphosphate	20.00	—	9.20	—
Polymer	0.20	—	—	—
Total	**100.00**	**9.57**	**9.71**	**10.30**

Table 24-13. Chemical composition (%) of an organo–mineral fertilizer, based on crop wastes and vinasse produced during the processing of cassava into bioethanol.

Moisture	Ash	C	N	P	K	Ca	Mg	Total S
9.22	28.58	30.10	6.48	6.04	1.26	6.55	0.33	0.40

Table 24-11. Nutrient contents present in vinasse and clarified byproducts formed during the processing of sugarcane into bioethanol.

Description	Total P	Total K	Total Ca	Total Mg	S	Fe	Cu	Na	Zn	Protein (%)	OM[a] (%)
	(%)					(mg/kg)					
Sugar cane vinasse	2.97	10.24	0.88	1.14	1.23	986.0	6.0	3066.0	54.0	6.95	56.83
Clarified sugar cane vinasse	0.00	1.06	0.48	0.12	0.14	32.0	0.0	366.0	3.0	0.81	6.79
Sugar cane clarified sludge	2.75	2.99	14.26	0.20	9.30	525.0	47.0	467.0	19.0	5.15	27.51

a. OM refers to organic matter.

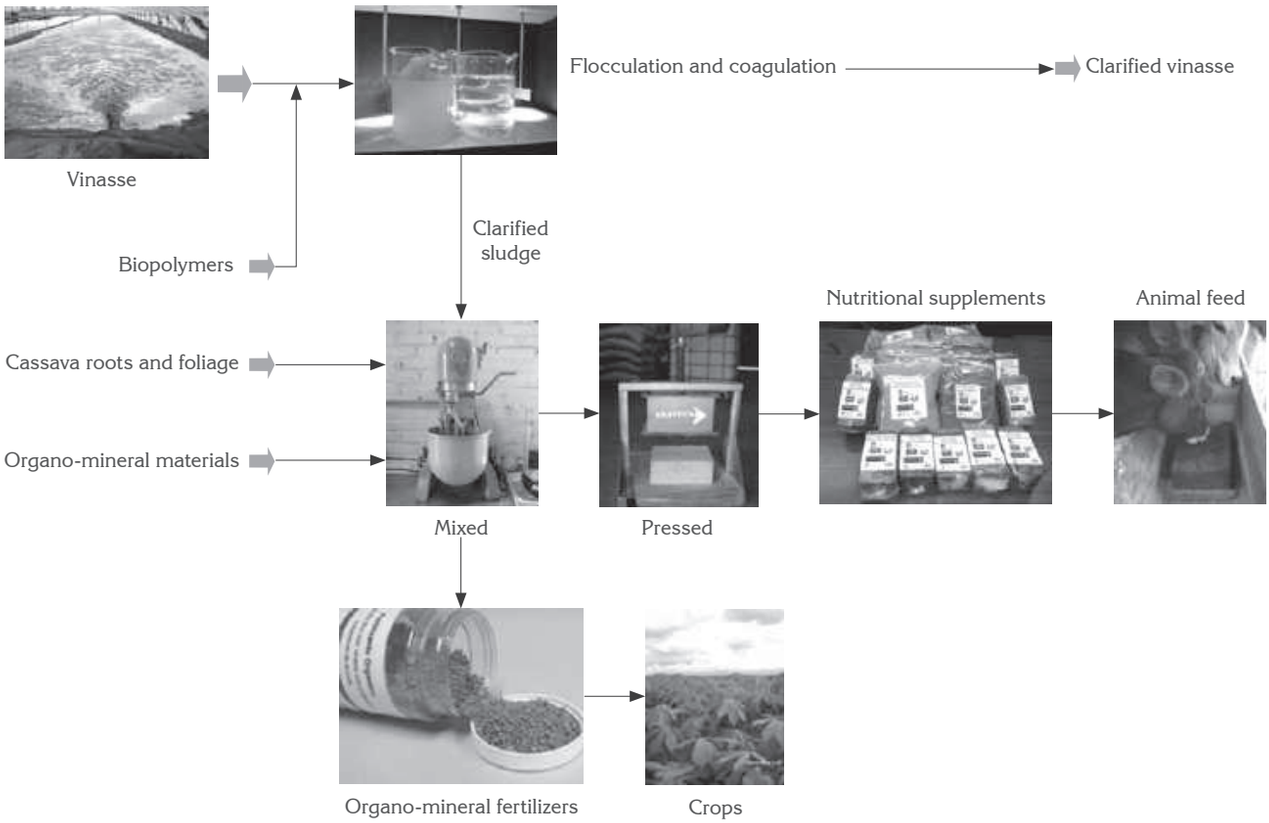


Figure 24-10. Management of wastes and effluents in the RUSBI methodology, established at CLAYUCA.

Figure 24-11. Final appearance of the organo-mineral fertilizer produced from crop wastes and vinasse produced during the processing of cassava into bioethanol.

the mineral contents of the vinasse are low, minerals must be added to the end product.

Animal feed prepared from vinasse has been mostly directed towards ruminants and, to a lesser extent, pigs and poultry. For cattle, the vinasse is used as a raw material to prepare nutritional supplements, which may have various presentations according to the type of production. Organic matter is sourced from vinasse, other byproducts, derivatives, and leaves,

stems, and bagasse from sweet potato, cassava, and sweet sorghum. These, together with urea, minerals, and additives, are incorporated into supplement preparations for ruminants (Figure 24-12).

Table 24-14 presents the results of bromatological analyses of the prepared supplements (protein-mineral and energy-mineral), using the strategy described above.

Nutritional blocks prepared from vinasse and wastes of ethanol production are highly palatable to animals (Torres 2010). They also present high levels of *in vitro* dry matter digestibility (ranging between 71 and 78%), which is very attractive to the national market. When levels of crude protein increase in vinasse, this may be attributed to the presence of yeast wastes. These enrich the product, enhancing its value (Loaiza 2008).

The microbiological quality of prepared supplements made from vinasse is adequate, according to Loaiza (2008) and Torres (2010). Their observations of the products under different storage conditions suggested that their microbiological quality complied with the guidelines established by the Colombian Institute of Agriculture (ICA, its Spanish acronym, and entity that governs the standardization of animal feed in Colombia; see www.ica.gov.co). That is, the products, stored under conditions established by the Good Manufacturing Practices for Animal Feed (BPFA, its Spanish acronym), maintained acceptable microbiological status for 40 days.

Adding protein-mineral supplements in feed for calves (Gil et al. 2007) and young bulls (Campos et al. 2007) consuming poor quality feed led to liveweight gains of between 350 and 550 g/day. This is similar to gains obtained with the more costly commercial supplements found on the market.

Table 24-14. Bromatological composition (%) of supplements for ruminants and prepared from byproducts, derivatives, and effluents of ethanol production.

Nutrient	Protein		Energy	
	Block	Salt	Block	Salt
Dry matter	78.01	93.44	78.99	94.15
Organic matter	67.59	59.43	67.67	65.04
Protein	33.07	39.51	9.61	17.20
Fat	0.82	2.20	1.30	1.59
TDN[a]	65.54	64.26	69.91	65.54

a. TDN refers to total digestible nutrients.

Conclusions

The goal of a Rural Social Biorefinery (RUSBI) is to use several types of biomass (e.g., cassava, sweet potato, and sweet sorghum) to produce ethanol for energy generation and, at the same time, use the various derivatives and wastes generated to obtain a range of byproducts, thus maximizing the added value of the raw materials.

Partial results from studies conducted by CLAYUCA in Colombia to evaluate cassava in the production of hydrated ethanol suggested that enormous potential exists. The cassava crop's genetic diversity must be explored and the processing of the biomass into ethanol in the pilot plant optimized. Further, more detailed, studies are needed on the balance of mass and energy and on bioeconomic efficiency to define energy expenditure and the cassava crop's economic viability as a raw material for ethanol production.

The economic and environmental sustainability of the RUSBI will depend on the correct use of byproducts and wastes generated by the process. Hence, more studies are needed to characterize these materials and propose alternative uses.

Nutritional blocks | Pellets | Meal

Figure 24-12. Animal feed products manufactured from crop wastes, byproducts, and vinasse produced during the processing of cassava into bioethanol.

The incorporation of the biorefinery concept into biofuel production has high potential to revitalize social-inclusion programs, adding value to products, and fostering the socioeconomic development of family agriculture. Hence, the RUSBI approach obviously implies the inclusion of sustainability of the environment and the socioeconomic development of rural communities where such biorefineries are established.

Rural social biorefineries can, in the future, become key components for the development of integrated production models for food, raw materials, feed and fuels, especially at the level of small rural communities located in marginal areas and with little access to conventional energy sources.

References

Arriaga HA. 2008. Análisis estadístico y producción en laboratorio de etanol de yuca (*Manihot esculenta* Crantz) fresca y seca de diferentes variedades de Colombia. MSc thesis in Environmental Sciences. Wageningen University, Wageningen, the Netherlands.

Assis D. 2008. Análise energética de sistemas de produção de etanol de mandioca, cana-de-açúcar e milho. Universidade Estadual Paulista "Júlio de Mesquita Filho" (UNESP), Botucatú, SP, Brazil.

Atthasampunna P; Liamsakul W; Artjariyasripong S; Somchai P; Eur-aree A. 1990. Cassava ethanol pilot plant: a demonstration project for upgrading of cassava wastes and surpluses by appropriate biotechnology. Doc. 7924 e. Microbiological Resources Centre (MIRCEN) of the Thailand Institute of Scientific and Technological Research (TISTR), Bangkok, Thailand.

Cajamarca JA. 2009. Optimización de la hidrólisis enzimática para la producción de bioetanol a partir de yuca. BSc thesis in Agroindustrial Engineering. Universidad Nacional de Colombia, Palmira, Colombia.

Campos R; Castrillón MI; Giraldo L; Patino H; Ocampo ID. 2007. Comparación del uso de suplemento proteico de yuca en un sistema de bovinos en el Valle del Cauca, Colombia. Revista Colombiana de Ciencias Pecuarias 20(4):617–618. (Also presented as a paper at the IX Encuentro Nacional and the II Internacional de Investigadores de las Ciencias Pecuarias [ENICIP] held in Medellín, Colombia.)

CIAT (International Center for Tropical Agriculture). 2011. Linking the poor to global markets: Pro-poor development of biofuel supply chains. In: Final report. CLAYUCA, Palmira, Colombia.

Del Ré D; Patino H; Ospina B; Gallego S; Cajamarca JA. 2010. Efeito da diminuição na utilização de água sobre o rendimento na produção de etanol a partir de mandioca (*Manihot esculenta* Crantz) em micro-usinas. Department of Zootechnics of the Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, RS, Brazil. (Also presented as a poster at the Simposio Estadual de Agroenergia—Reuniões Técnicas de Agroenergia (3°), da Mandioca (10°) e Batata-doce (2°) held in Pelotas, RS, Brazil.)

García A; Rojas C. 2006. Posibilidades de uso de la vinaza en la agricultura de acuerdo con su modo de acción en los suelos. Nota técnica. Tecnicaña 16:3–13.

Gomes AR. 2010. Avaliação de implementação de biorefinarias rurais e sociais na Colômbia. MSc thesis in Food Engineering. Universidade Técnica de Lisboa (UTL), Lisboa, Portugal.

Gil JL; Campos R; Giraldo L; Patino H; Perilla S. 2007. Desarrollo y evaluación de un suplemento utilizando la planta integral de yuca y subproductos de la agroindustria de la caña de azúcar. Revista Colombiana de Ciencias Pecuarias 20(4):623. (Also presented as a paper at the IX Encuentro Nacional and the II Internacional de Investigadores de las Ciencias Pecuarias [ENICIP] held in Medellín, Colombia.)

Jansson C; Westerbergh A; Zhang J; Hu X; Sun C. 2009. Cassava: a potential biofuel crop in China. Appl Energy 86:S95–S99.

Lezcano P; Mora L. 2008. Las vinazas de destilería de alcohol contaminación ambiental o tratamiento para evitarlo. In: Proc Encuentro de nutrición y producción de animales monogástricos held in La Habana, Cuba. Instituto de Ciencia Animal (ICA), San José de las Lajas, Cuba. p 48–52.

Loaiza JK. 2008. Usos de los subproductos de la caña en la elaboración de dos suplementos nutricionales para rumiantes en el Valle del Cauca. BSc thesis in Food Engineering. Universidad de Caldas, Manizales, Colombia.

Martínez GM. 2009. Determinación de la eficiencia en la producción de bioetanol a partir de yuca mediante balances de materia y energía. BSc thesis in Agroindustrial Engineering. Universidad Nacional de Colombia, Palmira, Colombia.

Ospina B; Gallego S; García JA. 2008. Diseño, construcción y puesta en operación de una planta prototipo para la producción de alcohol carburante a partir de yuca y otras materias primas. In: Informe de proyecto. CLAYUCA, Palmira, Colombia.

Patino H; Gil JL; Espinosa JD; Loaiza JK. 2007. Protocolo para el desarrollo y la evaluación de suplementos nutricionales para rumiantes elaborados a partir de subproductos de la agroindustria de la caña de azúcar. In: Informe de proyecto. CLAYUCA, Palmira, Colombia.

Patino H; Ospina B; Gallego S; Payán JS. 2009. BIRUS-Biorefinarias rurais sociais: Uma proposta para o etanol social. In: Proc First Simpósio Brasileiro de Agropecuária Sustentável, Agricultura, Pecuária e Cooperativismo held in Viçosa, MG, Brazil. Departments of Zootechnics and Rural Economics of the Universidade Federal de Viçosa, Viçosa, Brazil. p 283–298.

Robles V; Villalobos F. n.d. Vinazas mezcaleras: un problema de contaminación ambiental. (Available at www.utm.mx/~mtello/Extensos/extenso 080109.pdf; accessed 27 January 2011.)

Torres LA. 2010. Elaboración de bloques nutricionales a partir de residuos de la agroindustria de la caña de azúcar. BSc thesis in Food Engineering. Universidad de Caldas, Manizales, Colombia.

UNDP (United Nations Development Programme). 2004. Energy for sustainable development in Asia and the Pacific Region: challenges and lessons from UNDP projects. New York, USA. (Available at http://www.undp.org/energy/esdasiapac.htm; accessed 21 March 2008.)

Vinh NT. 2003. Ethanol production from cassava. In: Jacques KA; Lyons TP; Kelsall DR, eds. The alcohol textbook, 4th edn. Nottingham University Press, Nottingham, UK. p 59–64.

CHAPTER 25

Conserving and Treating Fresh Cassava Roots

Teresa Sánchez[1] *and Lisímaco Alonso*[2]

Cassava (*Manihot esculenta* Crantz) is an important and economic food source of calories, especially for the low-income population of the tropics. Scientists have accordingly made major efforts to develop higher yielding varieties and design appropriate low-input technologies that improve crop production. The on-farm application of these technologies has triggered significant production increases.

Because cassava is increasingly used as human food and in other fields, special attention should be given to the development and transfer of different postharvest technologies to solve the problem of the fast deterioration of cassava roots once harvested. Postharvest deterioration not only increases production costs and risks, but also causes considerable losses to wholesale dealers and retailers. As a result, high marketing margins are created for this crop to compensate the appreciable volume of roots lost.

To help solve this problem and increase the demand and marketing options for cassava, the Centro Internacional de Agricultura Tropical (CIAT)[3] and other research entities have developed ways of conserving harvested cassava roots that are low cost and allow long-term storage.

Physicochemical Composition of Roots

Cassava roots are rich in calories, but deficient in proteins, fats, minerals, and vitamins. Root tissues also contain several secondary compounds:

- **Polyphenols**—the most important—are involved in the postharvest physiological deterioration described above.
- **Tannins**, which are found in low concentrations in fresh parenchyma, but in larger quantities in the peel.

- **Dry matter** (DM), which accounts for 30%–45% of the parenchyma. Carbohydrates (the non-nitrogen fraction) account for 90%–95% of the DM (Table 25-1).

- **Cyanide** (CN^-), a radical that generates toxic compounds at certain levels, which is found in variable amounts in cassava roots. It is found mainly as a cyanogenic glucoside known as linamarin (90%), with the rest being free cyanide.

Table 25-1. Chemical composition of cassava roots.

Root component	Contents
Energy	1460 calories/kg
Water	66.00%
Carbohydrates	35%
Protein	1.2%
Fat	0.2%
Fiber	3.1%
Ash	1.9%
Calcium	330 mg/kg
Iron	7 mg/kg
Phosphorus	440 mg/kg
Vitamin A	0.21 mg/kg
Thiamine	0.6 mg/kg
Riboflavin	0.8 mg/kg
Niacin	6 mg/kg
Vitamin C	360 mg/kg

1. Chemist, Head of the Quality Control Laboratory, Cassava Improvement Project, CIAT, Cali, Colombia. E-mail: t.sanchez@cgiar.org
2. Agricultural Engineer, Postharvest Management Systems, CLAYUCA, Cali, Colombia. E-mail: l.alonso@cgiar.org
3. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

The characteristics described above vary according to variety and factors such as plant age, soil type, fertilizer applications, and harvest time.

Root Deterioration

After harvest, cassava roots may undergo two types of deterioration: one physiological and the other microbial.

Physiological deterioration

Physiological deterioration appears first with different root tissues acquiring a blackish-blue color, especially near the xylem (Figure 25-1). This is caused by a postharvest accumulation of certain phenolic compounds that, when polymerized, form the blackish-blue pigment.

Visible signs of physiological deterioration appear from 24 to 48 h after harvest. Before these signs appear, roots show brilliant blue fluorescence under ultraviolet light because of the accumulation of a phenol known as scopoletin. This fluorescence is a sure indication that deterioration has started. Physiological deterioration starts rapidly in wounds, which almost always occur in the root's distal and proximal extremes during harvest.

Physiological deterioration involves enzymatic reactions that need oxygen to develop. Therefore it can be prevented by impeding the access of oxygen to parenchymatous tissues or by inhibiting enzymatic reactions. Knowledge of these mechanisms led to the design of storage systems in which factors favoring deterioration in roots are eliminated. For example:

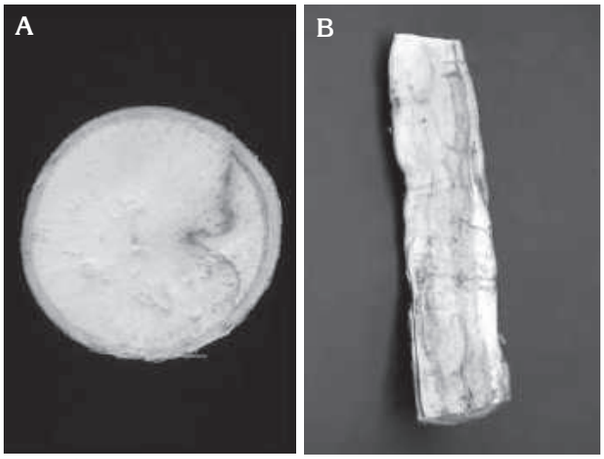


Figure 25-1. Physiological deterioration gives tissues close to the xylem a dark blue color (arrows): cross-sectional cut **(A)** and longitudinal cut **(B)** of a cassava root.

Storage in an atmosphere of nitrogen or vacuum eliminates environmental oxygen. This isolation can also be achieved by covering cassava roots with thin layers of paraffin that act as an artificial barrier to oxygen.

Roots may also be stored at low temperatures to inhibit enzymatic processes. At 2 °C, polyphenoloxidase and other related enzymes forming the typical pigments of physiological deterioration are inhibited.

Microbial deterioration

Microbial decomposition begins on days 5 to 7 after harvest. It initially manifests as a vascular streak, similar to that observed in physiological deterioration, and then becomes a moist rot, with fermentation and maceration of tissues (Figure 25-2).

Microbial deterioration is related to the activity of several pathogenic microorganisms and is therefore accelerated in an environment with high relative humidity and temperatures, especially in physically damaged roots. Etiological studies have isolated, from affected tissues, fungi of the genera *Penicillium, Aspergillus*, *Rhizopus*, and *Fusarium*, as well as several species of bacteria of the genera *Bacillus*, *Pseudomonas*, and *Corynebacterium*.

Root Quality

Quality comprises all the conditions and characteristics of a product, including its internal composition—enforced through legal provisions—and meeting consumer preferences or acceptability. Even if a product complies with legal provisions, it may, nevertheless, be rejected by the consumer because of its color, smell, or flavor. Roots must therefore undergo adequate treatment to meet the requirements of the markets in which they are to be offered.

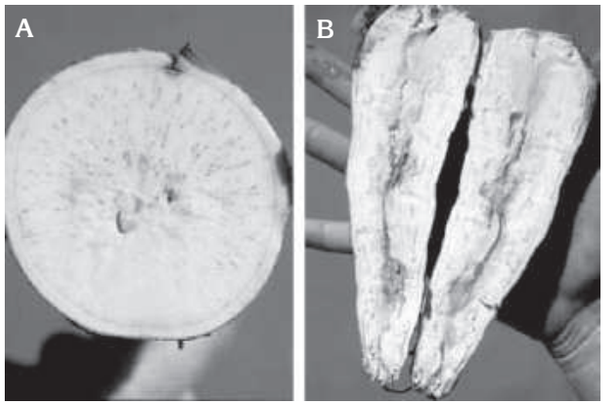


Figure 25-2. Microbial deterioration first appears as vascular streaking **(A)** and then as moist rot **(B)**.

Quality criteria for roots as demanded by the fresh market are rigorous even though they vary considerably from region to region. Good root quality is usually associated with the following aspects: low cyanide content, intermediate DM and starch contents, acceptable culinary quality, and resistance to deterioration. Total cyanide content of pulp for fresh-root consumption should not exceed 60 ppm. Cooking the roots eliminates the cyanide from the pulp tissue.

Culinary quality

Culinary quality refers to the time required to cook or prepare the roots as well as their acceptance by consumers. To determine the culinary quality of a given cassava variety, several plants are selected at random from the plot, their roots harvested, and then various roots selected at random for cooking.

For cassava, good cooking quality depends on:

- **Cooking time:** after 30 min of cooking, its consistency is between hard and very soft.
- **Flavor:** neither bitter nor sweet. Bitterness indicates that the roots have high hydrocyanic acid (HCN) content, whereas sweetness indicates high sugar content.
- **Fibers:** no fibers should be present nor should the parenchymatous tissues be lignified.
- **Consistency:** cooked pulp should be firm, without hard parts or a glassy appearance; the starch should be white or yellowish in color, never transparent.

These factors are mostly detected during consumption of the cooked cassava and cannot be distinguished by observing the roots' external appearance.

In brief, quality factors and conditions of cooked cassava should be as follows:

Quality factor	Conditions
Cooking time	<30 min (parenchyma)
Flavor	Neither bitter nor sweet
Consistency	Firm
Fibrousness	Absent
Starch color	White or yellow

Morphological quality

Morphological quality has to do with certain characteristics of the shape of the root that, depending on the variety, determine its suitability for conservation. The principal aspects affecting morphological quality include:

- **Shape of roots.** Cylindrical or conic roots, with well-developed peduncles, are highly desirable because they suffer less physical damage during harvest and storage. Round roots are also preferable because roots with imperfect shapes may suffer damage to the peel during transportation and storage.
- **Length of peduncles.** Long peduncles are better than short ones because it is difficult to separate the latter from the stump and, once separated, the peel almost always breaks and the parenchyma is damaged.
- **Length of roots.** Rather long roots are undesirable as long roots break easily during harvest (Figure 25-3).

The previous criteria indicate that the most appropriate cassava varieties for conservation are those with medium-sized roots and well-developed peduncles

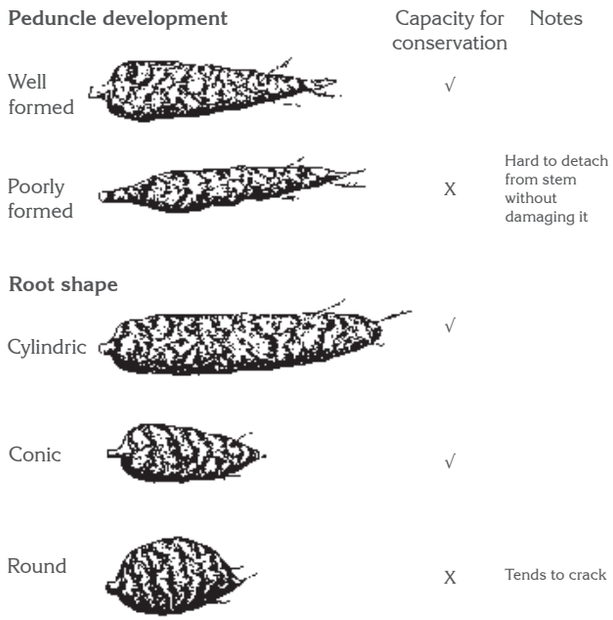


Figure 25-3. Characteristics of the cassava root peduncle and shape that make roots apt for conservation (X = not suitable).

(Figure 25-4). These roots suffer less physical damage during harvest, selection, and storage.

Sanitary quality

Healthy roots do not present external or internal rot. To ensure quality, any root presenting rot must be discarded, as only one, even with an incipient disorder, may cause the complete loss of an entire root lot.

Such rots are not always easy to detect. Internal rot due to cassava root smallpox is transmitted through a subterranean burrower bug (*Cyrtomenus bergi*). The rot is not visible on the outside, and roots must be peeled to evidence the rot (Figure 25-5). Some stem diseases can infect roots through the lignified peduncle. Therefore roots must be carefully selected after harvesting.

Storing Fresh Cassava

To date there is no universal technique to conserve cassava roots for commercial use. Even the most refined techniques have limitations, some because of their high costs. Furthermore, the simplest techniques have not been disseminated in agricultural practice, despite satisfactory results obtained at experimental levels. Depending on duration, there are three types of root storage: short-, medium-, and long-term.

Figure 25-4. Medium-sized roots with a well developed peduncle conserve better.

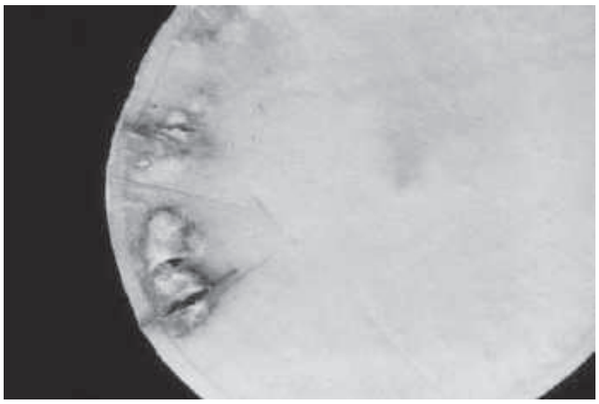


Figure 25-5. Root affected by the cassava smallpox disease.

Short-term storage (7 to 10 days) overcomes some of the obstacles currently hindering cassava marketing and can reduce losses by deterioration that tend to occur before the product is sold. This is a feasible system that should meet the following requirements:

- Be low-cost
- Be easy to apply and readily adaptable to the current marketing system
- Prevent physiological and microbial deterioration of roots by favoring the healing of wounds
- Be easy to transport
- Conserve the roots' culinary quality and appearance

Medium-term storage (2 to 3 weeks) tends to be more expensive and complex than short-term storage. Its principal objective is to provide conditions so that root wounds are healed, stopping the advance of physiological and microbial deterioration. Roots should still be easy to transport and root quality should remain unchanged. Examples of this type of storage are systems involving the application of paraffin, wax, and the use of boxes containing wet sawdust.

Long-term storage can conserve roots for more than 3 weeks. It is unlikely that this system will be used because of the difficulty of maintaining root quality over prolonged time periods, as the roots usually acquire a sweet flavor due to starch hydrolysis. Furthermore, the probability of loss due to microbial deterioration increases. Freezing is a good example of a long-term storage system that avoids these effects; however, it is expensive and only economical when roots are destined for export or supermarkets, in which case costs are not a significant factor.

Traditional methods

Traditional storage techniques are simple. For example, small quantities of roots are buried, covered with mud, or stored in water. These methods are successful because storage conditions are propitious for healing any wounds that the roots may have. They are inappropriate, however, for storing large amounts of cassava and much less if the storage period is prolonged.

Field silos. The earthen and straw silos used to preserve potato have been tested for storing cassava roots. The silo is built on dry and leveled land. Inside the silo, fresh roots are conically piled on a circular bed made of straw or dry cane or grass leaves, then covered first with straw, similar to that used at the base, followed by earth. A drainage ditch is then dug around the silo (Figure 25-6; Booth 1977).

The silo maintains high environmental humidity. Under suitable conditions, root wounds caused during harvest and transportation are healed by the formation of a waxy substance called suberin. Roots conserve well for 4 to 6 weeks, time after which starch content drops slightly and sugar content increases proportionately. These changes, however, do not affect the final quality of the roots. The healing and storage period may vary with silo design and prevailing conditions in the region.

The results of storing cassava roots in silos under environmental conditions different from those of CIAT–Palmira (mean temperature, 26 °C and 70% relative humidity) may vary greatly. In some cases, 80% of the roots were healthy after 1 month of storage, but in others, all roots presented symptoms of deterioration. This variation is related to the temperature and relative humidity of the storage period. In cool humid periods, storage results can be satisfactory, but in dry hot periods when temperatures may rise rapidly and remain at more than 40 °C, almost all the silage could be lost. Better results are obtained with silos that have openings to allow the entry and exit of air.

Silos were first used to store cassava roots in 1974. This method had proven efficient at the experimental level, but has not yet been applied in the field.

Wooden boxes. This method has proven to be very effective under the environmental conditions of CIAT–Palmira. Cassava roots are packed in wooden boxes measuring 50 cm long, 29 cm wide, and 30 cm high, containing sawdust to one-third the depth. Humidity in the box should be 50% to favor the healing of root wounds and to prevent excessive moisture loss (Figure 25-7). The moisture in the sawdust should be carefully controlled: if too dry, then the wounds are not healed and the physiological deterioration of the roots occurs rapidly. If too moist, there is excessive development of secondary roots and roots present severe rot.

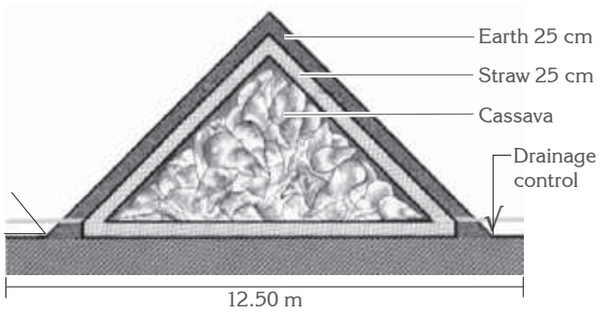


Figure 25-6. Cross-section of a pyramidal silo for storing cassava in the field.

The box is sealed with a wooden top, placed in the shade or in the field, and covered with a waterproof cloth. Under CIAT conditions, the internal temperature varies between 24 and 28 °C when the roots are placed in the shade, or between 26 and 34 °C when they remain in the open field.

In experiments conducted with this storage system, the quality of about 75% of the roots was still acceptable after 4 weeks of storage. However, if there is a delay of even 1 day between harvest and packaging, this percentage is reduced by as much as 49%. Sawdust is the major drawback of this storage system because it contains insects and fungi and increases transportation costs. In practice, this method has been little used.

Modern methods

Polyethylene bags. This new method of storing cassava roots addressed important issues such as time between harvest and packaging, effect of the sun on root quality, and required activity coordination.

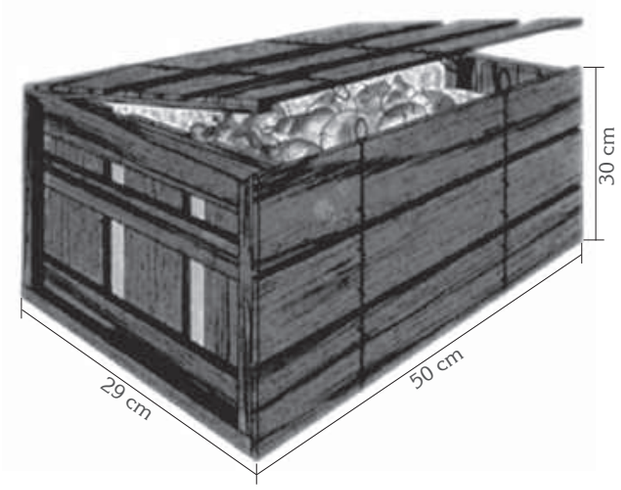


Figure 25-7. System of storing cassava roots in wooden boxes.

The latter is decisive: harvesting, packaging, and treatment should all be done rapidly and efficiently. To achieve this, workers are divided into groups, with each group being assigned a task (or stage), for example, harvesting, selection, packaging, treatment, sealing, and transportation. As a result of this coordinated effort, there is:

- A continuous, more efficient flow of work, with safer results. The opposite would occur if all the workers worked simultaneously on one stage of the process.
- No accumulation of cassava roots from stage to stage.
- Minimal damage of harvested roots when activities must be suspended because of rain or other causes, due to the short time that elapses between harvest, packaging, and treatment.

Figure 25-8 shows the stages of this method.

Harvesting of roots. Roots are harvested when plants are between 8 and 12 months old, that is, when yields are the highest. Care should be taken during harvest to avoid breaking or physically damaging the roots. Figure 25-9 shows different levels of damage and how they affect cassava's suitability for conservation.

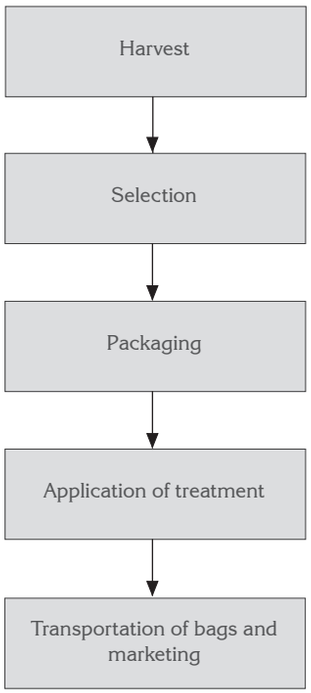


Figure 25-8. Flow of activities involved in the conservation of cassava in polyethylene bags.

Roots are harvested manually, separating the root from the stem (or stump) using a machete or secateurs. The latter tool is more adequate, as a more precise and careful cut causes less damage to the root. A small piece of peduncle is left on the root so that the parenchyma is not exposed to air (Figure 25-10).

Selection of roots. Harvested cassava is classified into three categories (A, B, and C) according to root type (commercial or noncommercial) and magnitude of physical damage received (Table 25-2).

Overall, for category A, from 80% to 90% of the roots are commercial and show little or no physical damage, making them suitable for treatment and conservation.

For category B, a smaller volume of roots is classified as commercial but the severe damage they

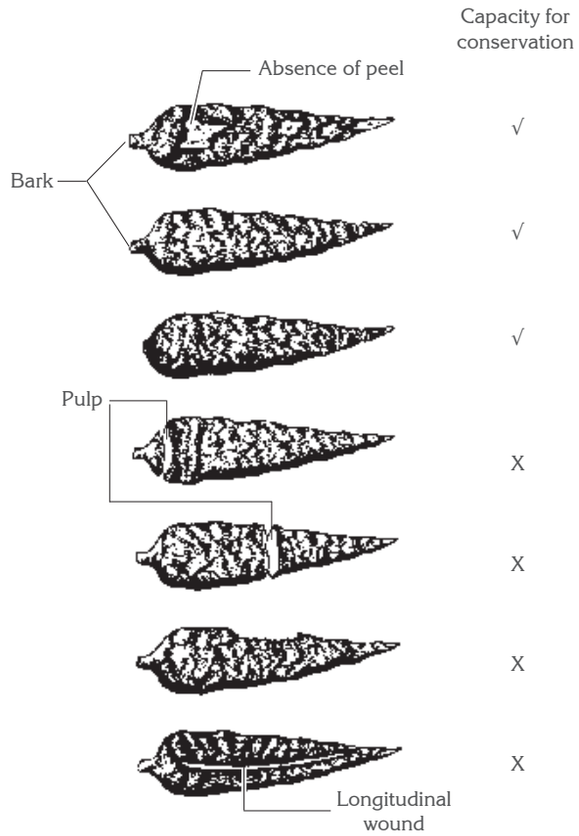


Figure 25-9. Conservation capacity of roots taking into account damage suffered during harvest (X = not suitable).

Figure 25-10. A good harvest practice is to leave a piece of peduncle adhered to the root.

Table 25-2. Categories in which cassava roots are classified according to use.

Category	Use of root	Physical damage to root	Frequency in lot
A	Commercial	Slight or none	80%–90%
B	Commercial	Severe	5%–10%
C	Noncommercial	Present or absent	5%–10%

present renders them non-apt for conservation. The frequency of roots falling into this category probably increases during summer months when harvesting is more difficult. Category B cassava has several potential uses: for sale in the fresh-root market for human consumption, as ensilage, as raw material for animal feed companies, or in starch production.

Noncommercial roots (category C) can be used for some of the above-mentioned uses, thus taking advantage of the entire harvest.

Packaging and treatment. Several aspects should be considered during this stage, as follows:

Time between harvest and packaging. Results of experimental tests as well as past experiences indicate that packaging and treatment should be carried out as soon as possible after harvest. A delay of more than 4 h may cause the complete loss of the entire produce due to physiological deterioration. The time elapsed between harvest and packaging should be less than 3 h. This requires that pertinent tasks be performed at the harvest site itself or somewhere close by.

Effect of the sun. The direct exposure of roots to the sun over a prolonged period will increase the risk of losing the harvest to physiological deterioration. Loss can be prevented by harvesting and packing roots at the harvest site during the early morning, late afternoon, or under shade.

Materials and equipment for treatment. A minimum amount of equipment and additional materials must be available at the operations site, including:

- A high-pressure pump or back sprayer, with a maximum capacity of 20 L.
- A fungicide, usually Mertect 450 FW, to apply to roots.
- Polyethylene bags. Two types are generally used: 4-kg bags, 0.4 mm thick, measuring 21 × 12 cm, and 12-kg bags, 0.6 mm thick, measuring 21 × 48 cm. The bag size used will depend on market needs.
- Labels that provide the following information: name of company distributing the cassava, harvest and packaging dates, weight of content, guaranteed shelf life, and instructions for proper handling of product. This information can also be printed directly on the polyethylene bags.
- An easy-to-handle scale, in good conditions.
- Staplers adequate for the type of packaging used, with sufficient replacement staples or fasteners.

Procedure. The following steps are involved: packaging of selected cassava roots, treatment with fungicide, and preparation of bags for transportation to marketing sites.

- Only package undamaged, previously selected, commercial-sized roots (Table 25-2). Place roots in the bags in vertical position, with the peduncle facing upwards. Package roots of different sizes in the same bag to avoid filling the last bags with smaller roots.

  Adjust the weight of the bags according to their capacity. If a 4-kg bag weighs less than the designated amount, then it is not fair to the consumer and, if the bag weighs more, then the farmer loses.

- Apply the fungicide, which consists of a solution based on Mertect 450 FW at 0.4% concentration, once the roots have already been placed in the bags. To prepare the solution, first

fill the fumigation tank (in this case, of 20 L) with water and then add 80 mL (0.08 L) Mertect (0.4% of 20,000 mL). Thoroughly mix the solution with a stick or with the pump lance. Replace pump filter and tank top. The fungicide solution is now ready for application. Introduce the lance of the pump into each bag and bathe roots with the solution, in particular root tips (Figure 25-11).

It is important to eliminate any excess fungicide solution from the bag because excess internal moisture favors the development of fungi. Turning the bags upside down to drain the excess liquid is not only impractical because roots could fall out but also represents additional labor.

The recommendation is to make diagonal cuts on the corners of the bottoms of the bags before beginning to pack the roots. These cuts prove highly practical, allowing the excess liquid to drain (Figure 25-12) while also helping to regulate the interior moisture of the bags, especially when roots have been harvested during the rainy season when moisture is excessive. This practice greatly favors root conservation.

Approximately 100 mL solution are needed to treat one 4-kg bag so 1 L Mertect 450 FW is enough to treat 10 t of cassava.

- Close the bags by folding the opened end of the bag 2 or 3 times and then staple the bag shut, using as many staples as necessary. Finally, staple the information label to the bag (Figure 25-13).

Figure 25-11. To treat with fungicide, introduce the spray lance into the bag and completely drench the roots.

Figure 25-12. A diagonal cut at the bottom of the bag helps drains excess fungicide.

Figure 25-13. The last step is to staple on the information label.

Transporting the bags. The polyethylene bags containing treated roots are transported in the same type of vehicles used to transport fresh cassava. However, because this first stage of the conservation process creates conditions that favor the healing of wounds or damage caused to the roots, which is very important for successful storage, prevailing climatic conditions should be closely monitored during transportation to ensure that the healing process continues unaltered.

The internal temperature of bags during transportation should be approximately 30 °C. When the climate is warm, it is not advisable to keep bags inside the vehicle for long periods of time since their internal temperature should not surpass the maximum level allowed (40 °C). On the other hand, in temperate or cold climates, it is sometimes necessary to cover bags with a canvas to protect them from the cold. In extremely cold climates, for example in the Andean region, bags traveling long distances should be

previously placed in a warm environment (30 to 40 °C) for 24 h to make sure that the wound healing process occurs prior to transportation.

It is also necessary to know the conditions of the roads. If roads are in poor conditions and the distances to travel are great, roots will undoubtedly suffer physical damage, which will in turn affect their conservation. It is therefore advisable to place the bags within the vehicle in such a way that there is no contact between them during the trip. Groups of bags can also be placed in plastic or wooden containers. Finally, the vehicle should be driven carefully.

When poor transportation conditions cause physical damage to the roots, guaranteed shelf life (usually 15 days) is almost always reduced, possibly to 10 or 7 days. The distributor could request that the shelf life indicated on the label be modified accordingly.

The temperature maintained during transportation should be maintained at the storage site upon arrival. Once it has been confirmed that root wounds have healed, bag temperature can be lower than 30 °C. However, under no circumstances should temperatures above 40 °C be accepted.

Marketing. Marketing surveys carried out in Bucaramanga, Colombia (CIAT, 1991), indicate that 4-kg bags are most appropriate for local consumers. This amount of cassava is sufficient to satisfy the needs of an average-sized family (5 members) for one week and the bag adequately conserves the cassava as it is consumed. In places where cassava consumption is lower, the distributor could retail the cassava in the 12-kg bags. This way the retail distributor benefits from the storage method and the consumer from the guaranteed quality of the product and the more favorable price.

Consumer acceptance studies have also been conducted in Bucaramanga (CIAT, 1991), involving bags containing cassava conserved for 1 or 2 weeks postharvest. Based on the data gathered, it was concluded that consumers did not detect changes in the culinary quality of roots and that 90% preferred to purchase cassava conserved in the polyethylene bags described herein.

Applying paraffin to fresh cassava roots

A little less than one fourth of the fresh cassava destined for human consumption is lost because the roots, once harvested, decompose 2 or 3 days later. This deterioration increases with increasing distance from the cultivation site to consumption centers and when the marketing of agricultural cops is deficient in the region. This is not an easy problem to solve.

Because cassava deteriorates so quickly (CIAT, 1976; 1987), it must be sold as soon as possible. Market prices vary significantly, affecting both producers and consumers. Much cassava is never sold because sales intermediaries discard it before it reaches the market.

The former Technological Research Institute (IIT, its Spanish acronym) in Colombia conducted several studies on how to best conserve fresh cassava roots. Results highlighted the application of paraffin and IIT presented this method as an alternative to delay deterioration and reduce cassava marketing losses (IIT, 1972; 1973).

Effectiveness

This method guarantees root conservation because it:

- Partially inactivates the enzymes present in cassava tissues
- Notably reduces permeability to oxygen and indirectly controls the action of peroxidases
- Reduces water loss
- Reduces contamination by microorganisms due to the high temperatures used in treatment
- Controls fermentation because of reduced yeast count

The application of paraffin therefore ensures good-quality fresh cassava, without notable changes in organoleptic characteristics, with a shelf life of 20 to 30 days (IIT, 1972).

Stages

Basic stages of the paraffin treatment process are indicated in Figure 25-14. Because the application of paraffin does not improve cassava quality, only its conservation, it should only be used with roots presenting very good culinary quality (IIT, 1973).

Paraffin should be applied within 4 h postharvest. Therefore the facility where the paraffin is applied should be located close to cultivation sites or collection sites of fresh roots.

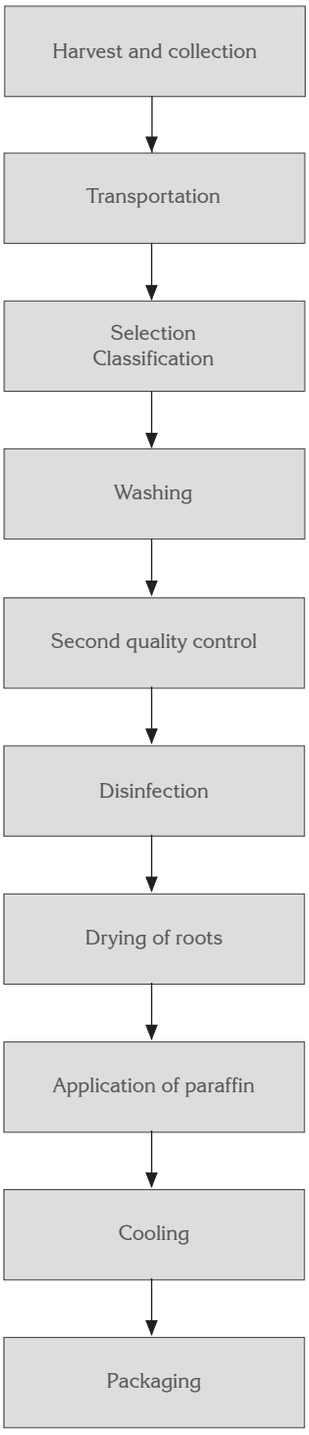


Figure 25-14. Flow chart indicating the main stages of paraffin treatment to fresh cassava roots.

Harvesting. Roots should be harvested with extreme care to avoid damaging their surface (Figure 25-15). The process practically begins with the careful harvest of roots, which will ensure that a high percentage will be suitable for paraffin treatment.

Figure 25-15. Cassava roots harvested with care.

Leaving sufficient peduncle helps protect the roots from bacteria attacking that tip of the root while facilitating their handling during the paraffin treatment process.

In cassava-growing regions where paraffin is applied to roots, between 15% and 30% of the roots harvested prove suitable for paraffin treatment (A Martínez 2010, pers. comm.). The remaining roots are sold on the fresh market or used as raw material to prepare frozen chips, sticks, or croquettes.

Transportation to the paraffin treatment facility. Transport roots in wooden or plastic boxes, as is the case of most delicate crops. Maximum capacity of each box is 20 to 25 kg (Figure 25-16).

Selection and classification. Once the roots arrive at the paraffin treatment facility, discard roots that are broken, damaged, or have an unacceptable size. Supermarkets usually define desired root dimensions depending on consumer preferences. During this first quality control check, also discard roots showing signs of physiological and microbial deterioration.

Washing. Use good quality water, preferably potable water, to wash the roots. Remove superficial earth by scrubbing the root with a sponge or using a brush with soft plastic bristles to avoid damaging the peel (Figure 25-17).

Figure 25-16. Packaging of fresh cassava roots in plastic boxes for transportation to paraffin treatment facility.

Then immerse the roots in a tank adapted with a bottom grid and a collector of solid residues to facilitate their precipitation, subsequent removal, and change of water. This system avoids dirty water mixing with clean water, while allowing the use of low-pressure water jets for sprinkling or spraying. Washing should completely eliminate any earth from the root surface so that the paraffin can adhere well to the root peel.

Submit washed roots to a second quality control check to discard any roots found unsuitable that may have been missed during the first quality control check. Check roots for signs of deterioration, adjust stumps or peduncles, and remove parts of the epidermis that have become detached.

Disinfection. After washing, spray roots with 'Lonlife', a new product based on citrus seed oil that protects roots from the attack of fungi and bacteria (Figure 25-18), mixed with water as follows: 1 g of Lonlife in 1 L of water for a concentration of 250 ppm active ingredient.

Roots can also be disinfected with Mertect 450 FW (thiabendazole) prepared by adding 1 mL product to 1 L water. Submerge the roots in the solution for 3 min.

Figure 25-17. Tank for washing fresh cassava roots.

Drying of root surface. Cassava roots are left to air dry under shade by some companies. Others place roots in a hot-air oven or tunnel at 40 or 45 °C. Paraffin treatment requires that the root surface be completely dry.

Paraffin treatment. A mixture of paraffin from China and locally obtained paraffin is generally used. Because of its rough consistency, the local paraffin does not adhere perfectly to the root peel. On the other hand, the finer Chinese paraffin adheres better to the peel and improves the appearance of the root; however, it is consumed in greater amounts during the process.

Figure 25-18. Lonlife is a product obtained from citrus seeds used to counteract fungi and bacteria attacking cassava roots.

In Colombia's coffee-growing region, some businessmen say that a 50%-50% mixture is perfect, processing some 4000 kg of fresh cassava (J Botero 2000, pers. comm.) with only 50 kg of paraffin. Others only use Chinese paraffin.

Temperature and inmersion time must be perfectly controlled. The poor, excess, or insufficient application of paraffin due to timing or temperature issues not only voids the process, but could accelerate root deterioration.

Submerge dry roots in a container with paraffin at a temperature ranging between 140 and 160 °C. If the temperature is below 140 °C, the root is covered with a very thick layer of dull-looking paraffin. Above 160 °C, paraffin evaporates hence its consumption would increase and roots could be even boiled. Have a thermometer on hand to permanently check the temperature of the container and turn the equipment on and off as necessary (J Botero, 2000, pers. comm.).

Paraffin is usually applied manually (Figure 25-19). First introduce half of the root into the container, wait until the paraffin film cools, then introduce the other half and wait until that paraffin film cools. Place the treated roots on a table next to the container until cooled completely.

A stainless steel basket was developed in Armenia, Colombia (SENA, 2001) that allows batches of 2 or 3 kg of roots to be treated at once (J Botero 2000, pers. comm.). The process only takes a few seconds—the time it takes to lower the basket to the bottom of the container and then lift it out (Figure 25-20). Roots

Figure 25-19. Manual application of paraffin to fresh cassava roots.

Figure 25-20. Steel rod basket that holds from 2 to 3 kg of fresh cassava roots, used during paraffin treatment.

should not remain in the paraffin more than 3 s to avoid subsequent cooking problems.

Cooling and packaging. Pack cooled roots in plastic boxes, when shipping to supermarkets, or wooden boxes (Figure 25-21). Boxes usually have a capacity to store 20–25 kg of roots. If you need to accelerate the cooling of the treated roots to avoid delays in shipping, submerge treated roots in cold water.

Based on April 2010 estimates, the cost of applying paraffin was COP460/kg fresh roots, distributed as follows: $130 for labor, $200 for paraffin, and $130 for packaging (A Martínez 2010, pers. comm.)

Roots should be free from wounds and cuts. Some supermarkets, however, request that the tip of treated roots be cut off so buyers can appreciate the quality of the parenchyma (Figure 25-22). This practice not only shortens shelf life to just 8 or 10 days, but increases the risk of the pulp becoming contaminated or acquiring a paraffin-like taste. Normal shelf life of intact roots ranges between 20 to 25 days (IIT, 1972; 1973).

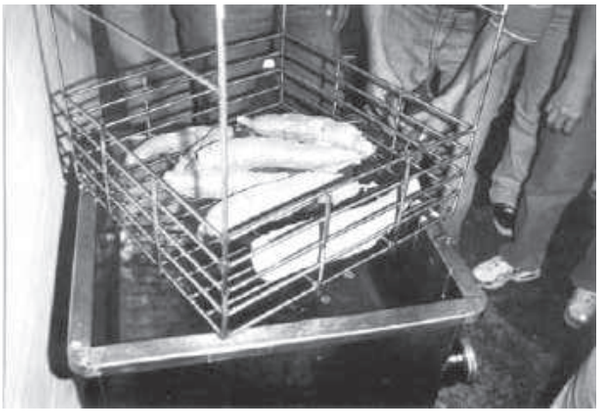


Figure 25-21. Cooling the paraffin-coated roots in the basket used to submerge roots.

Figure 25-22. Applying paraffin to part of the root.

Freezing of Cassava Chips or Sticks

Refrigeration, one of the techniques used to store fresh cassava, consists of storing roots in a cold storage room (temperature: 0–2 °C; relative humidity: 85%–95%). Low temperatures inhibit enzymatic processes causing physiological deterioration of roots. If, in addition, roots are kept in plastic bags under good storage conditions, their shelf life is further extended. Refrigerate cassava immediately after harvest. Storing roots in a normal household refrigerator will keep them in good conditions for 5 or 6 days (ITT, 1978). However, before refrigeration, select and wash roots. Scrub the roots with a soft bristle brush to eliminate earth and mud; then apply a disinfectant.

The sale of frozen, peeled cassava chips or sticks has increased in recent years. Some companies precook them before freezing to reduce the preparation time for the final buyer. The production of fresh cassava chips or sticks for freeze-conservation involves several stages (Figure 25-23). For complementary information, consult the guide distributed by CONGELAGRO, a Colombian company specializing in frozen foods, to its dealers (CONGELAGRO, 2000).

Harvest and selection

When a company markets fresh cassava for the production of frozen chips or sticks, it must first select the roots for paraffin treatment. Those that do not classify because of their lower quality are distributed to the local food markets or plazas as well as to the frozen chip market. Time of harvest is determined depending on cooking quality of roots.

Reception of raw material

Upon reception of raw material, a first quality control check is performed to verify variety, size range, organoleptic quality, and degree of healthiness (absence of deterioration, physical damage, fungi, viruses, and bacteria).

Organoleptic quality is assessed by cooking a sample of each material. Cooking time of 1 kg roots should take no longer than 20 min. In addition, the pulp should have a soft texture, good flavor, and preferably white in color. If not, then the quality of the raw material should be reevaluated.

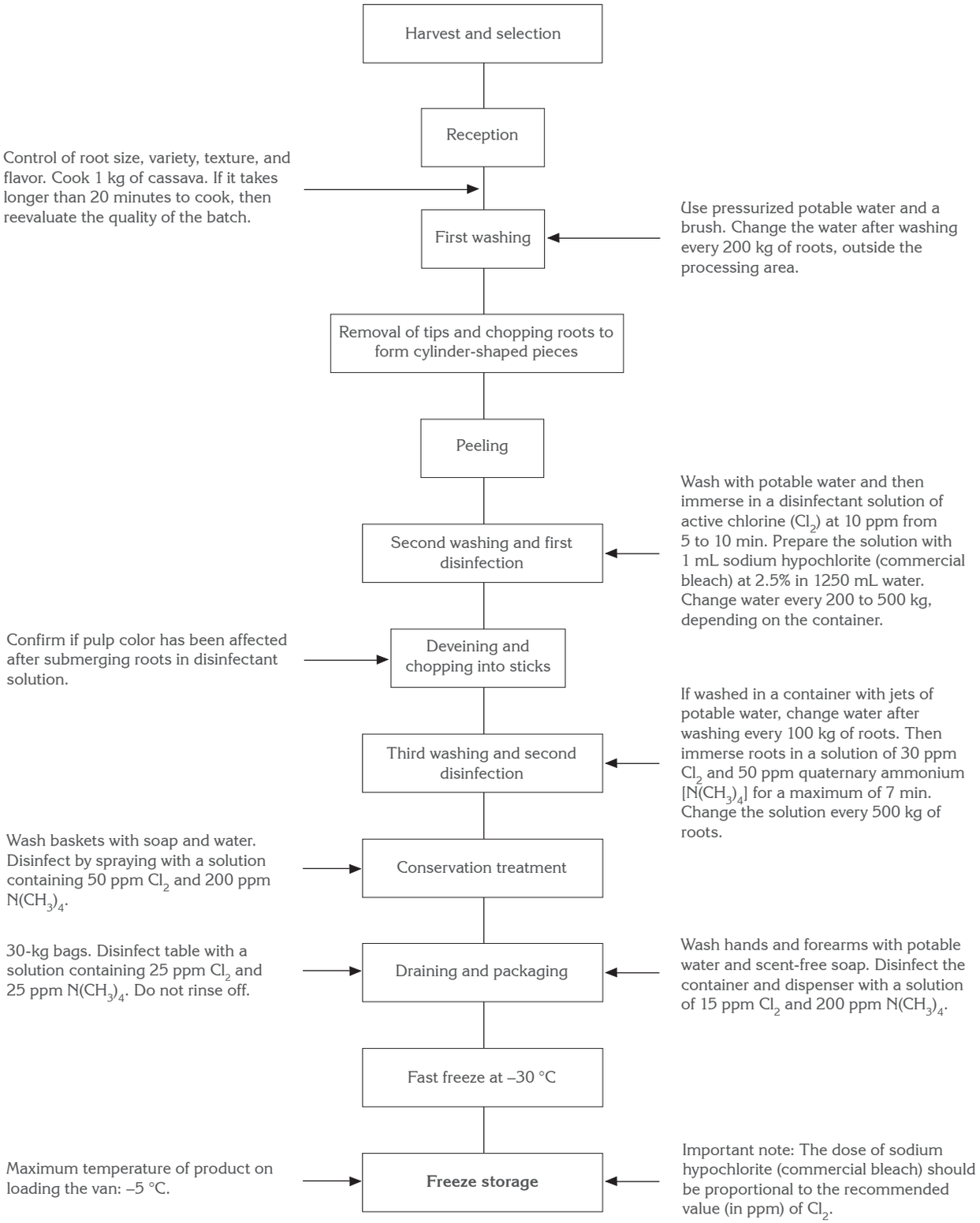


Figure 25-23. Stages of the production process of frozen fresh cassava sticks or chips.

Total cyanide (CN^-) content of pulp should be less than 60 ppm, usually, moist base . This parameter could vary depending on the variety. The cassava should not have a bitter taste, neither in the initial taste test upon reception of raw material nor in second taste test of end product.

Calibration and washing

Separate fresh roots according to length and diameter (commonly between 4 and 8 cm). Pressure-wash roots with potable water and, if necessary, use a brush to remove difficult earth or mud. If washing is performed outside the paraffin treatment facility, then change the water for each batch of 200 kg of roots when these are washed in 55-gallon containers.

Blunting, chopping, and peeling. Remove extremes (stump and tip) of roots and cut into cylinder-shaped pieces, 5 to 6 cm long (Figure 25-24). Then remove the cortex or thick peel from each cylinder (Figure 25-25).

Second washing and first disinfection. Wash cylinders with potable water for the second time and then submerge in a disinfectant solution of 10 ppm active chlorine (Cl_2) during 5 to 10 min. Prepare the solution with 1 mL sodium hypochlorite (commercial product, at 2.5%) in 1200 mL water. During disinfection, permanently check the root pulp for the appearance of brownish-gray spots. Change the water used for washing as well as the disinfectant solution after each batch of 200 or 500 kg of cylinders, depending on the size of the container used for this operation.

Figure 25-24. Removal of tips and chopping roots into cylinders.

Figure 25-25. Peeling the cylinder-shaped cassava roots.

Elimination of fiber and formation of cassava sticks. Cut cylinders lengthwise to obtain four uniformly sized pieces that meet production company requirements. Carefully remove fibrous tissue or central vein from each piece (Figure 25-26).

Third washing and second disinfection. Wash sticks with potable water. If a container is used, then change water after each batch of 100 kg of sticks. Subsequently submerge sticks in a solution of 30 ppm active chlorine (Cl_2) and 50 ppm quaternary ammonium [$N(CH_3)_4$] for a maximum of 7 min. Change the solution after each batch of 500 kg of sticks.

Conservation treatment. To avoid subsequent contamination of cassava sticks and thus guarantee their quality to the end-consumer, submerge sticks in an aqueous solution containing preservatives such as Sorbate (200 ppm) and potassium erythorbate (25 g/100 kg of cassava) for 20 min.

Figure 25-26. Deveining of roots by cutting cylinder-shaped pieces into four.

Draining and packaging

Drain the sticks (or cylinders) and package in low-density polyethylene bags of predetermined capacity. Make sure the area used for packaging is completely clean and disinfected to avoid recontamination of the end product.

- First wash the plastic baskets used to transport the product with soap and water and then disinfect by spraying them with a solution of 50 ppm Cl_2 and 200 ppm $N(CH_3)_4$.
- Make sure all workers wash their hands and forearms with scent-free soap and potable water and then rinse with a solution of 15 ppm Cl_2 and 200 ppm $N(CH_3)_4$ to avoid possible contamination of the product during this delicate stage of the process.
- Disinfect tables where operations are carried out on with a solution of 25 ppm Cl_2 and 25 ppm $N(CH_3)_4$. There is no need to rinse off the surfaces.
- Keep all cleaning solutions in containers with dispensers.

Fast freezing

Packaged cassava sticks freeze quickly at –30 °C. Sometimes sticks (or chips) are first placed in ample containers and, once frozen, packaged and stored.

Storage

Store packaged cassava sticks in cold rooms at –18 °C (Figure 25-27). After each operation, clean the work area and all equipment and tools (baskets, walls, trash cans, and other work elements) very well.

Quality control

Microbiological quality. The parameters established by CONGELAGRO, 2000, for suppliers of raw material (cassava roots) regarding the final microbiological status of the processed product (sticks) are as follows:

Aerobic mesophyl count:	<100,000 colony forming units (cfu)/g
Total coliform count:	<500 cfu/g
Fecal *Escherichia coli*:	<10 cfu/g
Fungi and yeasts:	<3,000 cfu/g
Psychrophils:	<1,000 cfu/g

Figure 25-27. Cassava sticks packed and stored at freezing temperature.

Each company purchasing or processing frozen cassava sticks establishes their own thresholds for these microorganisms, depending on their own standards of quality and the conditions in which the product is handled.

Organoleptic quality. The organoleptic quality of cassava sticks is evaluated based on the following parameters:

- *Taste.* After harvest, cassava should not have a bitter or unusual taste.
- *Texture.* At time of purchase, the stick or chip should be frozen and rigid; at time of consumption, it should be fiber-free, with a soft, not hard, farinaceous consistency. Hard, peeled cassava is rejected by consumers.
- *Cooking time.* It should not take longer than 20 minutes to cook cassava using a traditional pot.

Conclusions

The conservation and treatment methods or practices described herein, such as applying paraffin to cassava roots and preparing frozen cassava chips, have been successfully used by CIAT and others and are gaining importance in both national and export markets, mainly to USA and Europe.

Central American countries such as Costa Rica, which traditionally have not been cassava-growing countries, now export significant amounts of paraffin-treated cassava and frozen chips to the USA and European markets. If the markets for these products continue to grow, Colombia could become a major supplier.

References

Booth RH. 1977. Storage of fresh cassava (*Manihot esculenta* Crantz); II: simple storage techniques. Exp Agric 13(2):119–128.

CIAT (Centro Internacional de Agricultura Tropical). 1976. Almacenamiento de raíces de yuca. In: CIAT. Causas de deterioro que se presentan después de la cosecha de raíces frescas. Cali, Colombia. p 27–28.

CIAT (Centro Internacional de Agricultura Tropical). 1987. Almacenamiento de raíces frescas de yuca—Guía de estudio para ser usada como complemento de la unidad audiotutorial del mismo tema. Scientific contents: C Wheatley. Cali, Colombia. 34 p.

CIAT (Centro Internacional de Agricultura Tropical). 1991. Conservación de raíces de yuca en bolsas de polietileno—Guía de estudio para ser usada como complemento de la unidad audiotutorial del mismo tema. Scientific contents: C Wheatley. Cali, Colombia. 34 p.

CONGELAGRO S.A. (Compañía Congeladora de Productos Agrícolas). 2000. Descripción del procesamiento de yuca en los centros de acopio: Proveedores, norma y materia prima. Línea de croquetas de yuca. Manual. Bogotá D.C., Colombia. 4 p.

IIT (Instituto de Investigaciones Tecnológicas). 1972. La yuca parafinada. Tecnología 14(78):47–51.

IIT (Instituto de Investigaciones Tecnológicas). 1973. Proceso de parafinar yuca: Ventajas y economía. Bogotá, Colombia. Tecnología 14(86):33–51.

IIT (Instituto de Investigaciones Tecnológicas). 1978. Preservación del método de parafinado. Tecnología 15(36):1–15.

SENA (Servicio Nacional de Aprendizaje). 2001. La yuca: Producción, cosecha y poscosecha en la cadena agroindustrial. Programa Nacional de Capacitación en Manejo de Poscosecha de Frutas y Hortalizas. Centro Agroindustrial Vereda San Juan, Armenia, Colombia. 36 p.

CHAPTER 26

Sour Cassava Starch in Colombia*

Freddy Alarcón M.[1] *and Dominique Dufour*[2]

Introduction

Sour cassava starch is a fermented product used in the food industry. It was initially produced by rural families for domestic use, and they employed homemade, manual tools for its extraction. It has been used as an ingredient in different foods, especially those of regional or traditional origin where the breadmaking potential of cassava starch is needed.

As an agroindustrial activity in Colombia, cassava starch extraction began in the 1950's. The demand for the starch increased over the following years, and its extraction became a completely handmade agro-industry. From then on, mechanical innovations for certain processing steps were introduced, thereby boosting the production capacity of these small factories that began to call themselves "rallanderías" or "ralladeros"; in this text, they will be referred to as cassava starch extraction plants or simply extraction plants. This activity had a positive impact on the socio-economic level of poor smallholders living in the northern zone of the Colombian department of Cauca (CECORA 1988; Gottret et al. 1997a; Gottret and Ospina 2004).

More than 200 of these extraction plants involved in producing cassava starch for bakery goods (such as *pandebono*, *pandeyuca*, etc.) have been set up in Colombia, and they are harnessing that product's special breadmaking properties.

Sour cassava processing principles are applied across all extraction plants, although the technology used varies significantly. For example, some of them process everything completely by hand, others have implemented mechanization yet they are still very traditional, and then there are those with very high technological processes but remain at a small-scale industrial level (Zakhia et al. 1996).

Furthermore, there are plants that are large-scale producers of native or natural (unfermented) cassava starch in the departments of Atlántico and Sucre (Alarcón 1993a, 1993b); this process uses a higher degree of technology. Native starch (also known as sweet cassava starch) is used in different industrial sectors (mainly glue and paper manufacturing), the textile industry (warp sizing), and prepared food industry as well as in oil well drilling and dynamite manufacturing.

In 1989, the French Agricultural Research Centre for International Development (CIRAD)[3] and the Centro Internacional de Agricultura Tropical (CIAT) launched the Cassava Development Project in Latin America, which aimed to improve traditional technology used in small-scale cassava starch processing by developing technologies that would increase starch extraction profitability and product quality and could be transferred to rural producers (Chuzel and Muchnik, 1993; Alarcon, 1996).

Most of the project activities, including an important survey of producers in 1995, were undertaken in the department of Cauca, where cassava starch extraction plants are found on both sides of the Pan-American Highway along the section between

* Taken from the work of the same name, written by Freddy Alarcón M. and Dominique Dufour. 1998.

1. Plant Products Chemist, formerly of CIAT. Currently Director, Starch Technology, Inc., USA. E-mail: falarcon@starchtechnology.org
2. Food Science Specialist, CIRAD-UMR QUALISUD, Montpellier, France; CIAT, Cali, Colombia. E-mails: dominique.dufour@cirad.fr and d.dufour@cgiar.org

3. For an explanation of this and other acronyms and abbreviations, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Pasto-Popayán-Cali. These plants are basically dedicated to producing sour cassava starch. Only a few produce natural starch.

This collaborative project aimed to technologically improve cassava processing for obtaining the natural and sour starch from this root. Its results can be applied to most of the Latin American, Asian, and African cassava-growing regions that have an adequate water supply. CIAT and CIRAD objective is to spread these technological innovations among tropical smallholder farmers, whereby they can take advantage of an agricultural product that so far has served them only as a means of subsistence in order to improve their socio-economic level.

Since 1991, these two institutions have transferred sour cassava extraction technology (herein described) to different Colombian regions. In 1993 and 1994, this transfer work was continued in Ecuador. In 1997 and 1998 introduced the technology for improved sour starch processing to some cassava-producing regions of Nicaragua, and it is currently conducting a feasibility study for transferring it to other Latin American countries and other continents.

Cassava cultivation

Cassava (*Manihot esculenta* Crantz) is a starchy root crop grown in the tropics and subtropics. Although it is one of the most important food crops in tropical countries, it is not well known elsewhere.

It originated in tropical America. Even before the turn of the 17th century, Portuguese explorers were taking it with them to Africa and Asia. It is now cultivated in 92 countries, where it feeds more than 500 million people.

Plant and cultivation

At the present, there are more than 6500 cassava varieties, each one with its own peculiar characteristics.

Its flowers (male and female) are small and cross-pollination is a frequent occurrence. Its fruits are dehiscent, and seeds are small and oval-shaped. The root is conical, with an external and an internal bark (white or pink in color). The mature stalks are cut into 7–30 cm stakes or cuttings, which are subsequently used for propagation purposes.

Under experimental conditions and in a monocrop system, cassava yields up to 90 t of roots/ha (25–30 t dry matter/ha); however, average global yield in actual conditions (marginal soil, severe climate, and association with other crops) is 9.8 t/ha (12.4 t/ha in Latin America). One ton (1000 kg) of fresh cassava yields 280 kg of flour, 230 kg of starch, 350 kg of dry chunks, or 170 L of alcohol (CIAT 1996).

While cassava is a hardy plant, it is susceptible to three significant diseases: bacterial blight (on leaves and stems), root rot, and the African mosaic virus (just in Africa). Several sap-sucking insects (green aphid, mealybug, whitefly) and some phytophagous pests (hornworms) attack the leaves. The roots are sometimes damaged by burrower bugs.

Cassava can withstand drought (without affecting production) because it possesses three particular characteristics: (1) stomata close when air is dry, (2) roots extract water from deep soils (up to 2.5 m), and (3) its photosynthesis system captures atmospheric carbon even when it has limited water (under prolonged hydric stress).

This crop survives in low-phosphorus soil because it creates associations with fungi (mycorrhizae) that provide this element. It also grows in acid soils (with aluminum). Cassava does not tolerate waterlogging. Roots can be harvested 7 months after planting and can remain in the ground for up to 3 years. Once they are harvested, they deteriorate within 3 to 4 days. As a result, they must be consumed or processed without delay.

Cassava should not be simply regarded as a crop for human consumption since a considerable amount of production is processed and sold as starch and other derived products. Although the virtues of this crop are beginning to spread out, it is often feared that its expansion can damage soil fertility and cause erosion, particularly those seen as marginal agricultural lands.

In fact, cassava extracts an amount of nutrients that is similar to the level extracted by other plants. Moreover, under proper agronomic management, its production is sustainable. Furthermore, cassava has the ability to grow in depleted soils, an extraordinary advantage that, when coupled with its huge production potential, presages this crop will have an important future as a basic energy source for marginal regions of the tropics (Cock 1989).

Despite it prefers hot and humid climates, cassava adapts to a large range of climatic conditions. It grows very well between latitudes 30° N and 30° S.

Root analysis

Cassava roots (Figure 26-1) are composed of three tissues: periderm (bark), cortical parenchyma (peel), and parenchyma (Figure 26-2).

- Approximately 80% of the fresh root weight comes from the **parenchyma** or pulp, the tissue in which the plant stores the starch.
- Root dry matter content fluctuates between 30% and 40%.
- Parenchyma dry matter is primarily (90%–95%) composed of the non-nitrogenous portion, i.e. by carbohydrates (starches and sugars).
- The remainder of the dry matter is fiber (1%–2%), fats (0.5%–1.0%), ash or minerals (1.5%–2.5%), and protein (2.0%).
- Starch represents the largest portion of the carbohydrates (96%) and is, hence, the main component of the root dry matter.

Figure 26-1. Harvested cassava roots. See how the bark is partially peeled.

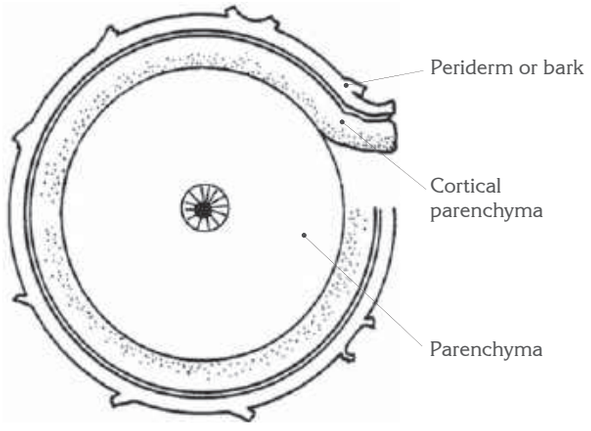


Figure 26-2. Cassava root transverse section.

Cultivated varieties with industrial uses should have high starch content (Wheatley 1991; Sánchez et al. 2009).

Cyanogenic compounds. Cassava contains a **cyanogenic glycoside** called linamarin that hydrolyzes and releases doses of cyanhydric acid (HCN) that range from innocuous to toxic and lethal when in the presence of enzymes (mainly linamarase) in an acid environment. This reaction normally occurs in decomposed plant tissues or in animal digestive tracts.

While botany and agronomy previously classified cassava varieties as "sweet" and "bitter" in relation to the amount of HCN they could generate, this classification is no longer used because there is no stability in the "content" of acid or its originator, linamarin, in either category. "Sweet" varieties generally produce below than 60 mg of acid per kilogram of fresh root (a rather small amount), while the "bitter" can generate more than 1000 mg/kg. To date, science has not discovered a non-cyanogenic variety. Environmental conditions may affect cassava's "content" of cyanogenic compounds such that a "sweet" cultivar grown in one region may become "bitter" in another region.

The root bark contains higher concentrations of cyanogenic compounds, and these are likewise found in leaves and other plant organs, although in lesser quantities. Conventional cooking methods are effective in reducing cyanogenic contents of cassava to harmless levels. However, when roots from a "bitter" variety are consumed, without proper previous cooking and when diets lack protein and iodine (conditions that are generated during war and famine), then people may suffer from cyanide poisoning, a situation that would seriously affect their health.

Processing the roots of a "bitter" variety is quite demanding. However, there are two reasons why some farmers prefer to plant them: (1) the cyanogenic compounds seemingly help to protect the plants from pests (current and potential) and (2) food products made with their starch have better texture.

When high cyanogenic content cassava varieties are processed, the final product (starch) does not contain any residual acid whatsoever, and the reason for that is HCN dissolves completely in the large volume of water required for processing and is thus removed from the starch.

Varieties

Each cassava variety behaves differently, and the optimal harvesting time is different for all of them. While these characteristics depend upon two conditions inherent to the place where they are grown, namely climate and altitude, they also depend upon the variety's genetic traits and management practices (Alarcón 1994a).

When cassava's optimal harvesting period is over, the water and fiber content increase, and the percentage of starch notably decreases. Therefore, in the process of obtaining the starch, a large amount of black starch called "mancha" in Colombia (scum skimmed off the surface of sedimented starch), a byproduct that contains poor quality starch, is produced.

- Pest- and disease-resistant cassava varieties that can adapt to different climatic and soil conditions have been developed. These are high-yield varieties that contain elevated concentrations of starch; many of them reach the harvesting stage in a short growing period (Domínguez [1983]).

- When inadequate growing practices are used, the variety's yield declines, diseases that attack the plant occur, and the soil loses its minerals and nutrients (Domínguez [1983]).

Production and yield

In the world. Cassava cultivation has been a major traditional activity for rural communities across many countries. It is one of the main components of the food diet of people living in developing nations, who also use it as animal feed, and when there is a surplus, it is sold in the market.

Global cassava production in 1999 yielded more than 169 million metric tons, of which 54.4% (92.5 million) was grown in Africa, 27.6% (47 million) in Asia, and the remaining 18% (29.3%) in Latin America and the Caribbean.

The main cassava-producing nations are Nigeria, Brazil, Zaire, Thailand, and Indonesia. Figure 26-3 shows fresh root production figures (FAO 1999). Annual per capita and per region consumption is higher in Africa (more than 90 kg), and Zaire is the country with the highest level of cassava consumption: 391 kg/person per year, or the equivalent of 1123 calories a day. Global consumption is around 18 kg/person per year.

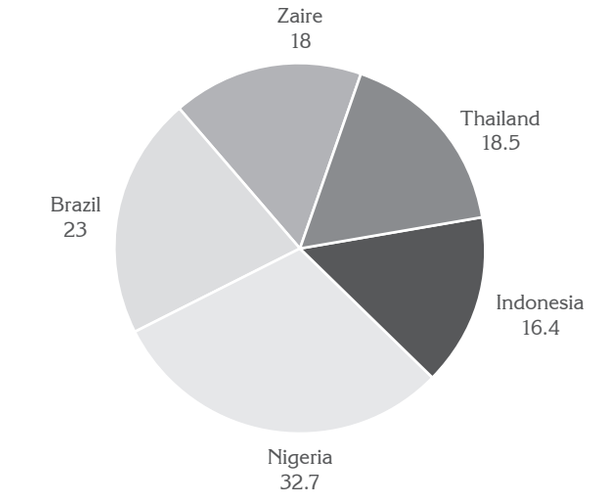


Figure 26-3. Cassava root production (millions of tons) in main producing countries worldwide (FAO 1999).

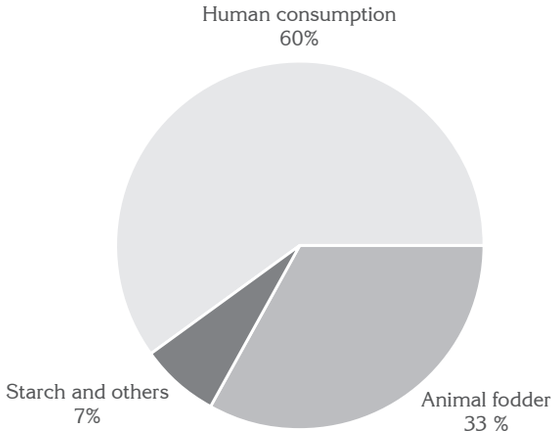


Figure 26-4. Distribution of cassava production allocated for local use (85%) in the world.
SOURCE: FAO 1999.

Close to 85% of global production (Figure 26-4) is used in the place where it is grown (*in situ*), and from that percentage, 60% is set aside for human consumption, nearly 33% for animal feed, and 7% for starch production and biotransformation (Jones, 1983).

The remaining 15% (around 30 million tons) is exported each year to Europe and Japan as **pellets** or starch, and 75% of the product is exported from Thailand, with the rest from Indonesia and China. The European Union annually uses 5 million tons of pellets to supplement animal fodder.

In Colombia. Cassava production in Colombia increased in 1999 to 2 million metric tons, making it

the 16th largest producer in the world (FAO 1999). Average yield is 9.93 t/ha. The primary producing region is the Atlantic Coast, yet a sizeable amount of this product is grown in the Eastern Plains (Llanos Orientales). The department of Cauca accounts for 4.6% of the total national production.

On account of the seasonal rains, most of the annual production takes place during certain times of the year. For the cassava agro-industry, this situation creates a raw material shortage in some months of the year and a surplus in others as well as the loss of fresh roots due to damage from extended storage, when the offer is high, and price fluctuations in raw material and starch.

In the department of Cauca. The department of Cauca (IGAC 1993) is the main producing region of sour cassava starch in Colombia since it processes nearly 80% of the entire national supply. In 1994, there were some 6450 ha of cassava fields in this department from which roughly 53,500 t of fresh roots were produced. This production accounted for 3.2% of the national total.

The average yield in this department, according to Ministry of Agriculture and Rural Development (MADR) of Colombia figures, is 8.3 t/ha. Local production is insufficient to meet the current demand by cassava starch extraction plants. When the department of Cauca experiences a shortage of cassava, it needs to be purchased from other regions of the country.

In order to fully use the installed capacity of the extraction plants, it is estimated that an area of 19,700 ha would have to be cultivated.

The CIAT Cassava Program tested, with good results, some varieties that had been improved in CIAT for Cauca conditions and requirements, in other words, for a determined time between planting and harvesting, high yield, and very high quality starch for breadmaking. Improved and tested varieties still recommended to farmers are the following:

- Catumare variety (CM 523-7). It is a good starch producer and is destined for fresh consumption and for the frozen food industry.

- MBRA 12 variety. It is a high-yield product, a good percentage of starch can be extracted from it, it produces high-quality starch for breadmaking, and it is not stolen from the fields since it is a bitter cassava.

Producers and processors. It is estimated that 97% of producers in Cauca use traditional farming practices for cassava cultivation, only 3% employ more technical methods, i.e., healthy cuttings are planted from improved varieties and farmers use a "package" of efficient agronomic practices, such as the ones recommended by the National Agricultural Research Program.

A 1995 survey found that there were 210 cassava starch extraction plants in the department of Cauca, and 51% of them were also cassava producers. Yet, the area that they cultivated represented just 8% of the department's entire cassava cultivation area (Gottret et al. 1997a).

Production and benefit. 3.6% of all departmental production is for direct human consumption or animal feed on farms. From the remaining 96.4%, which is the marketable share, agro-industry uses 90% to produce fermented (sour) starch and 10% is sold for direct human consumption in the department (Chacón and Mosquera 1992).

The entire regional agro-industrial sour starch production is estimated to be 10,700 t/year, a figure that represents 70%–80% of the country's entire production (Gottret 1996). Another 135 t/year of native starch is also produced for industrial use (Gottret et al. 1997b; Henry and Gottret 1998).

Cassava farming- and transformation-related activities in the northern sector of the department of Cauca occupy a major place in the regional economy. They are also the main source of income for almost 4000 rural families that manage the above-mentioned 210 sour cassava starch extraction plants.

Farmers located in areas near the plants supply them with cassava. During periods of raw material shortage, processors organize themselves and purchase cassava from Ecuador and the Colombian departments of Antioquia (the Urabá zone) and Quindío (Armenia). Roots, stored in trucks for the two or more days it takes to transport them, deteriorate and lose their quality.

Cassava Processing

After cellulose, starch is the most abundant carbohydrate in nature. It is one of the main energy reserves in plants and is found in sources as varied as cereals (corn, wheat, barley, and rice), potatoes, cassava (Figure 26-5), and many other crops.

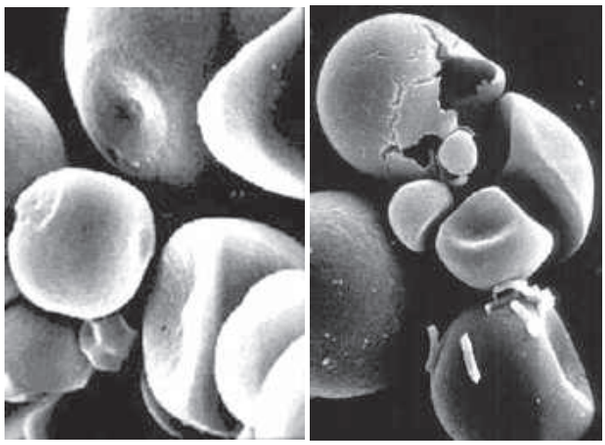


Figure 26-5. Natural or native starch granules under an electron microscope. It can be observed the erosive action of the amylolytic bacteria in fermented or sour starch granules (right).

Starch is the most important carbohydrate for human activity due to its role in nutrition and its multi-purpose character in industry and commerce.

As opposed to cereal starch, which requires very high-technology industrial processes to obtain, extracting starch from roots and tubers (potato, sweet potato, achira, and cassava) is very easy in rural settings since all that is needed is grating, sieving, separation with water, sedimentation, and drying.

The overall extraction process for cassava starch is illustrated in Figure 26-6. The washing, grating, and sieving operations have been mechanized, although processors in some regions still do those operations manually.

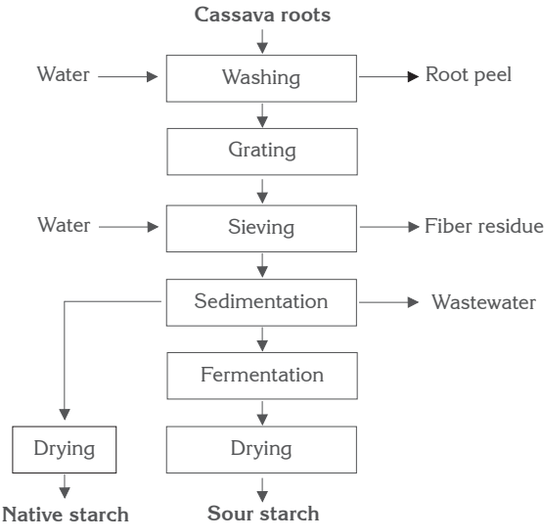


Figure 26-6. Overall flow of native and sour cassava starch extraction.

The extraction plants treat 1–10 t of cassava a day. The technology they used, described later on in this chapter, does not vary much from factory to factory and remains quite traditional. Some of these in the Colombian Andean region have been constructed according to the site topography (Figure 26-7) to harness energy derived from the gravity gradient.

Root washing

The purpose of this operation is to wash away the dirt and debris stuck to the cassava root bark and to remove the bark itself (external bark or periderm).

Washing methods.

Manual washing/peeling. This is done by hand, yet it is also done with the feet in some areas of the departments of Cauca (23 extraction factories) and Caldas (Figure 26-8). The bark detaches itself from the friction caused from one root rubbing against another during the washing. This operation uses a large number of rural family members and therefore is a source of income for communities.

Peeling. Roots are peeled manually (with knives) in these extraction plants. This means that the peel (cortical parenchyma) is cut away, leaving the pulp cleaned and bare.

Mechanical washing/peeling. Mechanical washing and peeling are done in a cylindrical drum. Cassava roots are washed as they rub against each other and the drum wall.

The wall is slatted (rectangular) so the waste products inside the drum are released through them. The water flow helps clean away the debris (dirt and the remains of the peels) and strip off the root peel.

Types of washers.

Side loading half-shaft cylindrical washer/peeler (Model 1). The drum is supported by a half-shaft coupled to a bearing housing on one of its ends. The half-shaft propels the drum. This system is installed on a tank where the water and debris are captured.

The drum (Figure 26-9) is made of a single sheet of galvanized steel and covered completely with oval-shaped openings through which water and debris are discharged.

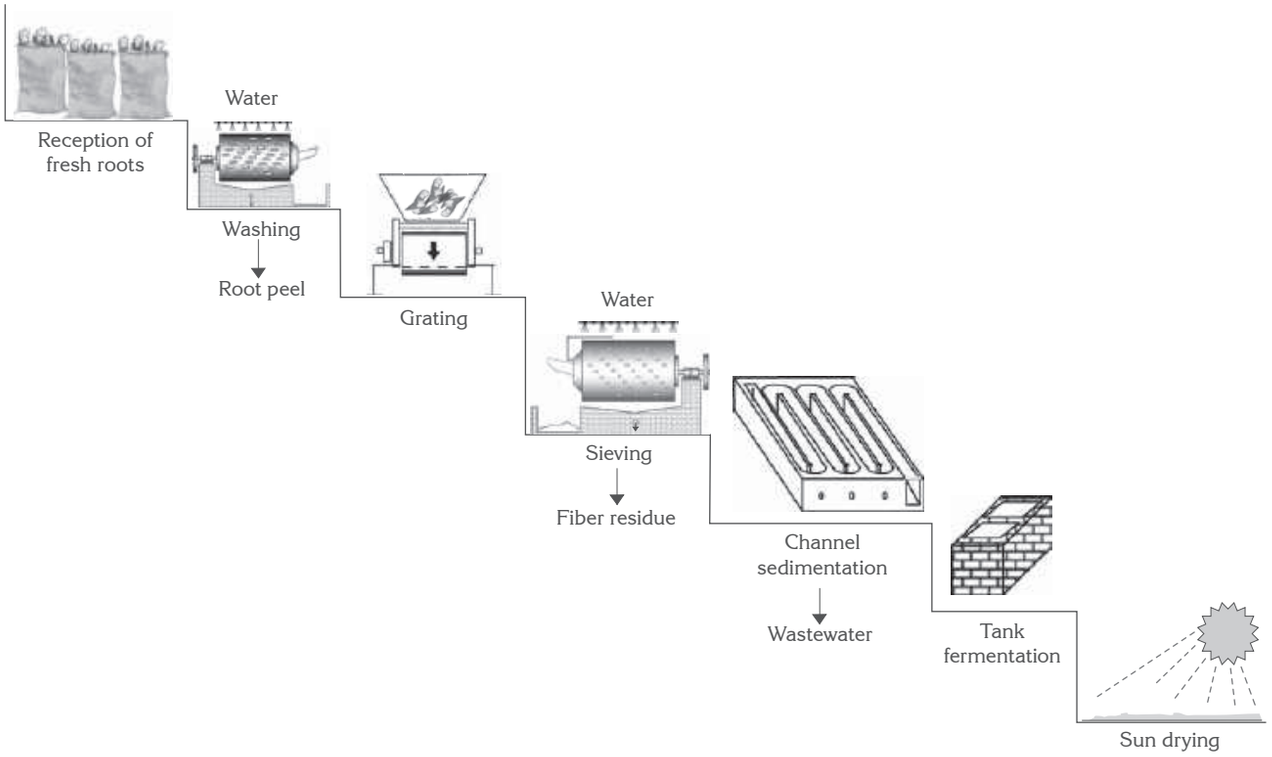


Figure 26-7. Schematic distribution of starch production operations in a cassava starch extraction plant that is designed for sloped terrain to harness gravity.

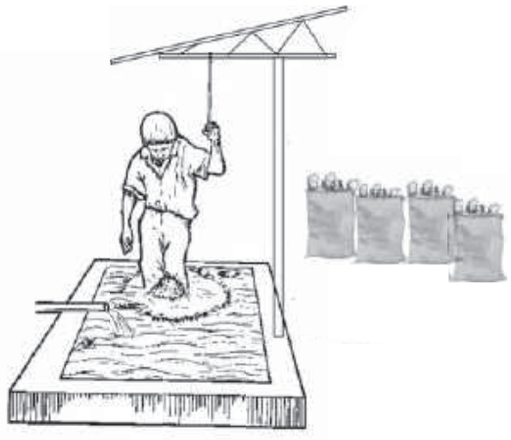
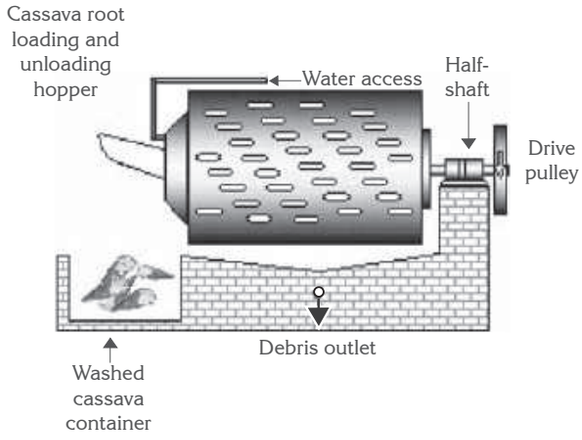


Figure 26-8. The roots are peeled by the feet during the washing operation in some cassava starch extraction plants. Friction causes the bark to come off.



Characteristics:

Capacity:	1000 kg of roots per hour
Water:	100 L/100 kg of roots
Rotational speed:	30 rpm

Figure 26-9. Side loading half-shaft cylindrical (drum) cassava root washer/peeler.

This washer is loaded and unloaded through a semi-circular opening in the center of one of the drum sides (or bases). There is a hopper (or similar apparatus) on that side for loading and unloading, which is very practically and easily done by hand and does not require the machine to be turned. Therefore, washing/peeling with this machine is quick and practically continuous.

A perforated pipe for supplying the water enters through the same side opening. The roots exit the washer/peeler and drop into a container underneath the hopper.

Front loading center shaft cylindrical washer/peeler (Model 2). This has a single drum driven by a center shaft that is supported on each end by a bearing housing (Figure 26-10a).

Drum walls are made of galvanized steel and contain oval- or rectangular-shaped openings. There is a hatch that runs along the length of the drum for loading and unloading purposes. A perforated pipe, fixed above and running parallel to the drum, sprays pressured water onto it.

These washers/peelers are difficult to load and unload as well as to start. It takes a considerable amount of time to wash and peel the different loads.

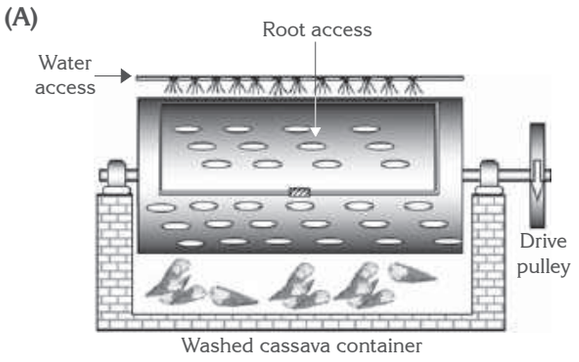
Semi-continuous cylindrical washer/peeler (Model 3). This has a single drum driven by a center shaft that spins on bearing housings.

Drum walls are made of galvanized steel and contain oval- or rectangular-shaped openings through which the water and debris are discharged. A hopper is attached to one end for loading the roots into the drum and an exit hatch is coupled to the other end.

To supply the water, a tube runs the entire length of the drum and enters it through special openings at either end in a suitable position so as not to hinder the drum's spinning (Figure 26-10b). In some of these models, the water is sprayed into the drum through a perforated center shaft.

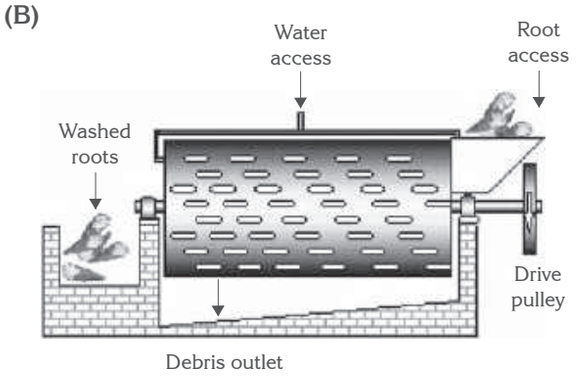
Washer/peeler capacity. Washer/peeler capacity depends on the type, whether a traditional (model 1 and 2) or semi-continuous (model 3).

- Traditional models have a capacity of 1000 kg/hr. Water consumption is less than 100 L for every 100 kg of roots. Each load takes approximately 10 minutes to complete.



Characteristics:

Capacity:	1000 kg of roots per hour
Water:	100 L/100 kg of roots
Rotational speed:	21 rpm



Characteristics:

Capacity:	1500 kg of roots per hour
Water:	130 L/100 kg of roots
Rotational speed:	30 rpm

Figure 26-10. **(A)** Front loading, **(B)** semi-continuous action center shaft cylindrical (drum) cassava root washer/peeler.

- The recently developed semi-continuous model 3 has greater capacity (1500 kg/hr) and reasonable water consumption (130 L/100 kg of roots). It is practical and easy to use. Each load takes approximately 5 minutes to complete. These can be attached to grating operations to provide more continuity and therefore streamline the process (CIAT 1995b).

Washing/peeling losses. Losses during the cassava root washing and peeling operation depend upon three factors: (1) the cassava variety, (2) the condition of the roots, and (3) the characteristics of the washer.

- Loss of raw material and, hence, of starch from the washer is mainly due to the length of the

washing process and the design of the drum holes. If these have a very large inner rim, they might tear the root tissue and thus shred it into tiny chips. Normal losses per washing load vary between 2% and 3% of the fresh root weight.

- Front loading center shaft-driving washers also lose water because a portion of it splashes out of the drum.

Grating the roots

Grating refers to the action of releasing the root starch through any method possible. The method's efficiency is called the grating effect (GE) and has been computed (Alarcón 1989) from this equation:

$$GE = \left\{1 - \frac{A_A \times F_R}{A_R \times F_A}\right\} \times 100$$

where:

A_A = starch recovered in the fiber residue (%)

F_R = raw fiber in the fresh roots (%)

A_R = starch in the fresh roots (%)

F_A = raw fiber in the fiber residue (%)

As the grating is performed, starch granules contained in the cells of the root are released (Figure 26-5). The efficiency of this operation determines in large part the total starch yield in the extraction process.

The grater. This is comprised of a wooden drum mounted on a steel shaft. The drum is covered on the outside with a sheet of galvanized steel that has been manually punctured along its entirety with a nail (or punch). Generally, there is one to two holes per each square centimeter.

The drum rotates between 1200 and 1300 rpm. The machine yields on average 1500 kg of roots every hour. When water is used, it consumes 90 L/100 kg of roots.

The grating operation. The rough, cutting surface of the drum, produced by the sharp edges of the numerous holes, establishes a cutting line (a rasp) with the inner side of a wooden plank that is placed in front of the drum. This grater produces a pile of grated cassava, the size of the individual pieces being fine or thick depending upon the space ("light") between the drum and the wooden plank (Figure 26-11).

Grating is usually done with dry roots. Only in special cases is it performed with water, for example, when the machinery can be installed on sloped terrain, thereby taking advantage of gravity so that the water used can easily flow to the next operation or to the waste water tank (where it is treated).

The percentage of starch extraction depends on the grater. If it does not sufficiently shred the root tissue to separate the starch granules from the fiber, then yield from the extraction process will be low, and plenty of starch in the fiber residue will be lost.

The grater cannot be too fine because very small starch granules would be damaged physically and afterward degrade enzymatically. Under these conditions, sedimentation would be slower (fine granules lose density), and greater quantities of black starch would form (CIAT 1995a; 1995b).

Appendix 1 (Photo 26A-2) shows a traditional grater used in cassava starch-extraction plants in the department of Cauca. The grating effect currently reached in this department is close to 80%, which means it is very efficient.

Sieving

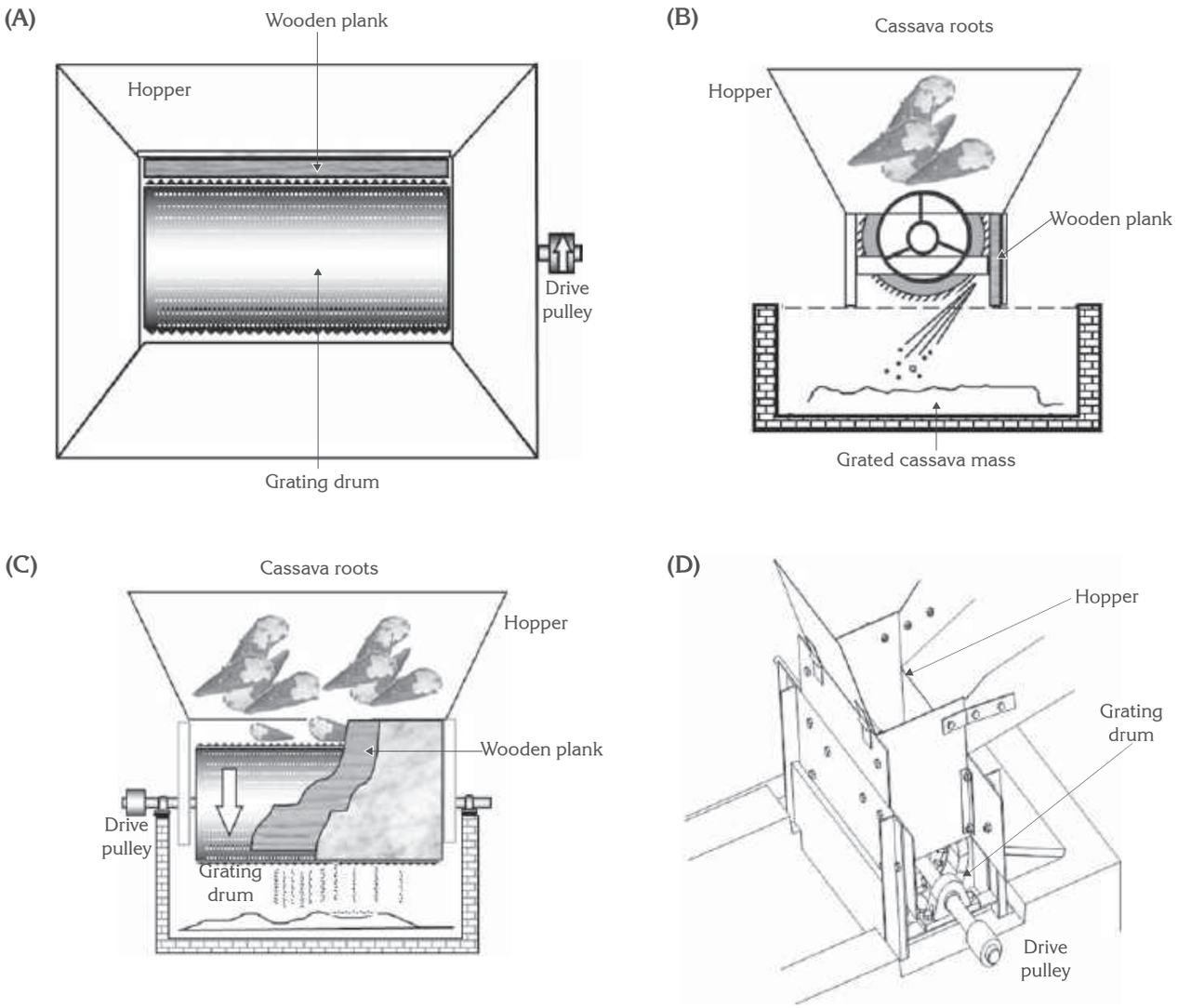
This operation can be done manually, with continuous mechanical sieves or with mechanical sieves that handle individual loads.

Manual method. There are 23 small cassava starch extraction plants in Cauca, in the northern section of Valle, and in Caldas that manually sieve grated cassava.

This is carried out using a piece of fabric attached to a wooden frame. The frame is then placed overtop a container or tank where the starch milk from the grated cassava that has been sieved is sedimented out (Figure 26-12).

Yield from the manual sieving process is equal to that of the mechanical sieves used in the Cauca department extraction plants. In fact, it depends upon the cassava variety, type of grater used, and the number of people, and their skill level, involved in the operation (CIAT 1995b).

Continuous mechanical method. In the department of Caldas, they use a wooden type of continuous sieve, with a worm gear, the lower part of which is supported by a piece of fabric equal in length to the gear (see Appendix 1, Photo 26A-3). The sieve is



Characteristics:

Capacity:	1500 kg of roots per hour
Water:	90 L/100 kg of roots
Rotational speed:	1200–1300 rpm

Figure 26-11. Traditional cassava root grater. There is a perforated sheet on the outside of the drum that, when spinning, grates the cassava against the flat wooden plank. **(A)** Upper view. **(B)** Side view. **(C)** Front view. **(D)** Blueprint.

located below the grater to help with the flow of the grated cassava mass.

The worm screw, 3.5–5 m long, extracts the starch very easily and facilitates fiber residue expulsion and compression, hence speeding up the time it takes to dry this byproduct at a later date.

Capacity of a sieve of this type is between 200 and 250 kg of cassava per hour. They are currently being used in Riosucio, department of Caldas.

Intermittent mechanical method. This mechanical sieve is made up of a drum connected to a half-shaft that is supported by a bearing housing. It rotates at 20 to 22 rpm and is loaded and unloaded at one end through a hopper (Figure 26-13).

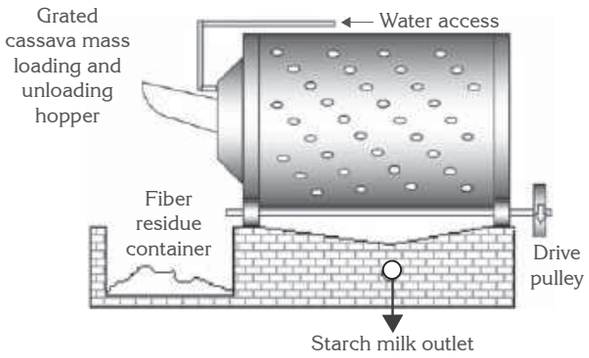
Inside the drum are blades that mix the grated cassava mass with water. The interior sheet is covered with an 80-mesh fabric or nylon sieve in which the grated cassava aqueous mass is strained. This sieve lets starch milk pass and retains the fiber.

Figure 26-12. Manual sieving of the grated cassava mass, as performed in the department of Cauca.

Normal capacity of this mechanical sieve is 250–300 kg of wet grated cassava mass per hour.

Starch quality, in terms of fiber and debris content, depends on the sieve. Using 120-mesh or finer sieves will produce better quality starch.

Another model of this type uses four rollers. The transmission (drive pulley and shaft) spins on two rollers which turn the drum that is also supported by the other two rollers (Figure 26-14). The drum spins counter clockwise to the spin of the bearings. Except for this, this model is the same or very similar to the above-described model.



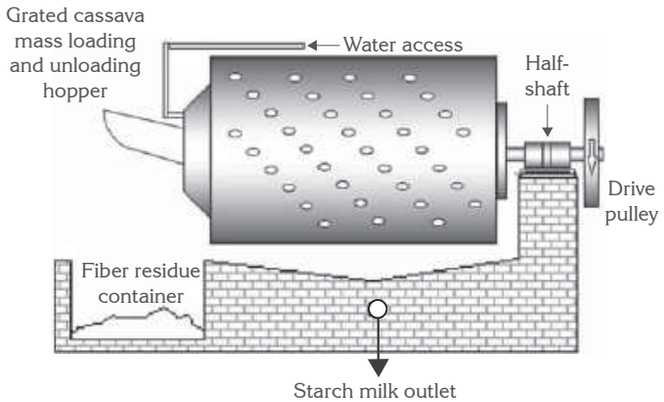
Characteristics:

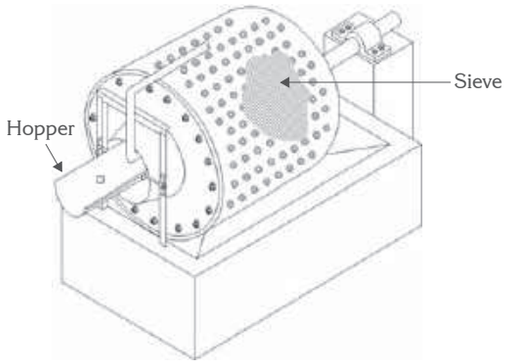
Capacity:	250–300 kg of grated cassava mass per hour
Water:	500 L/100 kg of grated cassava mass
Rotational speed:	20 rpm
Sieve:	100 mesh

Figure 26-14. Mechanical drum sieve supported on four bearing housings.

Sieving characteristics. Sieving is the slowest operation in the starch extraction process and is therefore its main constraint.

Fiber residue (byproduct). The byproduct generated by the sieving process is called fiber residue. After it has dried in the sun, it is used as feed supplements or as direct animal feed (Buitrago, 1990). A chemical analysis of this material indicates that dry fiber residue has a dry matter content of 80% to 85%, of which 60%–70% is





Characteristics:

Capacity:	250–300 kg of grated cassava mass per hour
Water:	500 L/100 kg of grated cassava mass
Rotational speed:	20 rpm
Sieve:	100 mesh

Figure 26-13. Intermittent, half-shaft cylindrical mechanical siever for grated cassava mass.

starch and 12%–14% is fiber. For instance, these figures are related to those obtained in the mass balance from Figure 26-21 for 1000 kg of fresh cassava roots. Thus, in the box titled "Fiber residue", there is a starch content of 56.0 kg, which falls within the above-mentioned percentage:

56.0/90.1 kg x 100 = 62.2%

Fiber residue production in the department of Cauca is figured to be 4500 t/year. This information was obtained by Gottret (1996) and through the cited survey.

Second sieving. In many cassava starch extraction plants, the starch milk is passed through small sieves after the main sieving process. The back and forth motion of these devices captures the fine fibers that might have been left over from the main sieving.

Starch sedimentation

Once the starch milk has passed through the sieve, it contains starch, fine fiber, and proteins in suspension. It is then directed into tanks or channels where the starch is sedimented out. It is from this starch milk, either flowing in channels or stagnating in tanks, that the densest component, the starch, whose different sized granules accumulate on the bottom, is separated.

In a channel system, this process can last up to 3 hours, yet in sedimentation tanks, it takes 6 to 8 hours. When this step is completed, there is a layer of compacted starch on the bottom (of the channel or tank). The supernatant water is discarded (read farther ahead).

Sedimentation tanks. There are 106 cassava starch extraction plants in the department of Cauca that use sedimentation tanks, which are made of brick and covered with tiles. The volume of water that passes through them per ton of fresh roots is 4.8 m^3.

This amount of water, 5 m^3 (500 L/100 kg of cassava), is also used to screen and sediment out 1000 kg of fresh roots (Figure 26-18).

The tanks are a rather large constraint to the process given the labor they require. Extraction plants do not actually have the proper number of tanks to handle their grated cassava production capacity. Moreover, the wait time for starch sedimentation on the bottom of the tank is 8 hours.

Tanks have two other disadvantages. First, they allow the starch to mix with the black starch and second they lose up to 2% of the sedimented starch when it is separated from that byproduct (a process called "desmanchar" in Spanish). In order to separate the two substances, the top layer of the sedimented starch must be cleaned using water and long handled squeegee (Appendix 1, Photo 26A-4).

Sedimentation channels. There are 100 cassava starch extraction plants in the department of Cauca that use sedimentation channel systems. These are covered with tiles or similar materials so the starch milk can flow. Channel length varies from 100 to 200 m, and it should be absolutely level to the floor. While the starch gradually settles, it forms a slight slope that helps the remaining starch milk to flow.

The recommended number of channels in a system is seven, each one measuring 25 to 30 m in length (Figure 26-15). These systems can be designed so as to adapt to the land topography (Appendix 1, page 516).

There should also be a grit chamber at the front of the channels where sand and other solids in the starch milk can accumulate.

The tiles make it so the starch milk flows evenly and without interruption, which will keep the black starch, sand (when there is no grit chamber), and other debris (fiber) in the starch from settling. If there are relatively large spaces between tiles, this will cause these starch contaminants to sediment.

When the sedimentation process has ended, there will be three layers in the channels and two different types of starch:

- The lower layer is the **starch**.
- The middle layer, called black starch, is a mixture of starch with proteins. Its thickness will vary.
- The top layer is the supernatant water or **wastewater**.

Wastewater. Wastewater is eliminated in the following manner:

- For **tank** elimination, pull out the plug from the drain pipe located near the base of the tank, a little higher than the level where the sedimented

Figure 26-15. System of 7 channels for starch sedimentation of starch milk.

starch layer usually ends (as the water flows out, it will carry away a little of the starch with it). If the plug is on the inside, it will have a string attached to help pull it out.

- For **channel** elimination, removing, one by one (from top to bottom), the four or five thin planks or hatches at the end of the last channel. As the level of starch milk rises during the sedimentation process, these planks, each measuring 60 x 8–10 cm (channel height is 40 cm), are placed one on top of the other.

With the removal of one large plank (60 cm x 40 cm) after the sedimentation process has been completed, the wastewater will exit the channel system, carrying with it a large part of the black starch and a decent percentage of the starch. Total wastewater volume of a channel system is around 50,000 L.

The channel system has the following advantages:

- Sedimentation in channels does not stop the benefit process, i.e. when the starch milk completes its flow through the system, the sedimentation is deemed complete and the next stage begins.
- To settle on the bottom, one starch grain must move 0.80 m in a tank and just 0.10 m in a channel. This difference explains, in large part, the above-mentioned advantage, specifically the speed of sedimentation.

When sedimentation is done in tanks, 2% of the starch is lost during the black starch separation stage. When sedimentation is done in channels, almost all the black starch exits with the wastewater such that very little of it accumulates as sediment on the layer of starch. During the black starch separation stage in the channel using the squeegee, there is no 2% loss of starch as there is in the tanks.

Black starch (byproduct). It is a byproduct of the starch production process, and it is obtained in this stage. The starch it contains is of low density, poor quality, and high protein content. It is used as pig feed and in glues (Alarcón 1994b).

Black starch production estimates for the department of Cauca are 750 t/year, as reported by Gottret (1996) and based on the above-mentioned survey.

Wastewater is left to sediment again in a tank (to separate the remaining black starch) and is later routed to rivers and streams. It may also be recycled for use in the washing process if water is a constraint and conserving it is convenient. It should be treated before disposal or recycling (see Appendix 4).

The starch that has settled on the bottom of the tanks or channels is subsequently directed to two places:

- The drying area, where it becomes natural or native starch for industrial and feeding purposes.
- Fermentation tanks, where it becomes sour starch for breadmaking after 20 to 30 days.

Starch fermentation

Fermentation is a natural process produced by amylolytic lactobacillus in anaerobic conditions (without oxygen in the environment). Cassava, a highly perishable agricultural product, it can be used best when conserved as fermented starch. This substance acquires special flavor, texture, odor, and leavening characteristics when baked that are desirable qualities for breadmaking and that cannot be found in native or unfermented starch (Figueroa 1991).

Sour starch is used in baking such breads as *pandebono*, *pandeyuca*, snacks, and others that have recently appeared in the markets and that are much sought after by populations living in different regions of the country (Pinto 1977).

Fermentation process. Sedimented starch is placed in fermentation tanks, and a thin layer of water is poured on top. There it is left for 20 to 30 days, a period that will vary depending on the region's climatic conditions. The tanks vary in size, according to the extraction plant's capacity (Figure 26-16), and are generally covered with wood on the inside.

Small tanks should be used for two reasons: (1) they are easy to fill and (2) they simplify the daily drying operation.

The necessary inoculant for fermentation can be the water that has been used in the fermentation process for several days or a piece of already fermented starch or even some dampened residual fiber spread over the top layer of starch in the tank.

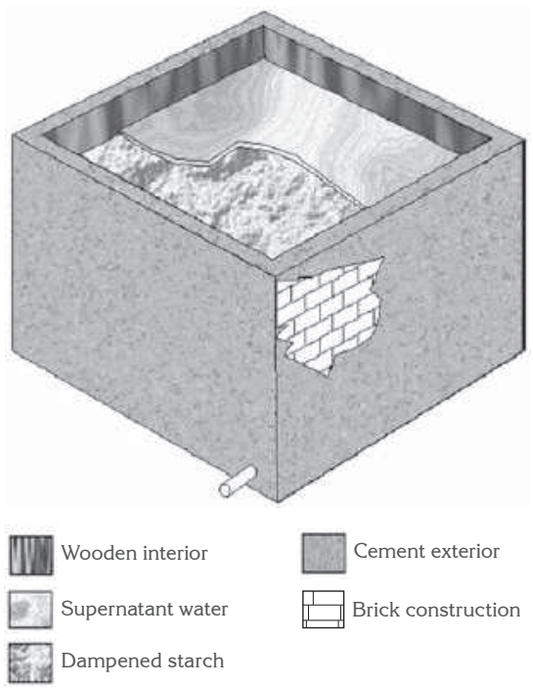


Figure 26-16. Sour cassava starch fermentation tank.

The supernatant water (3–4 cm higher than the starch) is left in the tanks to maintain the anaerobic state. Filled tanks are protected from the sun by damp residual fiber or wet polypropylene bags, thereby preventing the water from evaporating (see Appendix 1, Photo 26A-5). In very hot zones, the fermentation tanks should be buried.

Fermentation time is variable and depends on the ambient temperature.

One method of checking the fermentation is through its pH level, but this type of control is not practiced in the cassava starch extraction plants. The pH at the end of the process will be between 3.5 and 4.0.

Starch drying

Starch needs to be dried before it can be used. Native starch can be sun-dried or oven-dried, but sour starch can only be sun-dried. After fermentation, the starch is removed from the tanks or channels in compacted blocks and then transported to the drying patios where it is exposed to sunlight.

The blocks are milled to help the drying process, this being done by hand or with a drum grater that is covered on the inside with screws or nails and that "pulverizes" the starch blocks before drying.

It is then spread out in 1- 2 kg/m^2 layers on black polyethylene bags since they absorb large amounts of sunlight and thus contribute to rapid and uniform drying. In these conditions, 1 t of starch will need approximately 1000 m^2 of drying space. That area is, consequently, another constraint that clearly affects several of the cassava starch extraction plants considering they are located in regions whose topography is very rugged.

Starch can be dried on trays or sliding trays (Figure 26-17) built into the factories' roofs or above their floors (see Appendix 1, Photo 26A-6).

Starch drying requires roughly 6 hours in the sun in Colombia. The product is removed very gently 2 to 3 times during that period with rakes made from a pliable material so as not to damage the plastic. During the operation, winds will carry off starch dust, which leads to losses (0.7% in dry base) that are extremely difficult to avoid.

Final treatment of the starch

When the moisture content of the starch is between 12% and 14%, it is collected from the drying area. While it dries, the starch again forms relatively hardened lumps that must be milled and sieved.

The lumps are milled using the drum graters described above in the drying process. Sieving, on the other hand, is done with a mesh (100–120 mesh), whose caliber will depend on the desired results.

After being sieved, the starch is loaded in woven polypropylene sacks.

Figure 26-17. Sour cassava starch drying system in some of the extraction plants in the department of Cauca.

Yield

Figure 26-18 shows a flow chart summarizing the sour starch extraction process as it is carried out in La Agustina extraction plant located in the department of Cauca. The final quantity of starch in the flow chart is based on what 1000 kg of fresh MVen 25 cassava variety would produce. Another study was conducted recently to compare efficiency of Vietnamese and Colombian technologies for cassava starch production at low rural level (Da et al. 2012).

Quality

Breadmaking potential (BP) is the main criterion in sour starch quality. BP is defined as the capacity of the starch to leaven during baking. It is not possible to reach uniform quality with artisanal sour starch production, and this fact, consequently, hinders its access to market.

BP primarily depends on the variety of cassava and the fermentation and sun-drying processes of the starch. The choice of suitable varieties and proper management (and control) of both production processes would greatly improve sour starch quality (Dufour et al. 1996).

Studies have been conducted on the relationship between **fermentation inoculant microflora** and starch quality. Some starch producers use, as the inoculant in their fermentation tanks, water from a different tank in which high quality starch was produced. Also compared were results from sun-drying and oven-drying at different temperatures and under UV light (Brabet et al. 1996).

Sour starch quality improves when the **layer of water** in the fermentation tank (3–5 cm) guarantees anaerobic fermentation, lactic acid production (specific amylolytic bacteria strains), and a drop in pH to 3.5. In an oven that controls starch moisture and that bathes the starch in UV light, its quality could be improved to greater levels because starch extraction plants could uniformly dry their product. Unfortunately, it is not possible to achieve the same BP as with sun-dried starch.

Further studies have been performed that examined the influence of cassava type and root storage time on sour starch quality as well as the effect produced by the overall climate and water used in the production process (Brabet et al. 1996).

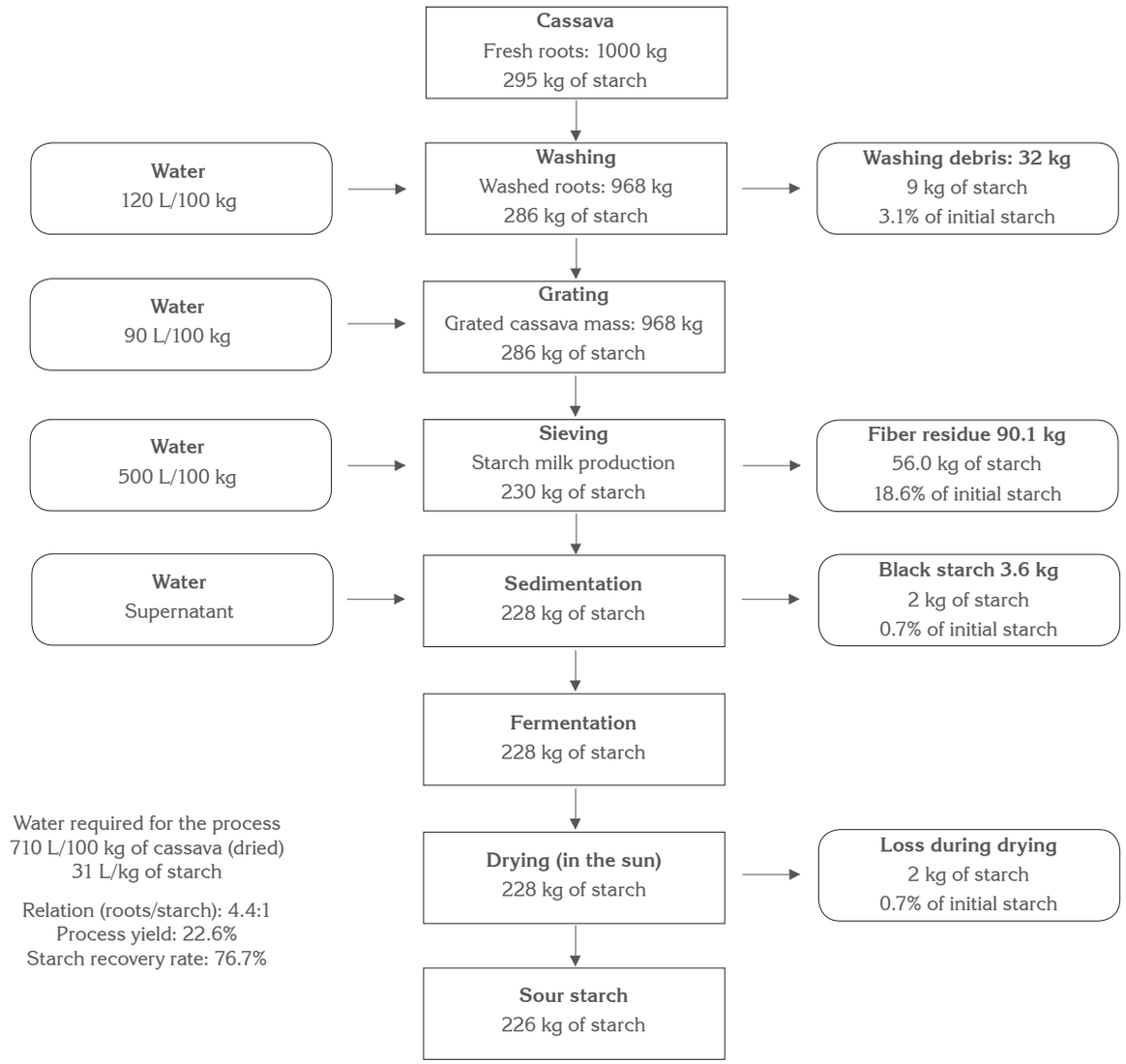


Figure 26-18. Example of the sour cassava starch (MVen 25 variety with 35% of dry matter) extraction process of La Agustina extraction plant located in the department of Cauca and starch yield figures. The initial quantity of starch in this example is represented in the 295 kg contained in the initial 1000 kg of fresh cassava. From that quantity, 226 kg of sour starch, or 76.6%, is recovered.

Marketing

Sour and native (sweet) starches are sold mainly through agents. In Cauca, these agents transport the product to Santander de Quilichao, a town in the northern sector of the department. Once there, they sell it to other agents, who then transport it to Colombia's major cities. Of the 210 cassava starch extraction plants in the Cauca department, 35 directly sell their product to bakeries, 8 to the snack food industry, 20 sell it through the Cooperative Association of Extraction of Cauca (COAPRACAUCA), and the rest deal with agents.

Truck drivers deliver the starch to major cities in the region (Cali, Buga, Cartago, and Tuluá), and in the country (Bogotá, Pereira, Ibagué, Medellín, Cartagena, Armenia, Monteria, among others).

General recommendations

For cassava starch extraction plants. Several years of research on cassava starch extraction plants in the department of Cauca, provides enough experience to recommend certain machinery, methods, and designs (Chuzel et al. 1995a). Nevertheless, each plant is a specific case, and any recommendation should be

tailored to fit their infrastructure and their owners' economic limitations.

Traditional extraction plants. These are labeled Type 1 processing plants (see above description), whose capacity ranges between 800 and 1000 kg of roots every hour.

1. The washer/peeler used in this extraction plant operates on a cycle-by-cycle (models 1 and 2), and operators lose time during each loading/unloading pass. These machines should be changed to a **semi-continuous** washer/peeler (see Figure 26-10B, model 3) because it simplifies the operation and also increases plant's capacity to 800 to 1500 kg of roots per hour.

2. Mechanical graters that feature four bearing housings (Figure 26-14) have certain drawbacks:

   - Overloading the machine is not a good idea since it will shut down or detach itself from the drive pulley.

   - Starch can become contaminated with rust or bearing grease because the starch milk can come in contact with the rollers. These should, therefore, be substituted for **"hanging"** or half-shaft sieves (Figure 26-13) since these do not present that problem. Additionally, the fabric or mesh that is outside the sieves should be finer (120-mesh) to be able to retain the fiber that passes through the sieves. This fiber affects starch quality.

3. Starch milk sedimentation capacity is the largest constraint to any starch extraction plant, and it depends upon the system used for sedimenting the daily production.

   - If sedimentation tanks are used, the capacity is limited by the number of tanks the plant has available. Likewise, the black strach and the starch mix together in the tanks, thus lowering starch quality to average.

   - If **sedimentation channels** are used, then the operation is non-stop. Also, the water carries off the less dense material (black strach) and leaves cleaner the starch on the bottom since the black starch does not mix with it.

   - Channels can be of different length. An important recommendation to keep in mind is that they have to be absolutely level to the ground and designed with ends that are curved or rounded so the starch milk does not strike the channel walls, thereby creating turbulence from the counterflow in which the black starch and the starch mix together.

4. Plant owners should carefully think about making the change from a system built on flat terrain to one that uses gravity to move the product. The change is so costly that it would mean making over the entire starch extraction plant.

5. If there are frequent power outages in the region where the extraction plant operates and if the cassava is not processed for hours or days, then a gas powered engine should be installed besides an electric backup plant.

6. The belts that drive the engines (transmission) are very dangerous. It is recommended installing them on just one side of the processing plant and to use protective shields around them to reduce risks.

7. For more industrial safety, then install several gear motors (one for each machine that may need it) instead of running all the equipment off just one engine alone (electric or gas powered). The cost of this improvement is high.

For a Type 1 cassava starch extraction plant to increase its production, the following measures should be taken:

- Install an additional sieve.

- Increase the number of sedimentation tanks or build a channel system.

- Increase the number of fermentation tanks in relation to daily production.

- Increase the drying area.

Improved cassava starch extraction plant. These are called Type 2 (see process description above). They use a channel system and have streamlined their operations by harnessing the terrain's slope (Chuzel et al. 1995b).

1. These starch extraction plants can improve their drying operation through installing a pulverizing mill to crumble or "break apart" the compacted starch. After being **crumbled**, the starch can be spread easily, quickly, and uniformly.

2. The water that runs through the channels can be recycled to wash cassava roots, thereby making more water available in the plant which will increase the speed and efficiency of the washing operation and the overall process. Figure 26-19 shows the ideal blueprint of a Type 2 starch extraction plant.

New cassava starch extraction plant. When planning to build a new extraction plant model, called a Type 3, the following should be kept in mind:

- Must use good quality and abundant water throughout the process: close to 30 m^3 per day.
- Water temperature must be below 25 °C (fresh water).
- It is recommended that the effluents from the sour starch production process be treated so they do not contaminate nearby streams. If the wastewater cannot be treated, then it should be directed to an area far from the extraction plant that would, therefore, be at a lower level on the terrain.
- The plant should be built at a site where gravity, due to its topography, can be harnessed for the process. The difference between the plant's highest and lowest points should be 3.5 m, making it possible to conduct the starch production process with the help of gravity. The system will facilitate a semicontinuous flow of operations at a lower cost.
- Fermentation tanks should be buried so that the top is at the same height as the upper part of the channels.
- Water from the last channel can be directed to flow around the tanks to keep their external temperature constant.
- If the chosen site is on flat terrain, it is still possible to raise the grating operation to the proper height (building a metal structure and using a conveyor belt) to create a system by gravity artificially.

The drawing of a new, Type 3 plant with all the above described starch extraction processes can be seen in Figure 26-19.

Comparative yield. The following table compares the **processing capacity** of the three models (in tons of fresh roots per month) and the extraction efficiency, which is the relation (in weight) between the processed roots and the starch extracted from them.

"Rallanderia"	Plant Capacity (t/month)	Ratio (by weight) roots: traditional starch
Traditional	20	5.5:1
Improved	30	5.0:1
New	50	4.5:1

Thus, building a plant with greater capacity means improving its starch extraction capabilities. Moreover, **profitability** of the extraction process noticeably depends upon the level of starch extraction.

For input management.

Water. 10,700 t of starch is produced in the department of Cauca each year. Processing each kilogram of starch requires 31 L of water, or an annual amount of 332,000 m^3, which is equivalent to the amount of contaminated water a town of 10,000 inhabitants would generate yearly.

The water used in the starch extraction process comes from a variety of sources and has the following characteristics:

- Lake, river, gully, or surface well water is usually contaminated with organic matter and microorganisms.
- Spring water normally has low mineral content and is very good for this process.
- Deep well water, compared with water from surface wells, is free of organic matter and microorganisms because it is purified as it filters through the different soil layers.

However, an underground well can become contaminated by abandoned septic tanks, gutters, and sewers. Contaminated water has been known to travel great distances through veins of limestone and other porous materials to end up polluting streams.

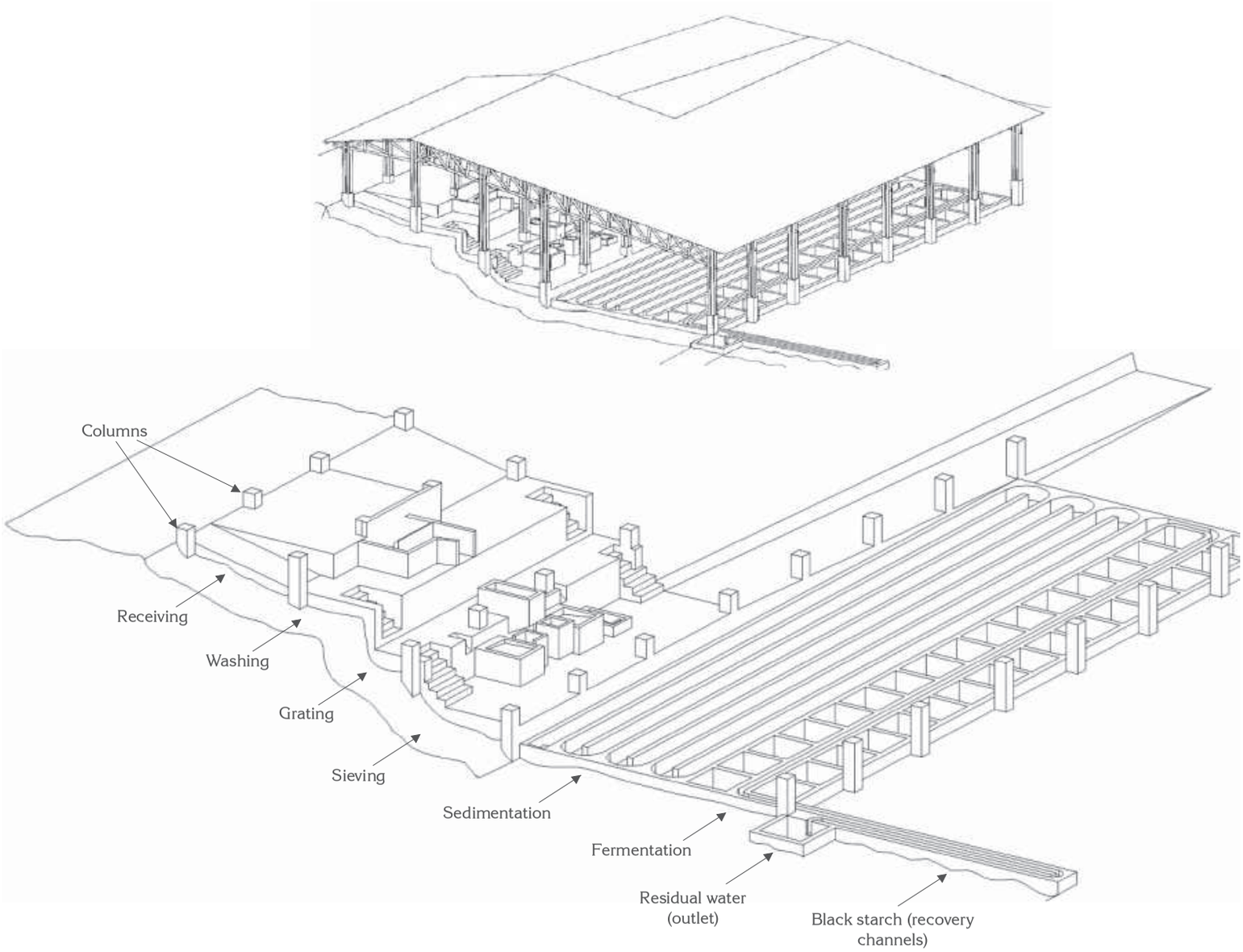


Figure 26-19. Descriptive plan of an ideal, well established extraction plant that graphically shows the sour cassava starch extraction process. The above figure shows the roofed version of this plant. Part of this design is currently being used in some plants in the department of Cauca (for example, the CETEC Totoyuca plant in Siberia, Caldono).

Therefore, a **natural filter** should be built for water used in the extraction process and designed with layers of thick gravel, fine gravel, and clay, which will reduce the minerals and solids suspended in stream, river, and well water (Rojas et al. 1996) (see Appendix 4).

Water that has been used in sedimentation channels is usually directed into **tanks** close to the factory for its subsequent transport to a water treatment plant. When the water is not dumped into a natural stream, it can be used again for the cassava washing process, which translates into a savings of nearly 17% in water consumption for the entire extraction process (Colin et al. 2007).

Raw material. The quality of the cassava is essential for extracting an important percentage of high **quality** starch that has elevated breadmaking potential (dough rising while baking). It is therefore vital to select the cassava variety to be grown wisely for the roots that will be processed.

Machinery. All machines in the plant should be placed in such a way so that the product moves with the help of gravity. This layout will improve production capacity, use less work area, and allow all machines to run on just one engine, thereby making the process very economical.

Appendix 1:

Graphic Description of the Starch Extraction Process

The photographs show the methods used in different regions (such as Cauca and Caldas). Please note the development of the process, from the traditional to the mechanized system.

Photo 26A-1. Washing cassava roots with the feet.

Photo 26A-2. Grating washed cassava roots.

Photo 26A-3. Continuous sieving of the grated cassava using a worm screw.

Photo 26A-4. Sedimented starch in tanks (the worker is separating the black starch).

Photo 26A-5. Starch fermentation in tanks.

Photo 26A-6. Fermented starch drying in the sun.

Figure 26-20A. Traditional system (type 1) to extract cassava starch.

Photo 26A-7. Sacks of cassava arrive at the extraction plant.

Photo 26A-8. Semi-continuous mechanical root washing.

Photo 26A-9. Grating the washed roots.

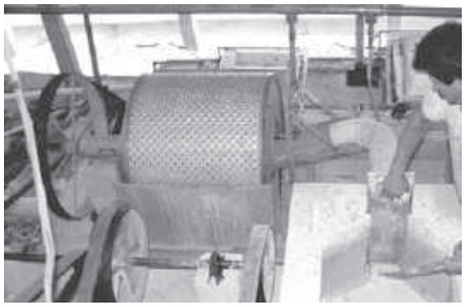


Photo 26A-10. Sieving the grated cassava mass.

Photo 26A-11. Starch sedimentation channels.

Photo 26A-12. Starch fermentation in tanks.

Photo 26A-13. Fermented starch drying in the sun.

Figure 26-21A. Mechanized system (types 2 and 3) to extract cassava starch.

Appendix 2:

Industrial Use of Cassava Starch

Starch production is a major world agroindustry, with a volume of around 33 million tons per year, of which just 3.8 million (11.4%) comes from cassava. The rest is from corn (21.2 million), potato (1.96 million), wheat (2.01 million), rice (0.05 million), and sweet potato (4.17 million) (Ostertag, 1996).

Food industry

Natural starch (also known as native, sweet, or industrial) is used, by itself or in a blend, to make macaroni and different flours. These are subsequently used to make puddings, baked goods, cookies, wafers, sponge cake, creams, ice creams, soups, salads, sausages, and other food products. **Fermented starch** (sour) is used to make traditional Colombian food products like *pandebono* and *pandeyuca* (Figure 26-22A).

- Native starch can be changed through physical means into **pregelatinized starch** (PG starch), which has the property of being soluble in water without first having to be cooked.

- It is used as a thickener, stabilizer, or glaze on fruit pies, dry mixes, puddings, and milk cream. Adding PG starch improves the texture and appearance of these and other, similar products.

- Native starch can also be changed through chemical means into a food industry product used as a thickener in white sauce and a stabilizer and emulsifier in salad dressings, nutritious gelatins, instant dessert mixes, ice creams, pudding, and baby food. Depending on how it is changed, it can be used in the paper, adhesive, and other industries (Balagopalan et al. 1988).

Figure 26-22A. Colombian food industry products made with sour cassava starch.

Paper industry

Native starch used in the paper industry is called **unmodified starch** (UM starch). There are three operations in its treatment process: (1) refining (or screening), (2) purifying (strictly industrial operation), and (3) drying.

Paper and cardboard. Producing paper and cardboard is a multi-step process and, in one (or more) of them, UM starch is added to the final product to give it certain properties and different grades of quality.

- The paper industry requires three basic characteristics from cassava-based UM starch: (1) whiteness, (2) low fiber content, and (3) few impurities. The starch may have other physical or chemical characteristics that affect the papermaking or slurry production process.

- UM starch helps the cellulose fibers bond and forms a top layer that reduces fuzz and increases the individual sheet's consistency, solidity, and durability. This thin layer also improves cardboard's strength of material.

- UM starch is also used as an adhesive for laminating certain papers, corrugated cardboard boxes, wall paper, cardboard tubes, and other articles. It is also used in paper and cardboard recycling.

Glues. UM starch is the raw material for making the basis of inexpensive glues or adhesive products.

- These adhesives are used to make such disposable products as packing materials, stickers, wrapping paper, and label/envelope glue.

- These inexpensive glues are very useful for high speed packing machines and labelers for two reasons: relative low cost and high gluing speed.

Organic decomposition. UM starch used in the paper industry lasts 3 to 4 days without decomposing, at which time it becomes fermented by different microorganisms.

This fermentation produces gases (whose foul odor is not immediately smelled) and denaturalizes the UM starch, thereby altering its properties, primarily losing 25% of its adhesive capacity, reducing its viscosity, and changing it acidity (pH).

Therefore, anti-bacterial substances should be added to UM starch to keep the lactic acid-producing and coliform bacteria, as well as fungus (genera Penicillium and Aspergillus and yeasts), from growing.

Textile industry

UM starch is the most abundant and inexpensive ingredient, and thus the most important, in different textile glues.

Warp sizing. The textile industry prefers (almost exclusively) to use UM starch for two reasons: (1) it is the only substance that can treat very white fabrics and (2) it degrades less than starches made from other sources. Fabrics can be sized temporarily or permanently.

- Temporary sizing is when starch is applied to warp yarns just before these are turned into fabric so that they are stronger, softer, smoother, and more flexible. The sizing agent is deposited as a film on, and totally covering, the warp threads.

- This process keeps the threads from unraveling, tangling, spotting, and breaking, any of which would seriously disrupt the textile making process.

- Permanent sizing is used in fabric finishing and is relatively stable since it remains on the fabric at least until it is in the hands of the consumer.

- The fabric is impregnated with starch, which improves its texture, increases the surface brightness, gives it "body" and solidness to help in its handling, increases the "weight", the print quality, and the overall appearance and feel of a good quality fabric.

Pharmaceutical industry

PG starch is used to dilute, to glutinate, to lubricate, or to disintegrate different solid products. It also helps absorb, gives viscosity, and acts as a vehicle for pasty, liquid, or semisolid substances in dermatological creams and lotions.

It is furthermore used to make fine facial, compact, and nutritional powders, and as raw material in making wafers (Balagopalan et al. 1988).

Other uses

UM cassava starch is used in the chemical industry to make alcohol, glucose, acetone, explosives, colorants, dry batteries, and dental impressions as well as to coagulate rubber.

The mining industry uses it as a flocculating agent and a component in oil drilling solutions.

Appendix 3:

Cassava Starch Extraction Plant Costs

Construction and set up

Table 26A-1 shows the infrastructure and equipment costs of a Type 3 starch extraction plant with a 30-t monthly production capacity (300 t/year for 10 months of operation).

Operating costs

A cassava starch extraction plant with the equipment listed in the above table generally operates at 80% of its capacity, thereby producing annually 250 t of sour starch. Operating costs, however, are estimated on its basic capacity (30 t/month) and expressed in United State Dollars (US$1.00 = Col$1450; from September 1998).

1. Cost of producing 1 t of dry starch:

Fixed costs

Administration (US$351.00/month)	US$11.75
Plant maintenance	3.55
Depreciation (Per unit produced. See below)	1.70
Subtotal (ST1)	17.00
Variable costs	
Labor (3 shifts, US$5.53/shift)	16.60
Electricity (2 kW/hour, US$0.20/kW)	0.40
Water (Natural streams, no cost)	—
Packaging (20, US$0.35/unit)	7.00
Miscellaneous costs	7.00
Freight cost	17.20
Subtotal (ST2)	48.20
Total (operating costs/t) = ST1 + ST2	US$65.20

2. Cost of producing 30 t (1 month of operating)

US$65.20/t x 30 t/month = US$1956/month

3. Yearly depreciation:

Equipment and machinery service life ≈ 10 years
Salvage value (junk) ≈ US$300
Production over course of service life ≈ 250 t/year x 10 years = 2500 t
Accounting period = 1 year

Applying the formula:

$$\text{Dep./t} = \frac{\text{US\$4500} - \text{US\$300}}{2{,}000\ \text{t}} \approx \text{US\$1.70 per ton produced}$$

Dep./Month = US$1.70 x 30 t ≈ US$51 per month in operation
Dep./Year = US$1.70 x 250 t ≈ US$420 per year in operation

These costs were updated in 2012 (Da et al. 2012).

Table 26A-1. Cassava starch extraction plant costs (values from September 1998).

Item	Quantity	Cost (US$)
Machinery and equipment for the process		
Cassava washer/peeler (2 t of roots/hour)[a]		1,000
Cassava grater (2 t of roots/hour)		500
(300 kg of grated cassava mass/hour)[b]	x 2	2,000
Reciprocating screen[c]		300
Motorized pulverizing mill (1.5 kg/hour)		700
Subtotal		4,500
Plant infrastructure		
Sedimentation channels (each 30 m x 60 cm x 40 cm)[d]	x 7	15,000
Starch drying patio (2000 m^2, 8 cm thick)		18,000
Fermentation tanks (1.5 m^3)[e]	x 20	15,000
General civil engineering work (400 m^2)[f]		10,000
Factory cover or roof[g]		6,000
Starch warehouse (30 m^3)		8,000
Black starch deposit tank (30 m^3)		8,000
Fiber residue deposit tank (15 m^3)		4,000
Power transmission		700
Subtotal		84,700
Total		**89,200**

a. Different washer/peeler models yield this amount.
b. Model: Intermittent mechanical.
c. For second sieving.
d. Covered in tiles.
e. Covered in tiles and wood.
f. Columns, walls, floors, and drains.
g. Bamboo and zinc, mainly.

Appendix 4:

Wastewater Treatment System

Ricardo Ruiz Cabrera[4]

The cassava starch extraction process consumes large quantities of water and produces effluents that have considerable negative impacts on biotic systems when directed into surface streams. From an economic and technical viewpoint, anaerobic systems and, in particular, biodigesters are an important alternative for treating these types of effluents.

This appendix will present and evaluate a normal digester and a digester complemented by aquatic plants.

Background

Wastewater from the sedimentation stage of starch extraction is the main environmental problem of that process. On average, a cassava starch extraction plant can produce somewhere between 20 and 30 m^3 of wastewater per day, depending on the level of technology used and the hours in a work day.

According to the studies conducted by Rojas in 1992, and reported in Rojas et al. (1996), this wastewater has considerable pollution capacity because it carries large amounts of particulate organic matter, possesses moderate acidity, and contains small quantities of the cyanogenic ion (CN^-).

Several studies have found (Duque 1994) that this type of effluent biodegrades at 70% for an insoluble sample and 92% for a soluble one. The 8% of the matter resistant to biodegradation is probably inorganic.

Extraction process effluents show OCD[5] values between 3000 and 7000 mg/L. The Sanitary Engineering Department, Universidad del Valle, has conducted different studies that show the feasibility of purifying wastewater when using anaerobic digestion systems, examples being the two-phase reactor and the upflow sludge blanket reactor.

4. Industrial Engineer, Rural Agro-industry, CETEC, Cali, Colombia. E-mail: todoyuca97@yahoo.com
5. OCD = Oxygen Chemical Demand. The amount of oxygen a determined volume of effluent requires for chemical degradation of the organic matter it contains. OCD is the amount of oxygen for microbiologically degrading the organic matter in an effluent.

Reactor evaluation

In 1997, the Corporación para Estudios Interdisciplinarios y Asesoría Técnica (CETEC) set up anaerobic treatment systems in three cassava starch extraction plants in Santander de Quilichao, Cauca, that dump their wastewater into the Mandiva River.

The reactor constructed in these factories was a tank digester supplemented with an aquatic plant system, and their performance evaluation was conducted by the Universidad del Valle Environmental Sanitation Department, the results of which were published in the thesis titled: "*Evaluación del desempeño de dos biodigestores en el tratamiento de las aguas residuales del proceso de extracción de almidón de yuca*" [Perfomance Evaluation of Two Biodigesters for Treating Wastewater from the Cassava Starch Extraction Process] and presented by Javier A. Manrique M. from the Chemical Engineering Department in June 1999.

Study objectives were:

- Setting up and operating a pilot treatment system.
- Evaluating system performance by measuring the percent of organic and solid matter removed.
- Determining the necessary conditions for adapting the biomass to the substrate and for guaranteeing the system's routine operation.

Its main conclusions were:

- Under the conditions in which the reactor operated, the largest drop in OCD was 76.6% and solid removal was 61%. These values were recorded for a 21 hour hydraulic retention period, as illustrated in Table 26A-2.
- It is not possible to assert that tank digesters are not a suitable alternative for treating wastewater from the cassava starch extraction process. If the operating parameters of the reactor were very strictly controlled, particularly pH (which should be

Table 26A-2. Tank digester operating results from a 1999 evaluation conducted by the Universidad del Valle.

Parameter (units)	Value Affluent	Value Effluent	Removal (%)
pH	6.7	6.9	
OCD_t (mg/L)	3806.17	890.23	76
OCD_s (mg/L)	3012.58	816.12	79
TSS (g/L)	0.58	0.23	61.15
VSS (g/L)	0.52	0.21	60.34

a. OCD_t = *total* oxygen chemical demand (includes algae in M.O. contents)
OCD_s = *soluble* oxygen chemical demand (excludes algae)
TSS = total suspended solids (in the effluent, for example)
VSS = volatile suspended solids (in the effluent, for example)

between 6.7 and 7.4), then it would be possible to achieve highly satisfactory results with it.

- To maintain wastewater pH within the optimal range for anaerobic digestion, it is necessary to have a system that allows an alkalizing solution to be continuously and proportionally introduced into the managed substrate flow. Calcium and sodium hydroxide returned good results in that area.

- If the alternatives sought out for treating wastewater have to be within reach of social sectors with limited access to technology and financial resources, then it is worth improving these types of reactors since the infrastructure costs are very low.

Tank digester description and set up

This system was set up in two cassava starch extraction plants in the northern sector of the Department of Cauca. Both dumped their wastewater into the Mandiva and Quinimayo basins. Each digester is comprised of two dual layer polyethylene heavy duty polyethylene tanks, 2.5 m in diameter, with additives to protect against acids and UV light. The tubes are buried in different pits with a cross-sectional area of 3 m^2. Both ends of the tubes are connected and completely sealed to concrete boxes that are the affluent inlet and effluent outlet. A sludge evacuation system is attached to the bottom part and a biogas outlet at the top.

Digester design parameters are:

- Average affluent flow: 2.7 m^3/hour

- Minimum hydraulic retention period: 21 hours

- Required volume: 57 m^3

Given these parameters, digester construction requires these elements:

- 2 pits, 16 m long, with a net cross-sectional area of 3 m^2 and real cross-sectional area of substrate occupation of 2 m^2.

- 2 dual layer, heavy duty polyethylene tanks, 2.5 m in diameter and 20 m long.

- 2 brick inlet boxes, 1.0 m^3 and 0.70 m high, with a 12” diameter concrete tube.

- 2 brick outlet boxes, 1.0 m^3, with a 12” diameter concrete tube.

- Sludge evacuation system and biogas routing and use system.

References

To save space, the acronym "CIAT" is used instead of "Centro Internacional de Agricultura Tropical".

Alarcón M, F. 1989. Obtención de dextrinas a partir del almidón de yuca. Thesis. Universidad del Quindío, Armenia, Colombia. 120 p.

Alarcón M, F. 1993a. Documento de asesoría técnica para la Costa Atlántica de Colombia. CIAT, Cali, Colombia. 6 p. (Multicopied.)

Alarcón M, F. 1993b. Documento de asesoría técnica para la zona del Patía, Colombia. CIAT, Cali, Colombia. 7 p. (Multicopied.)

Alarcón M, F. 1994a. Diagnóstico de la producción de yuca en Manabí, Ecuador. In: Producción, procesamiento, utilización y comercialización de la yuca. Proceedings of a seminar held in INIAP, Ecuador, October 1994. Portoviejo, Ecuador. p 10–12.

Alarcón M, F. 1994b. Utilización de los subproductos de la yuca en la alimentación animal. In: Producción, procesamiento, utilización y comercialización de la yuca. Proceedings of a seminar held in INIAP, Ecuador, October 1994. Portoviejo, Ecuador. p 15–17.

Alarcón F. 1996. Obtención del almidón de yuca a pequeña escala; proceso general de extracción. In: Montaldo A, comp. La yuca frente al hambre del mundo tropical. Universidad Central de Venezuela, Maracay, Venezuela. p 349–364.

Balagopalan C; Padmaja G; Nanda SK; Moorthy SN. 1988. Cassava in food, feed and industry. CRC Press, Boca Raton, FL, USA. 205 p.

Brabet C; Chuzel G; Dufour D; Raimbault M; Giraud J. 1996. Improving cassava sour starch quality in Colombia. In: Dufour D; O'Brien GM; Best R, eds. Cassava flour and starch: progress in research and development. Centre de Coopération Internationale en Recherche Agronomique pour le Developpement, Depártement des Systèmes Agroalimentaires et Ruraux (CIRAD-SAR), Montpellier, France; CIAT, Cali, Colombia. p 241–246.

Buitrago JA. 1990. La yuca en la alimentación animal. CIAT, Cali, Colombia. 450 p.

CECORA (Central de Cooperativas de la Reforma Agraria). 1988. Diagnóstico socioeconómico del Cauca. Colombia. 150 p.

Chacón MP; Mosquera L. 1992. Estudio del sistema socioeconómico de la producción de almidón de yuca en el norte del Cauca. Thesis. Programa de Economía, Corporación Universitaria Autónoma de Occidente, Cali, Colombia. 148 p.

Chuzel G; Muchnik J. 1993. La valorisation des resources techniques locales: l'amidon aigre de manioc en Colombie. In: Alimentation, techniques et innovations dans les régions tropicales. Harmattan, Paris. p 307–337.

Chuzel G; Pérez D; Dufour D; Alarcón MF. 1995a. Amelioration d'un système d'extraction par voie humide d'amidon de manioc. In: Agbor-Egbe T; Braumann A; Griffon D; Trèche S, eds. Transformation alimentaire du manioc (Cassava food processing). ORSTOM, Paris. p 637–647.

Chuzel G; Pérez D; Dufour D; Griffon D. 1995b. Amélioration technologique des equippements d'extraction d'amidon de manioc en Colombie. In Agbor-Egbe T; Braumann A; Griffon D; Trèche S, eds. Transformation alimentaire du manioc (Cassava food processing). ORSTOM, Paris. p 623–636.

CIAT. 1995a. La industria del almidón en el Departamento del Cauca, Colombia. CORPOTUNIA, CIRAD, CETEC, UNIVALLE, Fundación Carvajal, and CIAT, Cali, Colombia. 16 p.

CIAT. 1995b. Resultados de las visitas a las rallanderías del Cauca. Cali, Colombia. 12 p. (Multicopied.)

CIAT. 1996. Cassava: the latest facts about an ancient crop. Cali, Colombia. (Factsheet.)

Cock JH. 1989. La yuca: Nuevo potencial para un cultivo tradicional. CIAT, Cali, Colombia. 240 p.

Colin X; Farinet JL; Rojas O; Alazard D. 2007. Anaerobic treatment of cassava starch extraction wastewater using a horizontal flow filter with bamboo as support. Bioresour Technol 98(8):1602–1607. http://dx.doi.org/10.1016/j.biortech.2006.06.020

Da G; Dufour D; Giraldo A; Moreno M; Tran T; Vélez G; Sánchez T; Le Thanh M; Marouzé C; Maréchal PA. 2012. Cottage level cassava starch processing systems in Colombia and Vietnam. Food Bioprocess Technol. (Accepted manuscript number: FABT-2040-R3.) http://dx.doi.org/10.1007/s11947-012-0810-0

Domínguez CE, ed. [1983]. Yuca: Investigación, producción y utilización. CIAT; United Nations Development Programme (UNDP), Cali, Colombia. 660 p.

Dufour D; Larsonneur S.; Alarcón MF; Brabet C; Chuzel G. 1996. Improving the bread-making potential of cassava sour starch. In: Dufour D; O'Brien G M; Best R, eds. Cassava flour and starch: progress in research and development. Centre de Coopération Internationale en Recherche Agronomique pour le Developpement, Depártement des Systèmes Agroalimentaires et Ruraux (CIRAD-SAR), Montpellier, France; CIAT, Cali, Colombia. p 133–143.

Duque A. 1994. Proyecto para el control de los vertimientos generados en el beneficio de la yuca en el sector de Mondomo, Santander de Quilichao. Thesis. Faculty of Engineering, Universidad del Valle, Cali, Colombia.

FAO (Food and Agriculture Organization of the United Nations). 1999. Data Base. www.fao.org

Figueroa C. 1991. Fermentación del almidón de yuca. Thesis. Faculty of Biology, Universidad del Valle, Cali, Colombia. 100 p.

Gottret MV. 1996. Caracterización tecnológica y adopción de tecnología en las rallanderías del departamento del Cauca, Colombia. In: Segundo Simposio Latinoamericano de Investigación y Extensión en Sistemas Agroalimentarios, Bogotá D.C., Colombia. CIAT, Cali, Colombia. 15 p.

Gottret MV; Henry G; Dufour D. 1997a. Characterization of the cassava sour starch agroindustry in the department of Cauca, Colombia. Les cahiers de la recherche développement, Systèmes agroalimentaires à base de racines, tubercules et plantains (43):67–81, 114, 116.

Gottret MV; Henry G; Dufour D. 1997b. Adoption and impact of cassava sour starch processing technologies in Colombia. Cahiers de la Recherche Développement, Dossier: systèmes agroalimentaires à base de racines, tubercules et plantains 44:38–59.

Gottret MV; Ospina B. 2004. Twenty years of cassava innovation in Colombia: Scaling up under different political, economic, and social environments. In: Pachico D, Fujisaka S, eds. Scaling up and out: achieving widespread impact through agricultural research. CIAT, Cali, Colombia. p 105–126.

Henry G; Gottret MV. 1998. Client-led agro-industrial action development: the case of cassava starch in Cauca Valley, Colombia. AFSR&E Symposium, Pretoria, South-Africa, 30 November–4 December, 1998.

IGAC (Instituto Geográfico Agustín Codazzi). 1993. Cauca: Características geográficas. Bogotá, D.C., Colombia. (Maps.)

Jones SF. 1983. The world market for starch and starch products with particular reference to cassava (tapioca) starch. Report no. G173. Tropical Development and Research Institute, London, UK. 98 p.

Ostertag CF. 1996. World production and marketing of starch. In: Dufour D; O'Brien GM; Best R, eds. Cassava flour and starch: progress in research and development. Centre de Coopération Internationale en Recherche Agronomique pour le Developpement, Depártement des Systèmes Agroalimentaires et Ruraux (CIRAD-SAR), Montpellier, France; CIAT, Cali, Colombia. p 105–120.

Pinto R. 1977. Generalidades sobre procesamiento, utilización y comercialización del almidón de yuca. Instituto Colombiano Agropecuario (ICA), Bogotá D.C., Colombia. 90 p.

Rojas Ch O; Torres L P; Alazard D; Farinet J-L; Cardoso MC Z de. 1996. Cassava starch extraction: a typical rural agroindustry with a high contamination potential. In: Dufour D; O' Brien GM; Best R, eds. Cassava flour and starch: Progress in research and development. Centre de Coopération Internationale en Recherche Agronomique pour le Developpement, Depártement des Systèmes Agroalimentaires et Ruraux (CIRAD-SAR), Montpellier, France; CIAT, Cali, Colombia. p 233–238.

Sánchez T; Salcedo E; Ceballos H; Dufour D; Mafla G; Morante N; Calle F; Pérez JC; Debouck D; Jaramillo G; Moreno IX. 2009. Screening of starch quality traits in cassava (*Manihot esculenta* Crantz). Starch/Stärke 61(1):12–19. Erratum: 2009, Starch/Stärke 61(5):310. http://dx.doi.org/10.1002/star.200800058; http://dx.doi.org/10.1002/star.200990027

Wheatley CC. 1991. Calidad de las raíces de yuca y factores que intervienen en ella. In: Hershey CH (ed.). Mejoramiento genético de la yuca en América Latina. CIAT, Cali, Colombia. p 267–291.

Zakhia N; Dufour D; Chuzel G; Griffon D. 1996. Review of sour cassava starch production in rural Colombian areas. Trop Sci 36:247–255.

CHAPTER 27

The Use of Cassava Products in Animal Feeding*

Julián Buitrago A.[1], *Jorge Luis Gil*[2], *and Bernardo Ospina*[3]

Introduction

Improved feeding technology and the introduction of high yielding varieties of cassava have open the possibility to increase its participation in commercial production of animal feeds. Although yields of cassava roots may be as high as 60 t of fresh roots per hectare, under conditions of commercial cultivation it is possible to obtain production levels of 25 to 40 t of fresh roots (9.5 to 15 t of dry roots) and around 5 to 10 t of fresh foliage (1 to 2 t of dry foliage) per hectare. This productivity levels are almost impossible to obtain in tropical environments with other agricultural crops of direct application in animal feeding.

The main value offered by cassava root as a feedstuff is its capacity to provide starch which is a valuable source of useful energy for monogastric and ruminant animals. On the other hand, cassava foliage provides a high level of protein which can be used for ruminants and to a limited extent (as a dried product) in monogastric feeding. Table 27-1[4] illustrates the main nutrients present in fresh and dried samples of cassava products.

Most of the early studies with cassava products were based on the use of fresh roots in swine and cattle feeding as a day-to-day practice. Due to the high moisture level of fresh roots and foliage, its use in poultry and swine diets was not recommended.

The silage processing contributed to improve the management practices since the roots and foliage could be chopped and preserved for long periods before they were supplied to animals.

In later stages, natural drying (sun drying) or artificial drying (gas, diesel, coal, or steam) was introduced as a practice for commercial production of cassava root meal (CRM)[5] or cassava foliage meal, which opened the opportunities for large scale feeding programs, including poultry, swine, and aquaculture production.

Some feed management limitations (dustiness, palatability) with high levels of CRM were overcome with the introduction of new pelleting or extruding techniques. Through the inclusion of pelletized diets for poultry and swine, high levels of CRM and cassava foliage meal were included, and the performance results were comparable to those with conventional cereal diets.

The following revision shows some of the most relevant results with the inclusion of different products derived from cassava roots and foliage (fresh, ensiled, natural drying, artificial drying, and pelletized diets). The first part is directed to traditional feeding practices with fresh and ensiled products for swine and ruminants. The second part also presents traditional information with dried products for poultry, swine, and ruminants. The third part provides more recent developments, especially related to the introduction of fullfat soybean (FFSB) as a strategic complement to dried cassava diets in poultry and swine feeding.

---

* This chapter contains an authorized adaptation of text presented in the publication "The Cassava Handbook", edited by Reinhardt H. Howeler, 2012.

1. Medical Veterinary, consultant of CLAYUCA, Cali, Colombia. E-mail: julianbuitrago@yahoo.com
2. Zootechnician, research assistant of CLAYUCA. E-mail: j.l.gil@cgiar.org
3. Executive Director, CLAYUCA. E-mail: b.ospina@cgiar.org

4. To facilitate readability, all of the 70 tables referred to in this chapter can be found at the end of this document before the References section.

5. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

Fresh and Ensiled Cassava Roots and Foliage for Swine and Ruminants

The usual feeding practice in most traditional experiences with fresh cassava has been the daily supply of the whole chopped roots supplemented with a dry mixture of protein and micro ingredients (vitamins, minerals, and feed additives). As anticipated, this practice is mainly suitable for small-or medium-size swine and cattle enterprises where cassava production is usually a complement to the animal operations and where hand labor is not an important limitation.

For larger and more technified operations, the heavy hand labor requirements, the perishability of the product, and the troublesome management of the daily feeding program limit the extensive use of fresh products. The use of dried mixtures in automatic feeding systems is the general trend in these cases, where cassava roots and/or foliage should be dried and, preferably, pelletized, to be included in commercial diets.

Although the information with fresh and ensiled roots for swine and cattle feeding is quite lengthy, a summarized report of the most relevant studies is included, with special emphasis on the experimental work conducted at the Centro Internacional de Agricultura Tropical (CIAT), the Colombian Institute of Agriculture (ICA), and the Latin American and Caribbean Consortium to Support Cassava Research and Development (CLAYUCA).

Performance Results with Fresh Cassava Roots in Swine Feeding

Programs based on fresh cassava are suitable for feeding growing-finishing pigs and breeding sows. Due to the high moisture and low energy of roots, the animals have to be supplied with ample amounts of chopped cassava roots and a limited amount of a dry protein supplement (Figures 27-1, 27-22, and 27-3). Nevertheless, in most cases the animal is not able to consume the total energy requirements even though the product is offered at free choice. The maximum consumption of fresh roots obtained in most studies is around 3 kg for growing pigs, 4 kg for finishing pigs, and 6 kg for lactating gilts, which is less than the expected consumption of 3.5–4, 5–6, and 8–10 kg, respectively. Based on these limitations, the performance is partially affected although in most cases the cost:benefit criteria is positive for the small producer.

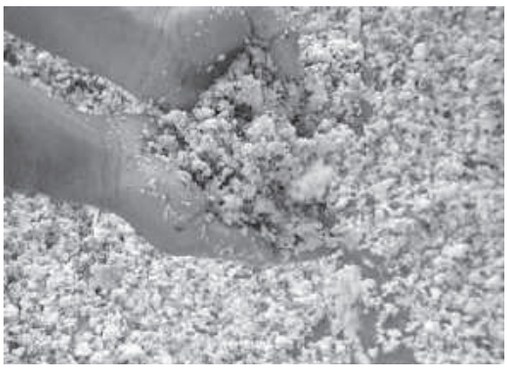


Figure 27-1. Fresh cassava chips.

Figure 27-2. Cassava chipper.

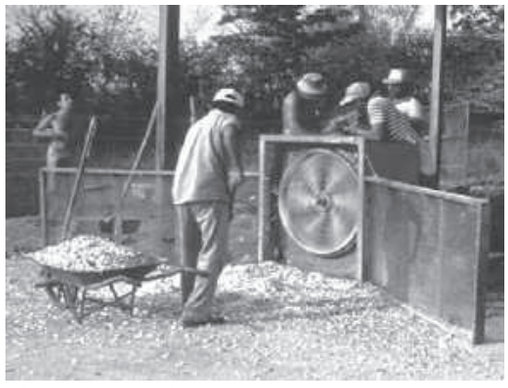


Figure 27-3. Chipping fresh cassava.

In the day-to-day feeding management program, cassava can either be supplied in a mixture together with the nutritional supplement or separately. Nevertheless, free choice supply of the supplement often results in over-consumption of protein, minerals, and vitamins, which generally raises the price and makes the feeding program inefficient.

The most recommended programs to fulfill the pigs' nutritional requirements and at minimal production costs are based on nutritional supplement supply in a daily controlled scheme, according to age and weight of the animals.

Fresh cassava from sweet varieties can be supplied either at free choice to pigs or in controlled amounts to avoid waste, although consumption should not be restricted. Each day, the corresponding amount of fresh roots must be offered to the animals (Figure 27-4).

Figure 27-4. Pig feeders for fresh cassava.

When pigs weight less than 50 kg, they consume smaller amounts of fresh cassava (2.5–3.5 kg/day), but afterwards, during the final fattening stages, consumption should increase up to 4.0–4.5 kg/day. Since these quantities still do not provide the pig with the required dry matter (DM) or energy level to obtain maximum performance, the animal tries to compensate this deficit with a higher consumption of the nutritional supplement (in the case that it is offered at free choice).

In the following tables, results of different trials with growing-finishing pigs and breeding females are analyzed.

Fresh cassava roots for growing-finishing pigs

Tables 27-2 to 27-7 illustrate different feeding approaches which have been tested as viable alternatives to maximize the consumption of fresh roots and to avoid the over consumption of protein supplement without affecting the performance of animals.

The information obtained from the performance results confirms most of the observations already mentioned and illustrates some new approaches to be considered for a more efficient use of fresh roots.

In general, performance results are a little lower than those obtained with commercial corn-soybean meal (SBM) diets. The main reason is associated with a lower consumption of DM when cassava roots are fed fresh, due to the incapacity of the pig to consume larger levels of the fresh product. The high humidity, and probably the effect of low levels of hydrocyanic acid (HCN) still present in sweet varieties of cassava roots, may also have some influence in this situation.

When the protein supplement is provided in a free choice arrangement, the animals will consume larger amounts as compensation to the reduced consumption of cassava roots. Therefore, an over-consumption of protein (approximately an extra 20%) will occur, which results in the higher cost of the total diet (Tables 27-3 and 27-5).

The over-consumption of protein supplement is observed regardless of the ingredients used in the formulation, but the inclusion of intermediate levels of meat meal and blood meal seem to stimulate a further increase in the daily consumption (Table 27-5).

As a mechanism to avoid the over-consumption of the protein supplement, it should be offered every day in controlled amounts related with the body weight of the pig. Although the protein consumption is controlled, the total consumption of DM is still deficient due to the lower cassava intake, which partially affects the animal's performance (Table 27-3).

In Table 27-4 it can be observed that the addition of sugarcane molasses or raw sugar to the cassava roots resulted in a small increase in consumption of roots and DM, and a lower consumption of the protein supplement, which improves the energy:protein ratio as well as the performance of the pigs.

Lowering the protein content of the supplements also helps in reducing protein consumption in pigs, although the consumption of fresh roots is also reduced. The total DM intake from cassava roots are reduced, while the supplement consumption and weight gains are improved by providing lower protein percentages, which also results in a better feed conversion (Table 27-6).

When bitter varieties (i.e., CMC-84) of fresh cassava roots are used, a decrease in its consumption is observed with a parallel increase in the consumption of protein supplement when it is offered *ad libitum* (Table 27-7). However, when the protein supplement is controlled to the required daily level, both the cassava and the protein supplement consumption are reduced, creating a larger deficit in the daily energy intake and a drastic reduction in animal performance.

Fresh cassava roots for gestating and lactating gilts

A small number of studies with fresh cassava roots have been conducted during gestation and lactation. While gestating females need small amounts of energy to fulfill their requirements, lactating females require two to four more intakes of energy as well as protein. Therefore, the reduced consumption of cassava roots should not be an important limiting factor in gestation, in contrast to the high demand during lactation.

Table 27-8 summarizes the feed treatments and the performance results of gestating gilts kept on pasture or in confinement. Both cassava roots and the 40% protein supplement were offered in controlled amounts to supply the daily requirements. The feeding of gilts on pasture was adjusted so they received smaller amounts of cassava and protein supplementation since the pasture provided part of the requirements.

The daily feed intake of cassava and protein supplement corresponded to the predicted daily need of DM and protein during gestation. While cassava fed gilts gained more weight during gestation, the litters were smaller and lighter. Piglet weight and litter weight at birth were lower in case of the cassava treatments, especially in the confined gilts.

On the other hand, the performance of sows and litters during lactation was not affected by the inclusion of cassava roots and protein supplement in a balanced proportion (Table 27-9). The mixture of cassava roots and protein supplement was equivalent to a 16% protein diet on a DM basis, which is similar to the control group given a corn-SBM diet.

Daily consumption of DM in the cassava group was smaller (3.40 kg) than in the control group (4.32 kg). In spite of the reduced consumption of DM, total litter weight at weaning was not affected, even with the smaller litter size of the cassava fed sows. The sows from the control group gained a little more weight during lactation since their DM consumption was higher.

Performance Results with Ensiled Cassava Roots in Swine Feeding

A large proportion of the information obtained with fresh cassava in animal feeding also applies to the preserved product obtained through the silage process (Figures 27-5, 27-6, and 27-7).

The principal nutritional differences are due to the starch fermentation and the reduction in moisture

Figure 27-5. Ensiled cassava chips.

Figure 27-6. Cassava roots silage in small polyethylene bags.

Figure 27-7. Cassava silage in big bags.

during the silage production process. Again, monogastric animals, like swine and poultry, generally are not able to consume the total amount of DM from the ensiled roots to satisfy the energy requirements during the higher demanding phases. Their performance is slightly affected in terms of weight gains, although feed efficiency and production costs will probably compensate for the slower weight gain. Growing-finishing pigs, gilts, and sows are suitable to be included in feeding programs based on cassava silage, once the performance limitations are considered.

As was already mentioned with the fresh cassava feeding practices, the ensiled product also has to be offered in a day to day scheme. Protein supplementation can be offered at free choice or in daily controlled amounts. However, the most recommended feeding practice consists in *ad libitum* supply of ensiled chopped roots plus a controlled quantity of protein supplement which has to be periodically calculated to fix the precise amount to be offered.

Ensiled cassava roots for growing-finishing pigs

The following information on the performance of pigs included in different feeding demonstrations with ensiled cassava, considers the use of ensiled cassava roots in a free choice supply and the controlled supply of protein supplement.

Table 27-10 refers to growing-finishing pigs which were fed three possible cassava-based feeding schemes: fresh roots, ensiled roots, and ensiled roots plus foliage. In all cases, the cassava products were supplemented with a fixed amount of protein supplement (38% protein) to satisfy the daily requirements.

From the performance results it may be concluded that the silage process of cassava roots is a valid alternative to be considered as a mechanism to preserve their nutritional value. The high perishability of the fresh roots may be overcome through the inexpensive practice of anaerobic silage production, which also facilitates the feeding management practices for the small- and medium-size producer.

Table 27-10 shows a very similar response in weight gains and feed efficiency when fresh roots are compared with ensiled roots on a DM basis. However, the inclusion of cassava foliage to the ensiled product negatively affected the consumption of the silage, which is reflected in lower weight gains and poorer feed conversion ratios. The lower consumption of the combined roots and foliage silage may be related to the lower palatability of leaves and stems even at minimum levels (10%).

The information presented in Table 27-11 illustrates the possibilities to include different ingredients as protein supplements to cassava silage in growing-finishing pigs. Excluding the high cottonseed meal supplement, where the consumption was reduced, these alternatives compare favorably with pigs fed commercial balanced diets.

The addition of 2% common salt (Table 27-12) to the cassava root silage showed a beneficial effect on feed conversion rate, without affecting the weight performance of pigs. The same experimental work demonstrated that silage stored for long periods (more than 6 months) does not affect production performance of pigs. The ensiled product progressively decreases in moisture content which resulted in better feed conversion ratios.

Ensiled cassava roots for lactating sows

In a similar experimental comparison as the one described for fresh cassava roots, ensiled cassava roots were also included in diets for lactating sows. Protein

supplemented cassava silage diets were compared with corn-SBM diets, either fed as mixed or separated products (Table 27-13).

Performance of sows and litters was not affected by the use of cassava silage as total replacement of the cereal grains normally used in the dry lactation feeds. Even though the amount of cassava silage was more than twice the amount of dry feeds consumed by the sows, a small shortage of DM and energy is still observed in their total daily consumption. However the performance of sows and their litters was not affected up to weaning time. Litter size, individual weights, as well as total litter weight were comparable among treatments, which demonstrate the feasibility for the inclusion of cassava root silage as the main component for lactating sows (Table 27-13).

Performance Results with Fresh Cassava Roots in Ruminant Feeding

Fresh cassava roots for dairy cattle

Tables 27-14 and 27-15 show the effect on the performance of heifers and milking cows when the feeding treatments were mainly based on fresh cassava roots and protein supplements.

Heifers fed with cassava roots and protein supplement (Figure 27-8), in addition to green forage (sugarcane tops), showed a slightly superior daily weight gain than heifers receiving a commercial concentrate based on conventional sources and the same green forage (Table 27-14).

Figure 27-8. Calves consuming fresh cassava.

Confined milking cows also showed a slightly superior production of milk associated with the consumption of cassava roots and protein supplement in addition to star grass hay (Table 27-15).

Fresh cassava roots for beef cattle

The results of a feedlot study are shown in Table 27-16 in which growing-finishing steers were supplemented with a fixed level of fresh grass (elephant grass) plus different dry supplements vs. the cassava group which was fed a similar quantity of fresh grass plus fresh cassava roots and a protein supplement with a high level of urea. One part of the protein supplement was mixed with 10 parts of cassava roots as a complement to the fresh grass in this last group.

The performance results demonstrated excellent growing rates and feed efficiency in the cassava fed group. The inclusion of a high level of urea in the cassava group provides an important advantage by replacing a high percentage of other costly protein sources.

Performance Results with Fresh Cassava Foliage in Ruminant Feeding

The use of fresh cassava foliage is almost limited to ruminant feeding, considering its high moisture (70%–72%) and fiber (4%–6%) levels. Due to its high quantity and quality of protein, the fresh product resembles conventional legumes and is suitable as a forage supplement for ruminants (Figure 27-9).

The best quality foliage should contain a larger proportion of green leaves, petioles, or tender parts from branches, and a minimum of stems or woody

Figure 27-9. Chopped cassava fresh foliage.

parts of the plant. The age of the plant is also an important factor in defining the nutritional quality: when cuts are made from the early stage forage (i.e., less than 3 months) and thereafter harvested at frequent intervals (i.e., every 2–3 months), an excellent product can be obtained in terms of nutrient quality and quantity.

Special care should be taken with fresh forage due to the higher level of HCN in leaves and petioles. The chopping or cutting procedure plus a wilting process during at least 6 hours is very effective in reducing the HCN concentration to safe levels in cattle feeding.

Tables 27-17 and 27-18 illustrate three examples with dairy and beef cattle where cassava foliage is included in a large proportion of the feeding program. In all cases there was an improvement in animal performance associated with the inclusion of cassava foliage. In one of the trials, cassava foliage was offered as a total replacement of alfalfa forage with superior performance results (Table 27-17).

Dry Cassava Root and Foliage Meal for Poultry, Swine, and Ruminants

The information concerning the use of dried cassava products for animal feeding is quite ample in all productive species, mainly swine, poultry, and ruminants. The dried products can be handled more easily and with higher accuracy than programs based on fresh or ensiled cassava (Figures 27-10 to 27-15).

The roots and foliage are dehydrated in order to increase the total nutrient concentration and to facilitate the preservation of the finished feed. In addition, dehydration by heat eliminates most of the cyanogenic components which produce toxic and deleterious effects on animal performance.

Figure 27-10. Solar drying of cassava root chips.

Figure 27-11. Drying trays for cassava root chips.

Figure 27-12. Industrial drying of cassava root chips.

Figure 27-13. Dried cassava chips.

CRM is essentially a carbohydrate product with a high concentration of starch (60%–65%). The metabolizable energy content of good quality meal for poultry and swine is around 3.20 and 3.40 Mcal/kg, respectively, while the total digestible nutrient (TDN) content is around 86%. Its main nutritional limitation is due to the low protein level, so that protein supplementation is required, with special emphasis on the first limiting aminoacid: methionine.

Figure 27-14. Cassava root flour.

Figure 27-15. Dried cassava foliage flour.

The quality of the roots being dehydrated to produce CRM has a natural, direct influence on the final quality of the product. Roots with fibrous impurities (stems, leaves, peels, waste material) or those contaminated with sand or soil affect the nutritional quality and reduce the energy concentration.

Although there is not an official method to grade the quality of CRM, Table 27-19 shows an approach, based on the proposal of Muller et al. (1972), and complemented by the authors of this chapter. This initiative refers principally to the parameters of primary importance for determining the energetic value (main contribution of the roots), and giving a secondary value to the elements of less importance on the root (protein, aminoacids). Based on the above classification, it is possible to recommend the use of CRM, according to more precise nutritional criteria, and better adapted to the different animal production stages, as follows:

Grade 1: broilers, piglets, and aquaculture
Grades 1 and 2: layers, growing-finishing pigs, and calves
Grades 1, 2 and 3: pullets, gestating, and lactating pigs
Grades 1, 2, 3, and 4: dairy, beef, goats, and horses.

Conversely, cassava foliage meal is characterized by its high fiber and protein levels. Depending on the leaves:stems ratio and the age of the plant, crude fiber may range between 18% and 30%, while the protein content may vary from 16% to 28%. Under practical conditions, the green plant top or its third superior aerial part, should be considered as the recommended material to be processed.

The plant top is a mixture of leaves, petioles, and primary and secondary stems. The proportion in which these elements participate in the final product will determine the nutritional quality of the foliage meal. Table 27-20 illustrates the differences in separate samples of the foliage components.

Different alternatives may be considered when foliage tops are harvested for feeding purposes: a single cut may be obtained simultaneously with the root at harvesting time, or the top cuts may be obtained periodically (every 2–3 months) without root harvesting. Moreover, the cassava crop can be completely oriented for just foliage production.

It is also important to note that foliage meal from early regrowth (less than 3 months) will provide better nutritional characteristics (more than 18% protein and less than 20% fiber) in contrast with late regrowths (less than 18% protein and more than 20% fiber) as is illustrated in Table 27-21.

Performance Results with Dried Cassava Roots in Poultry Feeding

The results of some selected experiences will be presented in the following tables, where CRM is included in medium to high levels of the diet for broilers and layers. Most of the early demonstrations were conducted with ground diets and free choice consumption. In the more recent experiences, pelletized

diets were introduced as an important mechanism to improve the performance of broilers and to reduce the dusty conditions in diets with high cassava meal content.

The economic considerations when CRM replaces corn or other cereal grains in commercial operations should consider the lower energy and protein values of the cassava root. These limitations normally indicate that CRM should have a cost not higher than 70% to 80% of the price of corn.

Dried CRM for broilers

Table 27-22 illustrates an early, but conclusive study to measure the effect of diets where cassava meal gradually replaced corn as the energy source for broiler diets, without the adjustment of energy level. The results show a slight decrease in performance mainly associated with higher levels of cassava meal due to the reduction in metabolizable energy.

The inclusion of vegetable oil in diets with high cassava meal compensates the lower energy and provides an improvement in performance of broilers, as is illustrated in Table 27-23, where the diets contained different levels of cassava meal but similar protein and metabolizable energy concentrations. In addition, vegetable oil provides an increment in linoleic acid, which is an essential fatty acid for poultry. Total replacement of corn by cassava meal did not affect body weight or feed conversion of broilers.

Pelletized diets provided an additional benefit to high cassava meal diets at the different levels of cassava meal inclusion for broiler diets (Table 27-24).

Dried CRM for layers

The inclusion of dried cassava roots in layer feeding has also been experimented in different comparisons where corn is gradually replaced. In several of the earlier studies there was not a precise adjustment in some of the nutrients, mainly metabolizable energy, methionine, and linoleic acid (Table 27-25), which lowers the production performance.

Egg production and feed conversion ratio are affected in most cases when cassava meal replaces corn without adjustments in the diet, especially at high levels of substitution. Egg yolk pigmentation is also affected with high levels of CRM due to the absence of xantophyl pigments in roots, in contrast with its high concentration in cassava leaves.

Once the nutrient adjustments are introduced in diets with high levels of CRM, improvement on production parameters are generally obtained. The essential aminoacid methionine and the energy concentration are important factors in egg production and egg size, while linoleic acid is mainly involved in egg size. Tables 27-26 and 27-27 illustrate the effect of high levels of CRM when the diets are correctly balanced in energy and methionine. The results obtained in egg production, egg size, and feed conversion ratio are generally comparable with corn-SBM diets. The use of FFSB (8% linoleic acid) shows a favorable effect in the size, pigmentation, and weight of eggs (Table 27-27).

Performance Results with Dried Cassava Roots in Swine Feeding

Several experiments have been conducted with swine in order to demonstrate the effect of different levels of CRM in conventional feeding programs for piglets, growing, finishing, gestating, and lactating pigs. Partial to total substitution of cereal grains, inclusion of different protein supplements, and comparisons between sweet and bitter varieties of cassava have been analyzed in a large number of feeding trials.

As already mentioned in poultry feeding, with high levels of cassava meal the dustiness of the diet may become one of the main limitations for an efficient use of the mixed diet. The addition of sugarcane molasses, animal fat, or vegetable oil helps in the prevention of the dusty presentation and to avoid feed waste. Whenever it becomes possible, pellet processing is the best practice when high levels of cassava meal have to be included.

Similarly to poultry feeding, the cost of cassava meal compared to corn or other cereal grains is the key factor in deciding the economics of its use. The lower energy and protein concentration in CRM generally bears to an adjustment in the price of cassava meal, which, in general, should be equivalent to around 70%–80% of the price of corn.

Dried CRM for growing-finishing pigs

Feeding practices with dried cassava roots have been extensively studied during the growing-finishing stage of pigs. Some of the most representative feeding studies have been selected in the following tables, which summarize the performance results under different environmental and management conditions.

Table 27-28 compares sweet (less than 80 ppm HCN) and bitter (150–200 ppm HCN) varieties of CRM as the main source of energy in diets for growing pigs. Although the sun drying process partially reduced the HCN content, there is still a negative effect in consumption and weight gains of the pigs. However, this effect is very marginal compared to the effect observed when the roots are fresh, since all HCN remains in the tissue of the unprocessed product.

In most studies the inclusion of low HCN cassava root varieties can replace cereal grains without detrimental effects in growing-finishing pigs, even though in some trials no adjustments were made in the energy levels of high cassava diets (Table 27-29). Yields of lean meat cuts were not affected and no clear differences were noticed on fat percentages, fat quality, or saturation index (iodine number), although all animals showed a larger proportion of body fat proper to the crossbred pigs available at the experimental time.

The addition of cane molasses, raw sugarcane, or animal fat to diets based on CRM as the only energy source, did not contribute to the improvement of feed consumption or performance in growing pigs, as shown in Table 27-30. Animal fat addition decreased feed consumption and improved the feed conversion ratio, due to the increment in energy density of the diet. Unexpectedly, methionine supplementation did not improve the performance of growing pigs in this study. Nevertheless, in other experiments the beneficial effect of methionine supplementation to diets containing high levels of cassava has been observed.

Table 27-31 illustrates the positive response to methionine, compared to other sulfur sources in an effort to explore the effect of sulfur in cassava based diets with high levels of HCN.

Dried CRM for gestating and lactating sows

The continued use of high levels of CRM has also been tried during gestation and lactation in order to evaluate its effects on the mothers and on their offspring. Tables 27-32 and 27-33 summarize the results observed in performance of Yorkshire and Duroc x Yorkshire females during gestation and lactation, as well as in piglets during the lactating period.

In Tables 27-32 and 27-33 a corn-based diet was compared with diets where the corn was completely replaced by CRM. The 16% protein diets were offered in controlled quantities during gestation and at free choice during lactation. In general, there are no detrimental effects in performance due to cassava usage, although the first trial (Table 27-32) shows a smaller litter size with no differences in the individual weight of piglets. Conversely, Table 27-33 shows no differences in litter size, individual piglet weight, or total litter weight. The weight differential between breeding time and weaning time of females was not affected when CRM totally replaced corn.

Dried CRM for piglets

Creep feed for lactating piglets with increasing levels of cassava meal has been offered from 10 days up to weaning time. The first trial results during a lactation period of 30 days are summarized in Table 27-34. No differences were observed in performance of piglets with levels up to 20% of CRM in the diet. Weight gains, feed consumption, and feed conversion were equivalent to piglets receiving diets with corn. In a second feeding trial (Table 27-35), creep feed diets with 0%, 20% and 40% cassava meal were compared in order to measure consumption of lactating piglets when fed at free choice up to weaning time at 56 days. There was a positive effect in feed consumption associated with higher levels of cassava meal. Palatability of the diet and performance of piglets were clearly improved with increasing amounts of CRM, even though dustiness was greater in these diets.

Performance Results with Dried Cassava Roots in Ruminant Feeding

CRM diets have been used at different stages of ruminant nutrition. A selection of experimental diets and production performance obtained in calves, milking cows, and growing-finishing steers are included in the following tables.

Dried CRM for calves

Tables 27-36 describes different feeding treatments with variable levels of CRM for early feeding of calves. At low levels of cassava meal, performance was maintained close to those of the corn or sorghum-based diets but levels higher than 25% usually produced a slight decrease in consumption and growth rate of calves. In this experiment calves were raised with cow milk until the sixth week, and from this moment until the fourth month the dry diet was provided at free choice plus forages (alfalfa hay or ensiled sorghum) at free choice.

Dried CRM for dairy cows

The results from two experiments with dairy cows are described in the following tables. Table 27-37 presents results in milking cows where dried diets were supplied in addition to sorghum silage. The inclusion of CRM in substitution of 50% of the sorghum in the dried feed did not affect milk production. Similar results were observed when cassava meal replaced oats as the main energy source of the dried supplement (Table 27-38).

Dried CRM for growing-finishing steers

Steers under intensive grazing or under total confinement have also been included in experiments where CRM has been used as a component of the dried feed supplements.

Table 27-39 shows the results with growing-finishing steers under intensive grazing (4.8 head/ha) conditions, supplemented with controlled quantities of dry feed based on CRM, cane molasses, urea, and blood meal. Animals with higher levels of cassava consumption showed a slight increase in daily weight gain.

Table 27-40 shows the results with feedlot steers consuming a controlled amount of sorghum silage plus a free choice of dry supplement based on cassava meal or sorghum. Daily feed consumption of the supplement decreased with increasing levels of cassava meal. Conversely, sorghum silage consumption was increased to fulfill the energy deficit. Nevertheless, there was a negative effect on daily weight gains associated with lower supplement consumption as a result of increasing levels of CRM in the diet.

Performance Results with Dried Cassava Foliage in Poultry Feeding

In general, dried cassava foliage does not have a significant potential for poultry feeding due to its low energy level and poor palatability. As it happens with other forage products, fiber is a limiting factor which dilutes the concentration of the essential nutrients, mainly energy and protein. Although the protein level in good quality dried cassava foliage is high (18%–26%), the high fiber and low energy concentration limits its use to levels not higher than 10%. The aminoacid profile is characterized by the high lysine content (7.2 g/100 grams of crude protein) and the low methionine level (1.7 g/100 grams of crude protein).

An important factor in cassava foliage, relevant to poultry feeding, is its high content in xanthophyll pigments (500-600 mg/kg), which improves the pigmentation of skin in broilers and egg yolk in layers when used at levels between 5% and 8% of the diet.

The best quality forage meal contains a larger proportion of leaves and young stems which can be easily obtained from plants less than 3 months of age. The nutritional quality decreases as the plant gets older and the leaf:stem ratio changes to a lower proportion of young leaves.

Though HCN levels in dehydrated foliage are generally over 200 ppm, the low foliage percentage recommended for poultry and pigs usually does not present a danger of toxicity; however, in some cases, a HCN content can affect the palatability of the diet, and, eventually, cause toxicity problems.

It is suggested than no more than 6% of forage meal is included in broiler diets and no more than 10% in layer diets. The addition of methionine and fat to these diets is a recommended practice in order to overcome the deficit in these nutrients. At this low level of usage, the cyanide content in dried forage does not constitute a limiting factor.

Dried cassava foliage meal for broilers

Low (less than 6%) levels of cassava foliage meal may be used, mainly as a natural skin pigmenter, with a very light negative effect on feed consumption and weight gain. When the inclusion of the foliage is higher than 6%, the growth rate and feed consumption are negatively affected. When a high level (more than 15%) of cassava foliage is compared with alfalfa meal, the performance results are negatively affected in both treatments, but a larger effect is observed for cassava foliage (Table 27-41).

Table 27-42 also shows the results of diets with high levels (20%) of cassava foliage and the effect of methionine supplementation, since this aminoacid becomes limiting in this type of diets. The growth rate is negatively affected with high foliage content. However, up to 0.3% methionine addition improves the growth performance, although it does not reach the levels obtained by broilers consuming high energy diets.

Dried cassava foliage meal for layers

Little information is available in performance of layers fed cassava foliage diets, except in relation to its pigmenting effect on egg yolk. Table 27-43 shows the effect of low levels (2.5% and 5.0%) of cassava foliage meal when added to white corn diets in comparison with yellow corn diets. There is a linear response to higher levels of cassava foliage, although the pigmenting effect of yellow corn is still superior at this low level of foliage meal. In recent evaluations, cassava foliage meal at levels around 8% show a pigmenting effect similar to yellow corn, without affecting the performance of layers.

Performance Results with Dried Cassava Foliage in Swine Feeding

Once again, since pigs are monogastric animals, the inclusion of cassava foliage does not have an important role in commercial feeding programs, especially for high energy demanding growing-fattening pigs. Gestating and lactating females provide a larger space for the inclusion of a higher percentage of cassava foliage, considering the need for crude fiber during these stages.

The high fiber content, low energy, and poor palatability of dried cassava foliage are the main limiting factors for its inclusion in swine diets.

As a general recommendation it is suggested that no more than 8% of cassava foliage meal may be included in the diets of growing-finishing pigs, no more than 15% in gestating females, and no more than 10% in lactating females. At this low level of usage, the cyanide content in dried foliage (200–500 ppm) does not constitute a potential danger of cyanide poisoning in pigs. Methionine and fat supplementation is a recommended practice whenever cassava foliage is included.

Dried cassava foliage meal for growing-finishing pigs

Some of the early studies (Tables 27-44 and 27-45) showed the effect of including more than 10% of dried cassava foliage in growing-finishing feeding programs. In every case there was a reduction in feed consumption and growth rate of pigs, even though the non-cassava foliage diets still did not have the needed energy concentration for modern genetic pig breeds. In the high demanding energy diets of modern lines, metabolizable energy and methionine supplementation are key factors to partially counteract the poor production performance with high cassava forage diets. These nutrient adjustments may be obtained if the dried cassava foliage is included at levels not larger than 6%–8%.

Recent Developments with Dried Cassava Roots and Foliage Meal for Poultry and Swine

Although cassava meal can be combined with several ingredients in order to obtain balanced diets, the FFSB has become a strategic product considering its nutritional benefits which somehow complements some of the cassava limitations (Figures 27-16 and 27-17). FFSB refer to the heat processed soybeans, through extrusion or toasting processes (Figures 27-18 and 27-19), which will guarantee the needed temperature to eliminate the antinutritional factors (trypsin inhibitors, hemaglutinins, and lipoxygenase) present in raw soybeans.

The inclusion of cassava meal and FFSB as the main ingredients in diets for poultry and swine, simplifies the feeding programs in most of their productive stages, where there is a high need for metabolizable energy, essential aminoacids, lecithin,

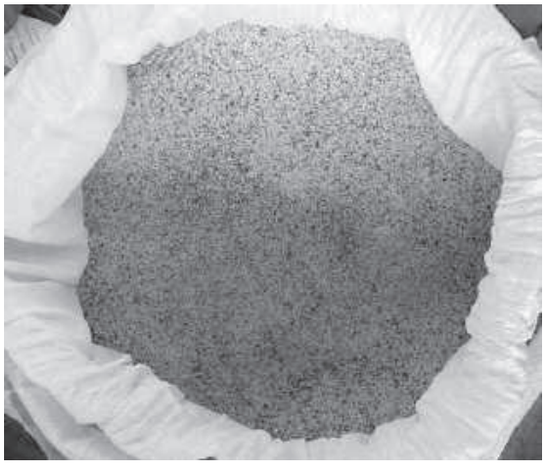


Figure 27-16. Cassava root flour.

Figure 27-17. Fullfat soybeans.

Figure 27-18. Soybean toaster.

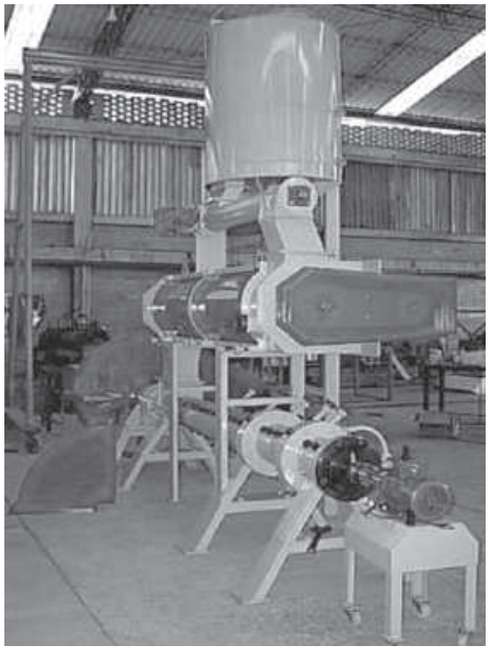


Figure 27-19. Soybean extruder.

and fatty acids. Cassava is rich in starches and energy, but poor in essential aminoacids and fatty acids. On the other hand, FFSB are poor in starches, but rich in essential protein, lecithin, and essential fatty acids.

As Table 27-46 indicates, the low concentration of some essential nutrients observed in CRM can be satisfactorily compensated by their high concentrations in FFSB.

In consideration to the previous observations, the following sections of this chapter will present various animal feeding programs for broilers, layers, and pigs, based on different combinations of CRM and FFSB (extruded or toasted FFSB).

Performance Results with CRM and FFSB in Broiler Feeding

Since the balanced feed for broilers is generally prepared in the form of a pelletized or crombelized product, the recommendations for the levels of CRM that can be used may go as high as the total substitution of cereal grains in diets for starting and finishing broilers. The dusty feature of diets with high levels of cassava meal is totally overcome during the pelletization process, without the need of agglutinants or special additives. The high oil content of these diets, due to the inclusion of FFSB, is also an important factor to improve the pellet quality. Moreover, this type of diets allows the incorporation of maximum levels of CRM (45%–50%) as well as the needed quantity of cassava foliage meal (5%–6%) in order to guarantee the proper pigmentation of broiler skins.

When the starting point is the mixture of CRM, cassava foliage meal, FFSB, and SBM, it is possible to formulate perfectly balanced diets for broilers, following the most recent National Research Council (NRC, 1998) nutritional requirements, in which these three ingredients can represent more than 95% of the total feed, as illustrated in Table 27-47. Table 27-48 provides more detailed information about the nutritional composition of the above mixtures.

Performance results based on diets with low and medium levels of cassava meal in broilers

Even though the results obtained with the total replacement of cereal grains by cassava meal in pelletized diets have demonstrated that this criterion may become a viable practice in commercial feeding programs for broilers, it is possible that in many occasions, it is more convenient to use a partial substitution of the traditional cereal grains. This last modality is even a must when the diets are prepared in meal or flour presentation, considering the dusty characteristics of the CRM. Nevertheless, pelletization or extrusion is always a very useful practice whenever CRM or other dusty products are used in a considerable percentage of the diet.

Tables 27-49 and 27-50 illustrate the composition of the diets with intermediate levels of cassava meal

plus FFSB, in which the objective was the substitution of about 40%–50% of the corn or sorghum used in pelletized diets for the starting (0–21 days) and finishing (21–42 days) phases.

Based on previous laboratory trials conducted with a small number of animals, the above diets were then tested with a larger number of chickens on commercial farms in two locations: diets from Table 27-49 were tested under mild environmental conditions in the Cauca Valley of Colombia (24 °C, 78% humidity, 1050 masl) and diets from Table 27-50 were tested under a warmer environment (32 °C, 86% humidity, 40 masl) near the north coast of Colombia (Cereté, Córdoba). A total of 15,350 birds were used in the first trial and 72,400 birds were used in the second trial. In both cases, the cassava diets were compared with corn-SBM commercial diets with similar nutrient composition.

The results obtained with respect to the performance of broilers are shown in Tables 27-51 and 27-52. In general, it can be concluded that broilers consuming diets with a substitution of 50% of corn or sorghum by CRM had the same (or better) performance than those that consumed the conventional diets with cereal grains. In terms of weight increase, feed conversion ratio, and carcass yield, there were no significant differences. Adverse effects, above the normal figures, were not observed in terms of mortality or morbidity as a result of the inclusion of CRM as the main energy source plus FFSB as the main protein source. Differences in humidity of the litter used in the different poultry houses were not appreciable either.

Performance results based on diets with maximum levels of cassava root and cassava foliage meal in broilers

Experimental work conducted at CIAT compared a commercial pelletized broiler diet based on corn and SBM with pelletized diets totally based on cassava root and cassava foliage meal supplemented with FFSB. The comparison between solar dehydration and artificial dehydration of cassava roots was also included in the same study. A detailed description of the experimental diets as well as its nutritional composition for the starting (0–21 days) and finishing (21–42 days) phases is presented in Tables 27-53 and 27-54.

Performance results demonstrated the feasibility of preparing broiler feeding programs totally based on CRM as the main energy source and limited levels of cassava foliage meal as a partial protein source, as long as FFSB is included to provide the deficit of energy, fatty acids, and protein.

Table 27-55 shows the overall performance of broilers until 42 days when the trial was finished. All groups consuming cassava products and FFSB obtained similar or better weight gains and feed conversion ratios when compared to the control group fed with corn and SBM. The consumption of the balanced feed was not affected by the inclusion of high levels of cassava meal during the starting and finishing production phases.

In the treatments that included CRM, the effect of artificial drying was superior to the sun drying procedure. Both steam and gas drying equipments were equally effective for the drying process. The high temperature obtained during the artificial drying facilitates the gelatinization of starches and the control of pathogenic germs. These two factors have probably an important influence on the superior performance of these groups when compared with the sun dried cassava group.

Although the diets with a high percentage of cassava meal and FFSB contain high potassium levels in their final composition, it was not observed to have an adverse effect on the chicken manure and humid litters. Humidity of the manure was analyzed at weekly intervals and no significant differences were observed. Additionally, the measure of the moisture content of the litter did not indicate differences among groups.

Through external measurements of the skin and by checking the chicken carcasses after sacrifice, pigmentation of legs, skin, and internal fat were analyzed. The groups with diets based on just cassava roots showed a poor pigmentation, while the group with cassava roots and foliage showed a pigmentation grade similar to that of the control group fed with diets based on yellow corn. The visual appreciation on a scale from 1 (pale) to 5 (optimum pigmentation), gave both the control and the group fed with cassava roots plus foliage meal a grade of 4, while the other groups without cassava foliage obtained a grade of 2 on the pigmentation scale.

Performance Results with CRM and FFSB in Layer Feeding

Feeding programs for layers generally involve the use of diets in meal presentation, which becomes an important limitation for the inclusion of high levels of CRM due to the dustiness of the final product. This

situation is no longer a problem when low or medium levels of CRM are included. Unless the possibility of using pelletized or crombelized diets is considered, it is difficult to incorporate levels higher than 25% of cassava root flour.

In relation to cassava foliage meal, it is also recommended that its use in diets should not exceed levels of 6% in order to minimize the negative effects on palatability or high HCN presence in the feed. When high quality foliage meal is included at levels between 5% and 6%, a satisfactory pigmentation of egg yolks is obtained, due to the presence of natural xanthophylls.

Table 27-56 illustrates an example of diets for replacement layer chickens and laying hens based on maximum levels of CRM combined with FFSB and 6% foliage meal, in which these ingredients can represent up to 85% of the total feed. The corresponding nutritional components are shown in Table 27-57. Tables 27-58 and 27-59 show similar examples in which CRM has been restricted to levels not higher than 25% of the chicken and layer diets.

Performance results based on diets with medium levels of cassava meal for laying hens

Field experiments have been conducted in one of the main poultry regions of Colombia (Cauca Valley). In all feeding trials the diets were prepared in meal or flour form and the level of replacement of corn was not more than 50%.

Tables 27-60, 27-62, 27-64, and 27-66 show the composition of the diets used in several experiments conducted in commercial layer farms, during different laying periods. CRM was included at levels from 10% to 20% of the total diet. FFSB, either extruded or toasted, was used in all cases at levels not higher than 20%.

Results in productivity of layers fed the experimental diets already described are presented in Tables 27-61, 27-63, 27-65, and 27-67.

No important differences were observed in the production parameters of all experiments. Laying percentage and feed conversion was similar in diets with no CRM compared to diets with 10%, 15%, and 20% CRM. A slight reduction in egg laying percentage and feed conversion was observed in brown layers fed with 10% or 20% CRM (Table 27-67).

Performance Results with CRM and FFSB in Swine Feeding

Nutritional considerations already analyzed in poultry feeding based on cassava and FFSB have a close similarity with other monogastric animals, mainly swine. CRM and cassava foliage meal can partially or totally replace the conventional cereal grains in commercial diets. FFSB also provide key nutrients which will complement the nutritional weaknesses of cassava.

When cassava root flour is included at levels above 20%, the pelletization or extrudization processes are always recommended, especially for starting piglet diets. In growing-finishing pigs and breeding animals, pelletization is also recommended, although the addition of molasses, fat, or FFSB can alleviate the dustiness of high cassava meal diets. As in broiler and layer feeding, it is possible to formulate balanced diets for the different production stages in pigs, based in the mixture of cassava roots and cassava foliage meal, FFSB, and SBM, in which these ingredients can represent more than 95% of the total feed, as illustrated in Table 27-68.

In recent studies, the inclusion of high levels of CRM has been successfully proven in finishing diets where FFSB has been also included. The total replacement of cereal grains by CRM is possible once the nutritional adjustments are introduced (Tables 27-69 and 27-70).

Table 27-1. Main nutrients in cassava roots and foliage.

Nutrients	Fresh products		Dry products	
	Roots	Foliage	Roots	Foliage
Moisture, %	64–66	70–72	12–14	12–14
Starch, %	28.0	4.1	73.0	14.0
ME, Mcal/kg[a]	1.20	0.34	3.0–3.1	1.38
Protein, %	1.10	6.5	2.80	21.0
Fiber, %	1.20	4.7	3.2	18.4
Fat, %	0.47	1.8	1.2	5.9
Ash, %	1.12	1.7	2.9	5.6
Methionine, %	0.01	0.07	0.03	0.28
Cystine, %	0.008	0.04	0.02	0.16
Lisine, %	0.02	0.37	0.06	1.6
Triptophane, %	—	0.05	—	0.2
Threonin, %	0.01	0.27	0.03	1.17
Calcium, %	0.10	0.52	0.30	1.7
Phosphorus, %	0.15	0.09	0.40	0.26
Potasium, %	0.25	0.34	0.65	1.2

a. Megacalories of metabolizable energy (ME) per kilogram of product.

SOURCE: Buitrago (1990).

Table 27-2. The effect of using fresh cassava roots and protein supplements in free choice supply to Duroc x Landrace growing pigs (15–50 kg)[a] on their performance.

	Diet 1	Diet 2	Diet 3	Diet 4
Protein supplement (Ingredients %)				
Cottonseed meal	16.0	23.0	23.0	—
Sesame meal	18.0	25.0	—	25.0
Peanut meal	14.0	—	25.0	23.0
Fish meal	36.0	36.0	36.0	36.0
Meat meal	14.2	14.2	14.2	14.2
Lysine	0.2	0.2	0.2	0.2
Vitamin premix	0.6	0.6	0.6	0.6
Nutritional composition				
Digestible energy, Mcal/kg	2.85	2.83	2.88	2.77
Protein, %	54.2	53.9	56.0	52.9
Methionine, %	1.20	1.27	1.07	1.23
Lysine, %	3.19	3.18	3.28	3.15
Performance of pigs				
Daily weight gain, kg	0.59	0.57	0.64	0.53
Daily feed consumption:				
Fresh cassava, kg	3.24	3.24	3.15	2.98
Protein supplement, kg	0.50	0.45	0.52	0.51
Feed conversion ratio (DM)	2.66	2.63	2.44	2.79

a. Chopped fresh cassava roots and protein supplement offered in different feeders for free-choice consumption.

SOURCE: Contreras (1973).

Table 27-3. The effect of using fresh cassava roots and protein supplements in free choice vs. controlled supply for Duroc growing-finishing pigs (18–100 kg)[a] on their performance.

Parameter	Free choice fresh roots + protein supplement[b]		Corn-SBM diet[c]
	Controlled supplement	Free choice supplement	
Soybean meal, %	61.50	61.50	10.59
Cottonseed meal, %	20.50	20.50	3.53
Minerals and vitamins, %	18.00	18.00	4.55
Corn, %	—	—	81.33
Daily consumption			
Fresh roots, kg	3.89	4.05	—
Protein supplement, kg	0.73	1.17	—
DM consumption, kg	2.07	2.52	2.60
Protein consumption, kg	0.372	0.564	0.459
Performance of pigs			
Daily weight gain, kg	0.79	0.83	0.84
Feed conversion ratio (DM)	2.90	3.36	3.43

a. Chopped fresh cassava and protein supplement offered in different feeders for free-choice or controlled consumption.
b. Protein supplement with 43% protein.
c. Commercial concentrate with 16% protein.

SOURCE: Buitrago (1964).

Table 27-4. Fresh roots and protein supplement added with molasses or sugarcane for Yorkshire growing-finishing pigs (20–90 kg).

Parameter	Feeding regime[a]		
	Only roots	Roots + molasses	Roots + sugar
Daily consumption (kg)			
Fresh cassava roots	2.99	3.27	3.11
Protein supplement (40% protein)[b]	1.02	0.92	0.85
Total DM	2.03	2.27	2.17
Total protein	0.54	0.51	0.46
Pig performance			
Daily weight gain, kg	0.69	0.72	0.74
Feed conversion rate (DM)	2.97	3.16	2.93

a. Molasses and sugarcane were used in a proportion equivalent to 15% of the total diet.
b. Protein supplement based on soybean meal (80.0%), corn (8.5%), and minerals and vitamins (11.5%). Free choice supply in feeders separated from the cassava treatments.

SOURCE: CIAT (1975).

Table 27-5. Fresh roots and protein supplements prepared with different protein sources for Duroc x Landrace growing-finishing pigs (19–90 kg)[a].

	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5	Diet 6
Protein supplement (Ingredients, %)						
Soybean meal	78.10	—	—	—	—	—
Cottonseed meal	—	—	78.10	—	30.00	30.00
Meat meal	—	70.50	—	44.30	21.30	—
Blood meal				20.00	20.00	—
Fish meal	—	—	—	—	—	36.70
Corn	11.20	26.80	11.20	33.00	25.00	29.60
Vitamins and minerals	10.70	2.70	10.70	2.70	10.70	10.70
Protein level (%)	43.0	39.4	37.7	48.5	44.7	40.2
Daily consumption (kg)						
Fresh roots	4.00	3.40	3.13	3.88	4.00	4.08
Protein supplement	0.80	0.78	0.79	0.94	0.90	0.79
Total protein	0.34	0.31	0.30	0.44	0.40	0.32
Pig performance						
Daily weight gain, kg	0.72	0.68	0.59	0.72	0.72	0.68
Feed conversion rate	3.25	3.07	3.38	3.32	3.38	3.47

a. Both cassava roots and protein supplements were supplied at free choice in separated feeders.

SOURCE: Maner et al. (1978).

Table 27-6. Fresh roots and protein supplements with different protein levels for Yorkshire growing-finishing pigs (19–90 kg).

	Diet 1	Diet 2	Diet 3
Protein supplement (Ingredients, %)			
Soybean meal	26.73	53.15	79.56
Corn	67.27	37.85	8.44
Minerals and vitamins	6.0	9.0	12.0
Protein level (%)	20.0	30.0	40.0
Daily consumption (kg)			
Fresh roots	1.79	2.74	3.37
Protein supplement	1.39	1.00	0.75
Total DM	1.92	1.94	1.97
Total protein	0.34	0.40	0.39
Pig performance			
Daily weight gain, kg	0.71	0.67	0.65
Feed conversion rate	2.71	2.90	3.02

SOURCE: CIAT (1974).

Table 27-7. Performance of Yorkshire pigs fed with sweet vs. bitter cassava roots plus a protein supplement[a] with different protein levels.

	Sweet roots		Bitter roots[b]	
	Free choice supplement	Controlled supplement	Free choice supplement	Controlled supplement
Daily consumption (kg)				
Fresh roots	2.99	3.40	0.98	0.93
Protein supplement	0.81	0.82	1.21	0.22
Total DM	1.78	1.80	1.43	0.52
Pig performance				
Daily weight gain (kg)	0.66	0.77	0.56	—
Feed conversion ratio	2.99	2.61	2.86	—

a. 40% protein supplement in all treatments.
b. CMC-84 variety with 200 ppm cyanhydric acid.

SOURCE: CIAT (1973).

Table 27-8. Fresh cassava roots and protein supplementation in Duroc x Landrace gestating gilts.

	Feed treatment		
	Control pasture[a]	Cassava + supplement pasture[b]	Cassava + supplement confined[c]
Ingredients (%)			
Soybean meal	18.0	64.08	66.75
Cottonseed meal	—	20.53	20.53
Corn	74.8	—	—
Minerals and vitamins	7.20	15.39	12.72
Protein level (%)	16.0	40.0	40.0
Performance of gilts			
Weight gain in gestation, kg	19.90	24.90	37.70
Piglets/litter, No.	10.4	10.0	7.7
Piglet weight, kg	1.28	1.12	1.18
Litter weight, kg	13.31	11.20	9.08

a. Daily consumption/gilt: 1 kg of a corn-soybean meal diet.
b. Daily consumption/gilt: 1.7 kg of cassava roots and 0.4 kg of protein supplement.
c. Daily consumption/gilt: 3.1 kg of cassava roots and 0.62 kg of protein supplement.

SOURCE: Maner et al. (1978).

Table 27-9. Fresh cassava roots and protein supplementation as compared to a corn-soybean meal ration in Duroc x Landrace lactating sows.

	Corn-SBM[a]	Fresh roots + protein supplement[b]
Ingredients (%)		
Soybean meal	15.00	87.10
Corn	81.35	—
Minerals and vitamins	3.65	12.90
Protein level (%)	16.0	40.0
Daily consumption (kg)		
Corn-soybean meal diet	4.82	—
Fresh cassava	—	6.50
Protein supplement	—	1.21
Total DM intake	4.32	3.40
Performance of sows		
Weight at farrowing, kg	179.30	158.30
Weight at weaning, kg	190.30	165.80
Performance of litter at birth		
Piglets, No.	10.8	9.3
Individual weight, kg	1.18	1.36
Litter weight, kg	12.74	12.65
Performance of litter at weaning (35 days)[c]		
No. piglets	9.0	7.6
Individual weight, kg	6.03	7.63
Litter weight, kg	54.27	58.00

a. Control group with free choice consumption; SBM = soybean meal.
b. Cassava roots and protein supplement in a mixture to provide the equivalent to a 16% protein diet. Free choice consumption.
c. Piglets received the same creep feed at free choice.

SOURCE: Maner et al. (1978).

Table 27-10. The effect of using fresh cassava roots compared with ensiled cassava roots and foliage for Yorkshire x Landrace growing-finishing pigs (18–98 kg).

	Ensiled roots[a]	Ensiled roots+ foliage[b]	Fresh roots
Supplement ingredients (%)			
Corn	10.9	10.9	10.9
Cottonseed meal	78.1	78.1	78.1
Vitamins and minerals	11.0	11.0	11.0
Daily consumption (kg)			
Ensiled cassava roots (and foliage)	3.84	3.05	—
Fresh cassava roots	—	—	4.04
Protein supplement (38%)	1.01	1.01	1.01
Total protein	0.38	0.38	0.38
Pig performance			
Daily weight gain (kg)	0.77	0.64	0.75
Feed conversion ratio (DM)	2.92	3.17	3.09

a. Only chopped roots.
b. Chopped roots, leaves and stems.

SOURCE: Buitrago et al. (1978).

Table 27-11. The effect of feeding ensiled cassava roots with different protein supplements to Yorkshire growing-finishing pigs (16–90 kg) on their performance.

	Ensiled roots plus protein supplement				Corn-SBM[a] diet
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
Supplement ingredients (%)					
Soybean meal	44.0	—	88.0	—	8.5
Cottonseed meal	44.0	48.5	—	97.0	8.5
Fish meal	—	48.5	—	—	—
Sorghum	—	—	—	78.0	
Minerals and vitamins	12.0	3.0	12.0	3.0	5.0
Protein level (%)	41.0	47.0	44.0	52.0	15.5
Daily consumption (kg)					
Cassava root silage	2.85	3.01	3.10	2.98	—
Protein supplement	0.86	0.67	0.73	0.60	—
Control diet	—	—	—	—	2.06
Performance of pigs					
Daily weight gain (kg)	0.59	0.55	0.59	0.50	0.56
Feed:weight ratio (DM)	3.27	3.31	3.24	3.50	3.31

a. SBM = soybean meal.

SOURCE: Buitrago et al. (1978).

Table 27-12. The effect of feeding ensiled cassava roots with different storage time and added salt to Yorkshire growing-finishing pigs (22–95 kg) on their performance.

Age of silage	Salt addition	Silage consumption	Supplement consumption[a]	ADG[b]	FCR[c]
> 6 months	—	3.30	0.78	0.63	3.34
	2%	2.87	0.78	0.62	3.10
< 6 months	—	3.45	0.78	0.63	3.46
	2%	3.20	0.78	0.63	3.27

a. 40% protein supplement with the following composition: 44% soybean meal, 44% cottonseed meal, 12% minerals and vitamins.
b. ADG = Average daily weight gain.
c. FCR = Feed conversion ratio.

SOURCE: Buitrago et al. (1978).

Table 27-13. Ensiled cassava roots (ECR) and protein supplement for Yorkshire lactating sows.

	ECR + supplement	Corn + supplement	Mixed corn-SBM[a]
Feed ingredients (%)			
Corn	—	—	78.1
Soybean meal	78.0	56.0	16.4
Minerals and vitamins	22.0	44.0	5.5
Protein level (%)	40	28	16
Daily feed consumption of sows (kg)			
Cassava silage	9.35	—	—
Corn	—	4.27	—
Protein supplement	1.11	0.66	—
Complete diet (corn-SBM)	—	—	4.54
Performance of sows			
Weight at farrowing, kg	140.9	168.5	155.4
Weight at weaning (35 days), kg	151.2	182.3	179.7
Performance of litters at birth			
Piglets, No.	10.6	10.0	10.7
Individual weight, kg	1.09	1.16	1.12
Total litter weight, kg	11.50	11.60	12.04
Performance of litters at weaning (35 days)[b]			
Piglets, No.	8.22	7.00	8.11
Individual weight, kg	5.54	4.95	5.33
Total litter weight, kg	45.51	34.66	43.23

a. SBM= soybean meal.
b. Piglets consumed the same creep feed at free choice.

SOURCE: Buitrago et al. (1978).

Table 27-14. Fresh cassava roots and protein supplementation in Holstein growing heifers[a].

	Commercial concentrate	Fresh cassava roots + protein supplement
Ingredients for supplemental feeding (%)[b]		
Corn	59.00	—
Sugarcane molasses	10.0	12.0
Wheat bran	14.0	16.3
Cottonseed meal	13.0	61.0
Urea	1.5	3.7
Minerals and vitamins	2.5	7.0
Daily consumption (kg)		
Commercial concentrate	2.64	—
Protein supplement	—	1.08
Cassava roots (DM)[c]	—	1.56
Sugarcane tops (DM)[c]	4.82	4.17
Total DM intake (kg)	7.46	6.81
Performance of heifers		
Initial weight, kg	191.8	190.6
Final weight, kg	366.8	377.3
Daily weight gain, kg	0.78	0.83

a. Heifers on group confinement from 8 to 16 months.
b. Heifers in the control group received 3 kg of commercial concentrate per day.
Heifers in the cassava group received 4.5 kg of fresh cassava and 1.23 kg of protein supplement per day.
Besides the supplemental feed all heifers received fresh sugarcane tops *ad libitum*.
c. Daily consumption expressed as dry matter (DM).

SOURCE: Pineda and Rubio (1972).

Table 27-15. Fresh cassava roots and protein supplementation in white Fulani milking cows[a].

	Commercial concentrate	Fresh cassava roots + protein supplement
Ingredients for supplemental feeding (%)[b]		
Corn	50.0	—
Palm cake	40.0	50.0
Peanut cake	10.0	50.0
Nutrient content (%)		
DM	90.0	91.0
Protein	15.7	26.7
Fiber	5.3	6.6
Fat	4.9	9.7
Performance of heifers		
4% fat corrected milk (kg)	6.8	7.2

a. Confined cows during an 84-days lactation period.
b. Cows in the control group received 0.42 kg of concentrate per kg of milk produced. Cows in the cassava group received 0.75 kg of fresh cassava roots plus 0.20 kg of protein supplement per kg of milk produced. Besides the supplemental feed all cows received star grass hay.

SOURCE: Olaloku et al. (1971).

Table 27-16. Fresh cassava roots and protein supplementation in growing-finishing Gyr x Brown Swiss steers[a].

	Cassava + commercial concentrates	Protein supplement		
	Diet 1	Diet 2	Diet 3	Diet 4
Ingredients (%)				
Corn	—	34.0	—	—
Rice polishings	—	53.0	—	—
Cottonseed meal	75.0	10.0	16.3	15.3
Corn husks	—	—	81.4	—
Cottonseed husks	—	—	—	82.4
Urea	12.0	—	—	—
Minerals and vitamins	13.0	2.3	2.3	2.3
Nutrient content (%)				
Protein	64.65	13.95	9.58	9.09
TDN	45.0	63.0	50.0	48.0
Ca	4.1	0.93	0.74	0.82
P	1.02	0.98	0.93	0.94
Daily feed consumption (kg)[b]				
Elephant grass	9.8	9.8	9.8	9.8
Fresh cassava	15.8	—	—	—
Protein supplement	1.6	—	—	—
Commercial concentrate	—	8.9	5.6	9.6
Total DM intake	8.4	9.3	6.4	9.9
Performance of steers				
Initial weight, kg	252	252	252	252
Final weight, kg	402	432	346	359
Daily weight gain, kg	1.39	1.66	0.87	0.99
Carcass yield, %	56.7	54.0	46.0	50.4

a. 22–24 month old steers.
b. Cassava roots were supplied at free choice in a 10:1 ratio with the protein supplement. Commercial feeds were supplied at free choice.

SOURCE: Terleira et al. (1975).

Table 27-17. Fresh cassava foliage as a complement to grazing Holstein heifers[a].

Feeding program	Diet 1	Diet 2
Daily consumption (kg/day)		
Fresh cassava foliage	7.50	—
Fresh alfalfa	—	10.00
Cane molasses	0.50	0.50
Mineral salt	*Ad libitum*	*Ad libitum*
Performance of heifers		
Initial weight, kg	189.3	183.6
Final weight, kg	256.3	241.3
Daily weight gain, kg	0.68	0.59

a. Growing heifers on star pangola grazing lots.

SOURCE: Zapata et al. (1985).

Table 27-18. Fresh cassava foliage and elephant grass for crossbred Zebu finishing steers on group confinement[a].

Feeding program	Diet 1	Diet 2	Diet 3
Elephant grass, % of mixture[b]	100	75	50
Cassava foliage, % of mixture	—	25	50
Performance of steers			
Initial weight, kg	265.5	276.3	270.0
Final weight, kg	342.5	392.7	379.0
Daily weight gain, kg	0.31	0.46	0.44
Feed conversion rate	17.6	13.7	13.7

a. Growing steers on group confinement.
b. Fresh mixture offered for free choice consumption.

SOURCE: Moore (1976).

Table 27-19. Quality grading of cassava root meal based on energy concentration.

Grade	Raw fiber (%)	Ash (%)	Fiber + azsh (%)	Metabolizable energy (Mcal/kg)
1	< 2.8	< 2.0	< 4.8	3.30
2	< 3.6	< 2.5	< 6.1	3.15
3	< 4.5	< 3.2	< 7.7	2.92
4	< 5.2	< 4.0	< 9.2	2.60

SOURCE: Buitrago (1990).

Table 27-20. Nutritional composition of cassava foliage meal with different proportions of leaves, petioles, and stems[a].

Nutrients, %	Leaves	Leaves and petioles	Leaves, petioles, and stems
Protein	22.7	21.6	20.2
Ash	10.9	9.8	8.5
Fat	6.3	6.3	5.3
Fiber	11.0	11.6	15.2
Calcium	1.68	1.70	1.68
Phosphorus	0.29	0.24	0.28
Potassium	0.69	0.60	1.09

a. Products with 8%-10% humidity.

SOURCE: Van Poppel (2001).

Table 27-21. Nutritional composition of cassava foliage meal at different harvesting times.

Main nutrients	Cassava foliage meal[a]		
	2–3 months	5–6 months	More than 8 months
Protein, % of DM	22.0	18.0	16.0
Fiber, %	16.0	20.0	26.0
Ash, %	5.5	5.8	5.8
Fat, %	5.2	5.6	5.6
Calcium, %	1.6	1.7	1.7
Phosphorus, %	0.26	0.28	0.28
TDN[b],%	68.0	66.0	58.0
DE[b], Mcal/kg	2.94	2.65	2.40

a. Third superior top (including leaves, petioles, and young stems).
b. TDN = total digestible nutrient; DE = digestible energy.

SOURCE: Buitrago (1990).

Table 27-22. Different levels of cassava root meal in diets for broilers[a].

	Cassava content							
	0		15%		30%		45%	
	S[b]	F[b]	S	F	S	F	S	F
Ingredients (%)								
Cassava root meal	0	0	15.0	15.0	30.0	30.0	45.0	45.0
Corn	59.9	64.0	42.9	47.4	26.3	30.7	9.7	14.1
Soybean meal	30.7	27.6	31.0	28.2	32.0	29.0	33.0	30.0
Fish meal	6.0	4.0	7.3	5.0	7.9	5.8	8.5	6.5
DL-methionine	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Minerals and vitamins	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Nutritional content								
ME, Mcal/kg	2.94	2.96	2.86	2.89	2.78	2.79	2.70	2.72
Protein, %	22.1	20.0	22.1	20.0	22.1	20.0	22.1	20.0
Methionine + cystine, %	0.87	0.80	0.87	0.79	0.86	0.80	0.86	0.79
Lysine, %	1.26	1.10	1.33	1.26	1.39	1.22	1.44	1.28
Performance of broilers								
Final weight, kg		1.47		1.50		1.45		1.39
Feed consumption, kg		3.33		3.39		3.48		3.29
Feed conversion ratio[c]		2.45		2.42		2.56		2.56

a. 0–8 weeks broilers.
b. S: starting: 0–5 weeks.
c. F: finishing: 5–8 weeks.

SOURCE: Enríquez V et al. (1977).

Table 27-23. Different levels of cassava root meal in iso-energetic diets for broilers[a].

	Cassava meal level (%)					
	0	20	30	40	50	58
Ingredients (%)						
Cassava root meal	0	20.0	30.0	40.0	50.0	58.0
Corn	54.0	30.0	16.0	9.0	3.9	—
Rice polishings	10.0	9.0	8.6	8.1	0	—
Fish meal	6.0	6.0	6.0	6.0	10.0	11.0
Soybean meal	27.0	31.0	35.0	32.0	32.0	27.0
Vegetable oil	—	1.0	1.4	1.9	2.0	2.0
Minerals and vitamins	3.0	3.0	3.0	3.0	2.1	2.0
Broiler performance						
Final weight, kg	2.04	2.05	2.04	2.03	2.04	2.04
Feed conversion ratio	2.61	2.59	2.64	2.61	2.56	2.53
Mortality, %	9.2	3.0	3.0	4.0	10.2	5.0

a. 0–6 week broilers.

SOURCE: Chou et al. (1974).

Table 27-24. Different levels of cassava root meal in pelletized iso-energetic diets for broilers[a].

	Cassava meal level (%)					
	0	10	20	30	40	50
Ingredients (%)						
Cassava root meal	0	10.0	20.0	30.0	40.0	50.0
Wheat	53.9	48.9	38.9	28.8	18.3	6.1
Corn	16.2	10.5	9.5	9.0	9.0	10.0
Soybean meal	16.3	14.8	13.8	12.8	11.6	11.1
Fish meal	5.0	6.8	8.9	10.5	11.4	12.5
Meat meal	3.0	3.0	3.0	3.1	4.3	5.0
Vegetable oil	3.1	3.9	3.9	3.9	3.6	3.5
DL-methionine	0.11	0.12	0.15	0.18	0.20	0.23
Minerals and vitamins	2.4	2.0	1.9	1.7	1.6	1.4
Nutritional composition						
ME, Megajoules/kg	13.7	13.5	13.8	13.9	13.9	13.8
Protein, %	19.3	19.7	20.0	19.4	19.4	19.8
Broiler performance						
Final weight, kg	2.31	2.39	2.30	2.31	2.31	2.30
Feed consumption, kg	4.45	4.49	4.39	4.59	4.38	4.62
Feed conversion ratio	1.92	1.88	1.91	1.99	1.90	2.01

a. 0–7 week broilers.

SOURCE: Stevenson and Jackson (1983).

Table 27-25. Performance of Leghorn layers with increasing levels of cassava root meal[a].

	Diet 1	Diet 2	Diet 3	Diet 4
Ingredients (%)				
Cassava root meal	—	10.0	25.0	50.0
Corn	62.0	50.0	32.1	2.1
Soybean meal	9.20	11.20	14.1	19.1
Rice bran	5.0	5.0	5.0	5.0
Copra meal	7.5	7.5	7.5	7.5
Fish meal	5.0	5.0	5.0	5.0
Meat and bone meal	2.5	2.5	2.5	2.5
Leucaena meal	3.0	3.0	3.0	3.0
Vitamins and minerals	5.8	5.8	5.8	5.8
Performance of layers				
Egg production, %	63.9	62.8	58.7	62.8
Weight of eggs, g	58	57	57	57
Feed conversion ratio	2.01	2.10	2.22	2.12
Yolk pigmentation[b]	6.0	6.0	5.0	3.5

a. 20–48 week layers.
b. Roche pigmentation scale.

SOURCE: Enriquez and Ross (1972).

Table 27-26. Performance of Hisex layers with increasing levels of cassava root meal[a].

	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5	Diet 6
Ingredients (%)						
Cassava root meal	—	10.0	20.0	30.0	40.0	50.0
Wheat	50.0	50.0	46.1	30.8	15.5	—
Corn	13.2	8.5	5.8	8.8	11.9	15.2
Barley	12.7	5.4	—	—	—	—
Fish meal	3.0	3.0	3.0	3.0	3.0	2.9
Soybean meal	7.9	9.9	11.9	14.2	16.5	18.8
Meat and bone meal	5.0	5.0	5.0	5.0	5.0	5.0
Animal fat	1.0	1.0	1.0	1.0	1.0	1.0
DL-methionine	0.05	0.06	0.07	0.08	0.09	0.09
Vitamins and minerals	7.2	7.1	7.1	7.0	7.0	6.9
Nutritional composition						
ME, Megajoules (MJ)/kg	11.0	11.0	11.0	11.0	11.5	11.1
Protein, %	15.9	15.7	15.9	15.8	15.9	16.0
Calcium, %	3.2	3.3	3.3	3.3	3.3	3.3
Phosphorus, %	0.64	0.63	0.63	0.60	0.58	0.57
Performance of layers						
No. eggs in 280 days	205	203	205	215	201	196
Weight of eggs, g	55	56	55	55	55	56
Daily feed consumption, g	119	119	111	113	112	109
kg of eggs/kg of feed	0.38	0.34	0.35	0.38	0.35	0.36

a. 27–67 week layers.

SOURCE: Stevenson (1984).

Table 27-27. Performance of Shaver layers with increasing levels of cassava root meal[a].

	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5	Diet 6
Ingredients (%)						
Cassava root meal	—	25.0	50.0	—	25.0	50.0
Sorghum	65.2	38.7	12.1	57.3	28.3	—
Soybean meal	11.3	14.8	18.3	—	—	—
Fullfat soybeans	—	—	—	15.3	20.0	24.7
Fish meal	7.0	7.0	7.0	7.0	7.0	7.0
DL-methionine	0.13	0.16	0.18	0.14	0.17	0.19
L-lysine	0.17	0.10	0.04	0.15	0.08	--
Corn cobs	6.6	4.9	3.2	10.6	10.1	6.8
Vitamins and minerals	9.6	9.3	9.2	9.5	9.3	11.3
Nutritional composition						
ME, Mcal/kg	2.65	2.65	2.65	2.65	2.65	2.65
Protein, %	15.5	15.5	15.5	15.5	15.5	15.5
Methionine + cystine, %	0.66	0.66	0.66	0.66	0.66	0.66
Lysine, %	0.98	0.98	0.98	0.98	0.98	0.98
Linoleic acid, %	0.78	0.51	0.24	1.92	2.01	2.10
Performance of layers						
Egg production, %	72.3	77.9	78.0	72.6	72.0	74.5
Weight of eggs, g	69	67	67	70	71	69
Daily feed consumption, g	125	133	132	122	121	120
Yolk pigmentation[b]	5.1	4.9	4.7	6.4	6.5	6.3

a. 42–62 week layers.
b. Roche pigmentation scale.

SOURCE: Hennesey and Ayala (1986).

Table 27-28. Bitter vs. sweet varieties of cassava root meal for growing Yorkshire pigs[a].

	Bitter[b]	Sweet[c]
Ingredients (%)		
Cassava root meal	71.0	71.0
Soybean meal	25.0	25.0
Vitamins and minerals	4.0	4.0
Performance of pigs		
Daily weight gain, kg	0.56	0.62
Feed consumption, kg	1.35	1.77
Feed conversion ratio	2.43	2.86

a. 38–58 kg.
b. CMC-84 variety with 150-200 ppm HCN.
c. 80 ppm HCN.

SOURCE: Gómez and Buitrago (1982).

Table 27-29. Root meal of low-HCN cassava varieties in substitution of corn for growing crossbred pigs and their effect on carcass characteristics[a,b].

	Diet 1	Diet 2	Diet 3	Diet 4
Ingredients (%)				
Cassava root meal	—	20.0	40.0	58.5
Corn	60.0	40.0	20.0	—
Meat meal	5.0	5.5	6.0	6.5
Sesame meal	20.0	23.0	26.0	29.0
Rice polishings	9.0	5.5	2.0	—
Cane molasses	5.0	5.0	5.0	5.0
Vitamins and minerals	1.0	1.0	1.0	1.0
Performance of pigs				
Daily weight gain, kg	0.79	0.78	0.84	0.80
Feed conversion ratio	3.50	3.60	3.30	3.30
Carcass characteristics				
Carcass length, cm	74.0	72.1	73.0	74.0
Dorsal fat, cm	3.10	3.40	3.30	2.90
Iodine number	69.3	64.5	71.3	69.3

a. 40–82 growing-finishing pigs.
b. 40 ppm HCN in fresh roots.

SOURCE: Chicco et al. (1972).

Table 27-30. Effect of adding cane molasses, raw sugar, or animal fat to diets based on cassava root meal for Landrace x Yorkshire pigs[a].

	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
Ingredients (%)					
Cassava root meal	65.9	65.7	55.5	55.5	55.5
Soybean meal	29.4	29.4	29.8	29.8	29.8
Cane molasses	—	—	10.0	—	—
Raw sugar	—	—	—	10.0	—
Animal fat	—	—	—	—	10.0
DL-methionine	—	0.2	—	—	—
Vitamins and minerals	4.7	4.7	4.7	4.7	4.7
Performance of pigs					
Daily weight gain, kg	0.71	0.68	0.69	0.68	0.63
Daily feed consumption, kg	1.94	1.88	1.89	1.84	1.59
Feed conversion ratio	2.73	2.76	2.74	2.70	2.53

a. 20–50 kg growing pigs. Isoproteic (16 %) diets.

SOURCE: Maner et al. (1978).

Table 27-31. Effect of adding methionine and other sulfur sources to diets based on cassava root meal for Landrace x Yorkshire pigs[a].

Feed treatment	Performance of pigs		
	Daily weight gain, kg	Daily feed consumption, kg	Feed conversion ratio
Control diet (CD)[b]	0.67	1.81	2.43
CD + 0.2% methionine	0.70	1.77	2.29
CD + 0.8% sodium thiosulphate	0.61	1.58	2.32
CD + 0.2% elemental sulfur	0.65	1.64	2.29

a. 20–50 kg growing pigs.
b. 16% protein control diet based on cassava root meal (70%), soybean meal (25%), and vitamin-mineral mixture (5%).

SOURCE: CIAT (1975).

Table 27-32. Cassava root meal vs. corn in diets for gestating and lactation sows[a].

	Diet 1	Diet 2
Ingredients (%)		
Cassava root meal	—	67.0
Corn	76.4	—
Soybean meal	18.8	28.2
Vitamins and minerals	4.8	4.8
Nutritional composition (%)		
Protein	16.0	16.0
Metionine + cystine	0.55	0.47
Lysine	0.77	0.92
Performance of sows		
Breeding weight, kg	127.6	118.5
Farrowing weight, kg	160.6	146.1
Weaning weight, kg	153.9	159.6
Performance of litters at farrowing		
Piglets, No.	10.0	8.4
Individual weight, kg	1.09	0.97
Litter weight, kg	10.9	8.15
Performance of litters at weaning		
No. of piglets	9.4	6.6
Individual weight, kg	15.87	15.70
Litter weight, kg	149.18	103.62

a. 56–day weaning time.

Table 27-33. Cassava root meal vs. corn in diets for lactating sows[a].

	Diet 1	Diet 2
Ingredients (%)		
Cassava root meal	—	59.1
Corn	81.5	—
Cane molasses	—	10.0
Soybean meal	15.0	27.4
Vitamins and minerals	3.5	3.5
Nutritional composition (%)		
Protein	16.0	16.0
Metionine + cystine	0.52	0.44
Lysine	0.71	0.89
Performance of sows		
Farrowing weight, kg	179.3	170.6
Weaning weight, kg	190.3	183.0
Performance of litters at farrowing		
Piglets, No.	10.8	10.1
Individual weight, kg	1.18	1.22
Litter weight, kg	12.74	12.32
Performance of litters at weaning		
Piglets, No.	9.01	7.90
Individual weight, kg	6.08	6.80
Litter weight, kg	54.0	53.7

a. 35-day weaning time.

SOURCE: Maner et al. (1978).

Table 27-34. Effect of partial substituting of corn by cassava root meal in lactating piglets[a].

	Diet 1	Diet 2	Diet 3
Ingredients (%)			
Cassava root meal	—	10.0	20.0
Corn	59.6	49.0	38.0
Soybean meal	27.7	28.3	28.9
Dehydrated milk whey	10.0	10.0	10.0
Vitamins and minerals	2.7	2.7	2.7
Nutritional composition			
Protein, %	18.5	18.1	17.8
Lysine, %	1.12	1.12	1.12
Calcium, %	0.78	0.78	0.78
Phosphorus, %	0.59	0.59	0.59
Performance of piglets			
Daily weight gain, kg	0.38	0.37	0.39
Daily feed consumption, kg	0.68	0.60	0.60
Feed conversion ratio	1.63	1.62	1.64

a. 7–18 kg piglets (30 days).

SOURCE: Ravindran et al. (1983).

Table 27-35. Feed consumption in lactating piglets associated with increasing levels of dry cassava root meal in their feed[a].

Age of piglets (days)	Total feed consumption per litter (kg)[b]		
	0% cassava meal	20% cassava meal	40% cassava meal
14 – 42	1.8	3.0	12.4
42 – 56	14.7	26.2	39.1
14 – 52 (total)	16.5	29.2	51.5

a. 1–56 day piglets.
b. Free choice cassava-sorghum-soybean diets with 20% protein.

SOURCE: Gómez et al. (1981).

Table 27-36. Effect of partial substitution of corn by cassava root meal in the feed of dairy calves[a].

	Energy source in dry feed[b]		
	50% sorghum	25% sorghum 25% cassava	50% cassava meal meal
Performance of calves (kg)			
Initial weight	35.15	34.10	34.26
Final weight	89.0	92.4	81.03
Daily weight gain	0.48	0.52	0.42
Total feed consumption in 112 days (kg)			
Dry feed	109.3	108.2	82.0
Alfalfa hay	28.4	28.6	29.1
Milk	132.7	135.3	126.9

a. 1 to 112-day Holstein calves. Only milk during the first 42 days and *ad libitum* dry feed plus alfalfa hay from 42 to 112 days.
b. Dry feed also supplemented with protein, mineral, and vitamin sources.

SOURCE: Peixoto (1973).

Table 27-37. Effect of partial substitution of sorghum by cassava root meal in dairy cows[a].

	Diet 1	Diet 2
Ingredients in dry diets (%)[b]		
Cassava root meal	—	27.0
Sorghum	54.0	27.0
Cottonseed meal	44.0	43.5
Urea	—	0.50
Salt	1.0	1.0
Minerals	1.0	1.0
Nutritional composition (%)		
NDT[c]	69.0	67.4
Protein	15.7	15.7
Daily milk production (kg)		
Non-corrected milk	12.0	12.4
4% fat corrected milk	11.4	11.3

a. 63–day lactation period.
b. Daily supply of 0.42 kg of dried feed per kg of milk produced plus *ad libitum* sorghum silage.
c. TDN = Total digestible nutrients.

SOURCE: Ribeiro et al. (1976).

Table 27-38. Effect of partial substitution of oats by cassava root meal in the feed of dairy cows[a].

	Energy source in dry feed[b]		
	Oats	Oats + cassava meal	Cassava meal
Ingredients (%)			
Cassava root meal	—	12.5	25.0
Oats	25.0	12.5	25.0
Peanut meal	20.0	25.0	25.0
Legumes hay	35.0	35.0	35.0
Wheat bran	20.0	20.0	20.0
Nutritional composition (%)			
TDN[c]	69.0	67.0	65.0
Protein	15.5	16.0	15.5
Daily milk production (kg)			
Non-corrected milk	6.97	7.20	7.84
4% fat corrected milk	7.81	7.91	7.84

a. 140–day lactation period.
b. Daily supply of 1 kg of dried feed per 3 kg of milk produced plus *ad libitum* Para grass hay.
c. TDN = total digestible nutrients.

SOURCE: Mathur et al. (1969).

Table 27-39. Growing-finishing crossbred Zebu steers under intensive grazing supplemented with two levels of cassava root meal[a].

	Dry supplement (kg/animal per day)	
Ingredientes (%)		
Cassava root meal	0.65	1.10
Cane molasses	4.5	4.5
Urea	0.23	0.25
Blood meal	0.22	0.22
Performance of steers (kg)		
Initial weight	336.0	336.0
Final weight	403.0	411.0
Daily weight gain	0.71	0.77

a. Steers on intensive grazing (4.8 head/ha) plus controlled dry supplement.

SOURCE: Lozada and Alderete (1979).

Table 27-40. Feedlot crossbred Zebu steers under total confinement with free choice consumption of sorghum-cassava meal supplement and controlled sorghum silage[a].

	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
Ingredients in dry supplement (%)					
Cassava root meal	—	20.5	41.0	61.5	82.0
Sorghum	88.5	66.4	44.3	22.2	—
Cottonseed meal	7.8	9.2	10.5	11.9	13.3
Urea	1.7	1.9	2.2	2.4	2.7
Vitamins and minerals	2.0	2.0	2.0	2.0	2.0
Performance of steers					
Initial weight, kg	302.7	306.2	317.2	305.8	315.4
Final weight, kg	424.4	425.1	427.2	412.4	404.3
Daily weight gain, kg	1.16	1.13	1.05	1.01	0.85
Dry supplement consumption, kg	10.2	9.3	8.6	8.1	6.9
Silage consumption, kg	3.1	5.0	5.5	5.2	5.2
Dry feed/weight gain	8.79	8.23	8.18	8.08	8.18

a. Free choice supplement and controlled sorghum silage (1.5 kg/100 kg body weight).

SOURCE: Delgado et al. (1975).

Table 27-41. Effect of including high levels of cassava foliage meal or alfalfa meal for Leghorn broilers[a].

	Diet 1	Diet 2	Diet 3	Diet 4
Ingredients (%)				
Cassava foliage meal	15.0	—	20.0	—
Alfalfa meal	—	15.0	—	20.0
Corn	53.6	53.6	51.9	51.9
Soybean meal	19.9	19.9	16.6	16.6
Tuna fish meal	5.0	5.0	5.0	5.0
Meat and bone meal	5.0	5.0	5.0	5.0
Vitamins and minerals	1.5	1.5	1.5	1.5
Performance of broilers				
Weight at 3 weeks, g	191	212	186	203
Daily feed consumption, g	21.8	21.5	22.5	21.6
Feed conversion ratio	2.40	2.13	2.54	2.24

a. 1–21 day old broilers.

SOURCE: Ross and Enriquez (1969).

Table 27-42. Effect of including a high level of cassava foliage meal and different levels of methionine in the feed of Leghorn broilers[a].

	Diet 1	Diet 2
Ingredients (%)		
Cassava foliage meal	—	20.0
Corn	66.5	51.9
Soybean meal	22.0	16.6
Tuna fish meal	5.0	5.0
Meat and bone meal	5.0	5.0
Vitamins and minerals	1.5	1.5
	Body weight at 21 days (grams)	
Methionine addition (%)		
0	208	114
0.2	220	185
0.3	—	211
0.4	—	205
0.5	—	202
	Feed conversion rate	
Methionine addition (%)		
0	2.10	2.73
0.2	1.99	2.32
0.3	—	2.18
0.4	—	2.35
0.5	—	2.18

a. 1–21 day old broilers.

SOURCE: Ross and Enriquez (1969).

Table 27-43. Effect of including low levels of cassava foliage meal on egg yolk pigmentation of Leghorn layers.

	Diet 1	Diet 2	Diet 3	Diet 4
Ingredients (%)				
Cassava foliage meal	—	2.5	5.0	—
White corn	68.5	66.0	63.5	—
Yellow corn	—	—	—	68.5
Wheat bran	2.5	19.9	16.6	16.6
Dextrose	0.5	0.5	0.5	0.5
Fish meal	2.5	2.5	2.5	2.5
Peanut meal	5.0	5.0	5.0	5.0
Soybean meal	13.0	13.0	13.0	13.0
Vitamins and minerals	8.0	8.0	8.0	8.0
Egg yolk pigmentation				
Grade on Roche scale	1.0	4.9	5.4	9.5

SOURCE: Agudu (1972).

Table 27-44. Effect of including high levels of dried cassava foliage meal in Landrace x Yorkshire growing pigs[a].

	Diet 1	Diet 2	Diet 3	Diet 4
Ingredients (%)				
Cassava foliage meal	—	10.0	20.0	20.0
Corn	74.40	66.85	59.85	59.65
Fish meal	8.0	7.0	7.0	7.0
Meat and bone meal	7.0	7.0	5.0	5.0
Soybean meal	7.95	6.50	5.50	5.50
DL-methionine	—	—	—	0.20
Vitamins and minerals	2.65	2.65	2.65	2.65
Performance of pigs				
Daily weight gain, kg	0.35	0.31	0.29	0.32
Daily feed consumption, kg	1.21	1.10	1.08	1.13
Feed conversion ratio	3.42	3.52	3.79	3.50

a. Growing pigs with initial weight of 13.6 kg, consuming isoproteic (18%) diets.

SOURCE: Choo and Hutagalung (1972).

Table 27-45. Effect of including high levels of dried cassava foliage meal in landrace x yorshire growing pigs[a].

	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
Ingredients (%)					
Cassava foliage meal	—	20.0	20.0	20.0	20.0
Corn	77.6	57.1	52.1	54.1	51.9
Soybean meal	14.8	10.3	10.3	10.3	10.3
Fish meal	2.5	2.5	2.5	2.5	2.5
Meat and bone meal	2.5	2.5	2.5	2.5	2.5
Molasses	—	5.0	10.0	5.0	10.0
Palm oil	—	—	—	3.0	—
DL-methionine	—	—	—	—	0.20
Vitamins and minerals	2.6	2.6	2.6	2.6	2.6
Performance of pigs					
Daily weight gain, kg	0.53	0.43	0.46	0.44	0.50
Daily feed consumption, kg	1.90	1.66	1.71	1.68	1.84
Feed conversion rate	3.60	3.90	3.74	3.80	3.68

a. Growing pigs with initial weight of 31 kg, consuming isoproteic (18%) diets.

SOURCE: Choo and Hutagalung (1972).

Table 27-46. Main nutritional differences between cassava root meal (CRM) and fullfat soybeans (FFSB).

Nutrients	Unit	CRM	FFSB
Protein	%	2.8	38.0
Fat	%	1.2	19
Starch	%	70	9
ME, poultry	Mcal/kg	3.1–3.2	3.6–3.8
ME, swine	Mcal/kg	3.2–3.4	3.7–3.8
Linoleic acid	%	0.2	8.9
Fiber	%	2.6	4.9
Ash	%	3.2	5.2
Methionine	%	0.03	0.51
Cystine	%	0.02	0.60
Lisine	%	0.05	2.31
Threonine	%	0.05	1.43
Thryptophane	%	0.02	0.52
Lecithin	%	0.1	2.1

SOURCE: Buitrago (1990).

Table 27-47. Broiler diets totally based on cassava root meal, cassava foliage meal, and fullfat soybeans.

Ingredients (%)	Starter (0-3 weeks)	Finisher (3-6 weeks)	Finisher (6-8 weeks)
Cassava root meal	41.05	44.70	50.50
Cassava foliage meal	—	6.0	6.0
Fullfat soybeans	44.50	44.74	40.80
Soybean meal	10.60	1.40	—
DL-methionine	0.25	0.16	0.10
L-lysine	—	—	—
Dicalcium phosphate	1.70	1.30	1.00
Calcium carbonate	1.20	1.00	0.90
Salt	0.30	0.30	0.30
Vitamins, minerals, additives	0.40	0.40	0.40

Table 27-48. Nutritional composition of broiler diets totally based on cassava root meal, cassava foliage meal, fullfat soybeans, and soybean meal.

Nutrients	Starter (0-3 weeks)	Finisher (3-6 weeks)	Finisher (6-8 weeks)
ME, Mcal/kg	3.20	3.20	3.20
Protein, %	23.0	20.0	18.0
Lisine, %	1.30	1.15	1.00
Methionine, %	0.55	0.43	0.34
Methionine + cystine	0.90	0.72	0.60
Threonine, %	0.85	0.78	0.69
Tryptophane, %	0.30	0.25	0.20
Fiber, %	4.3	5.0	4.8
Fat, %	8.8	8.9	8.3
Ash, %	7.2	6.6	6.1
Calcium, %	1.00	0.90	0.80
Available phosphorus, %	0.45	0.36	0.30
Linoleic acid, %	3.5	3.8	3.5

Table 27-49. Composition of broiler diets with intermediate levels of cassava meal and fullfat soybeans[a].

	Starting	Finishing
Ingredients (%)		
Corn	25.34	30.79
Cassava roots meal	25.0	25.0
Fullfat soybeans (toasted)	31.4	33.8
Soybean meal	12.1	4.8
Chicken viscera meal	3.00	3.00
Dicalcium phosphate	1.30	1.00
Calcium carbonate	1.00	0.90
DL-methionine	0.23	0.10
Salt	0.35	0.30
Vitamins and minerals	0.12	0.10
Anticoccidial	0.05	0.10
Fungicide	0.10	0.10
Nutritional composition		
ME, Mcal/kg	3.10	3.20
Protein, %	22.0	17.0
Methionine, %	0.56	0.40
Met + cystine, %	0.90	0.72
Lysine, %	1.24	1.10
Threonine, %	0.80	0.75
Linoleic acid, %	3.25	3.48
Calcium, %	0.90	0.82
Available phosphorus, %	0.42	0.39

a. Commercial Farm El Recreo–Carioca. Buga, Colombia.

SOURCE: Buitrago et al. (2002).

Table 27-50. Composition of broiler diets with intermediate levels of cassava meal and FFSB[a].

	Starting	Finishing
Ingredients (%)		
Cassava roots meal	20.0	25.0
FFSB (toasted)	32.0	34.0
Soybean meal	8.20	2.80
Fish meal	3.50	4.00
Palm oil	—	0.10
Dicalcium phosphate	0.90	0.70
Calcium carbonate	0.80	0.90
DL-methionine	0.27	0.22
Salt	0.25	0.25
Chline chloride	0.12	0.10
Vitamins and minerals	0.12	0.10
Anticoccidial	0.05	0.10
Fungicide	0.10	0.10
Nutritional composition		
ME, Mcal/kg	3.15	3.20
Protein, %	21.0	19.0
Methionine, %	0.58	0.51
Met + cystine, %	0.88	0.77
Lysine, %	1.23	1.10
Threonine, %	0.60	0.59
Linoleic acid, %	3.08	3.10
Calcium, %	0.90	0.91
Available phosphorus, %	0.43	0.42

a. Commercial Farms: Avités – Nutrilisto. Cereté, Colombia.

SOURCE: Buitrago et al. (2002).

Table 27-51. Results on the performance of broilers with intermediate levels of cassava root meal in the diet[a].

	Control (corn-SBM)[b]	Cassava-FFSB[c]
Number of birds at starting	7.680	7.673
Number of birds at finishing	7.415	7.108
Number of days	42	42
Mortality, %	3.2	5.7
Final weight, g	1.976	1.942
Feed consumption, g	3.754	3.781
Conversion efficiency	1.90	1.94
European conversion efficiency	239	218

a. El Recreo Farm. Buga, Cauca Valley, Colombia.
b. Control commercial diet based on corn and soybean meal.
c. Experimental diet based on cassava root meal and fullfat soybeans.

SOURCE: Buitrago et al. (2002).

Table 27-52. Results on the performance of broilers with intermediate levels of cassava root meal in the diet[a].

	Control (sorghum-SBM)[b]	Cassava-FFSB[c]
Number of birds at starting	48.441	24.000
Number of birds at finishing	46.199	22.392
Number of days	42	42
Mortality, %	4.6	6.7
Final weight, g	1.934	1.915
Feed consumption, g	3.559	3.152
Feed conversion ratio	1.84	1.69
European conversion efficiency	239	218

a. Avites Farm. Cereté, Córdoba, Colombia.
b. Control commercial diet based on sorghum and soybean meal.
c. Experimental diet based on cassava root meal and fullfat soybeans.

SOURCE: Buitrago et al. (2002).

Table 27-53. Composition of broiler diets with maximum levels of cassava meal and FFSB in the starting phase.

	Control (corn-SBM)	CRM + FFSB[a]			CRM + CFM + FFSB[d]
		Solar drying	Artificial drying		
			A[b]	B[c]	
Ingredients (%)					
Corn	59.37	—	—	—	—
CRM	—	45.75	45.75	45.75	40.45
CFM	—	—	—	—	6.00
FFSB	12.8	30.0	30.0	30.0	30.0
Soybean meal	21.0	18.7	18.7	18.7	18.7
Palm oil	3.0	2.9	2.9	2.9	4.5
DL-methionine	0.16	0.29	0.29	0.29	0.29
L-lysine	0.07	—	—	—	—
Bone meal	1.70	1.90	1.90	1.90	1.90
Ca carbonate	1.50	—	—	—	—
Salt	0.30	0.30	0.30	0.30	0.30
Vitamin Premix	0.10	0.10	0.10	0.10	0.10
Nutritional composition					
ME, Mcal/kg	3.20	3.20	3.20	3.20	3.20
Protein, %	22.0	22.0	22.0	22.0	22.0
Methionine, %	0.59	0.59	0.59	0.59	0.59
Met + cystine, %	0.90	0.90	0.90	0.90	0.90
Lysine, %	1.26	1.26	1.26	1.26	1.27
Linoleic acid, %	2.62	3.42	3.42	3.42	3.56
Ca, %	0.91	0.91	0.91	0.91	0.91
Available P, %	0.42	0.42	0.42	0.42	0.42

a. Cassava root meal + fullfat soybeans.
b. Equipment with steam heating.
c. Equipment with propane gas heating.
d. Cassava root meal + cassava foliage meal + fullfat soybeans.

SOURCE: Gil et al. (2001).

Table 27-54. Composition of broiler diets with maximum levels of cassava meal and FFSB in the finishing phase.

	Control (corn-SBM)	CRM + FFSB[a]			CRM + CFM + FFSB[d]
		Solar drying	Artificial drying		
			A[b]	B[c]	
Ingredients (%)					
Corn	66.85	—	—	—	—
CRM	—	49.8	49.8	49.8	46.1
CFM	—	—	—	—	6.00
FFSB	6.1	41.6	41.6	41.6	45.1
Soybean meal	20.7	5.2	5.2	5.2	—
DL-methionine	0.13	0.23	0.23	0.23	0.23
Lysine	0.19	—	—	—	—
Bone meal	1.60	1.90	1.90	1.90	1.90
Ca carbonate	1.10	—	—	—	—
Salt	0.30	0.30	0.30	0.30	0.30
Vitamin Premix	0.10	0.10	0.10	0.10	0.10
Nutritional composition					
ME, Mcal/kg	3.20	3.20	3.20	3.20	3.20
Protein, %	20.0	20.0	20.0	20.0	20.0
Methionine, %	0.49	0.49	0.49	0.49	0.49
Met + cystine, %	0.78	0.78	0.78	0.78	0.78
Lysine, %	1.12	1.12	1.12	1.12	1.12
Linoleic acid, %	2.20	3.60	3.60	3.60	3.85
Ca, %	0.90	0.90	0.90	0.90	0.90
Available P, %	0.40	0.40	0.40	0.40	0.40

a. Cassava root meal + fullfat soybeans.
b. Equipment with steam heating.
c. Equipment with propane gas heating.
d. Cassava root meal – cassava foliage meal + fullfat soybeans.

SOURCE: Gil et al. (2001).

Table 27-55. Results on the performance of broilers with maximum levels of cassava root meal and FFSB in the diet during the starting and finishing phases.

	Control (corn-SBM)	CRM + FFSB[a]			CRM + CFM + FFSB[d]
		Solar drying	Artificial drying		
			A[b]	B[c]	
Initial weight, g	39.8	39,5	39.4	39.5	39.7
Final weight, g	2,139	2,279	2,237	2,387	2,113
Feed consumption	4.73	4.88	4.65	4.68	4.72
Feed conversion rate	2.21	2.14	2.08	1.96	2.24

a. Cassava root meal + fullfat soybeans.
b. Equipment with steam heating.
c. Equipment with propane gas heating.
d. Cassava root meal + cassava foliage meal + fullfat soybeans.

SOURCE: Gil et al. (2001).

Table 27-56. Example of layer diets with maximum levels of cassava root meal fullfat soybeans and cassava foliage meal.

Ingredients (%)	Replacement chickens		Laying hens	
	0-6 weeks	7-15 weeks	Phase 1	Phase 2
Cassava root meal	59.3	61.4	41.6	51.9
FFSB[a]	9.6	9.2	38.9	28.0
Cassava foliage meal	—	6.0	6.0	6.0
Soybean meal	26.9	19.6	1.9	3.6
Calcium phosphate	1.4	1.2	1.2	1.2
Calcium carbonate	1.9	1.8	9.5	8.4
DL-methionine	0.21	0.10	0.23	0.23
Salt	0.30	0.30	0.30	0.30
Vitamins and minerals	0.40	0.40	0.40	0.40

a. Fullfat soybean.

Table 27-57. Nutritional composition of layer diets with maximum levels of cassava root meal, fullfat soybeans, and cassava foliage meal[a].

Nutritional composition	Replacement chickens		Laying hens	
	0-6 weeks	7-15 weeks	Phase 1	Phase 2
Metabolizable energy, Mcal/kg	2.80	2.75	2.90	2.80
Protein, %	18.0	15.5	18.0	15.0
Lisine	0.98	0.68	0.86	0.75
Methionine	0.42	0.30	0.38	0.36
Met + cystine	0.72	0.54	0.73	0.64
Threonine	0.65	0.60	0.66	0.50
Calcium	0.90	1.10	4.00	3.60
Available phosphorus	0.38	0.35	0.32	0.32
Fiber	3.8	4.6	4.6	4.4
Fat	2.0	2.9	7.8	6.0
Linoleic acid	1.0	1.0	2.5	2.4
Ash	6.6	7.2	14.2	13.0

a. Nutrient requirements based on NRC (1998).

Table 27-58. Example of layer diets with medium levels of cassava root meal, fullfat soybeans, and cassava foliage meal.

Ingredients (%)	Replacement chickens		Laying hens	
	0-6 weeks	7-15 weeks	Phase 1	Phase 2
Corn	39.0	42.9	19.7	31.0
Cassava root meal	25.0	25.0	25.0	25.0
FFSB	10.0	9.84	34.6	19.1
Cassava foliage meal	—	6.0	6.0	6.0
Soybean meal	21.6	12.2	2.8	7.2
Calcium phosphate	1.3	1.2	1.1	1.1
Calcium carbonate	2.20	2.10	9.9	9.7
DL-methionine	0.14	0.06	0.20	0.17
Salt	0.30	0.30	0.30	0.30
Vitamins and minerals	0.40	0.40	0.40	0.40

Table 27-59. Nutritional composition of layer diets with medium levels of cassava root meal, fullfat soybeans, and cassava foliage meal[a].

	Replacement chickens		Laying hens	
	0-6 weeks	7-15 weeks	Phase 1	Phase 2
Metabolizable energy, Mcal/kg	2.80	2.75	2.90	2.80
Protein, %	18.0	15.5	18.0	15.0
Lisine, %	0.98	0.68	0.86	0.75
Methionine	0.42	0.30	0.38	0.36
Met + cystine	0.72	0.54	0.73	0.64
Threonine	0.65	0.60	0.66	0.50
Calcium	0.90	1.10	4.00	3.60
Available phosphorus	0.38	0.35	0.32	0.32
Fiber	3.8	4.6	4.6	4.4
Fat	2.0	2.9	7.8	6.0
Linoleic acid	1.0	1.0	2.5	2.4
Ash	6.6	7.2	14.2	13.0

a. Nutrient requirements based on NRC (1998).

Table 27-60. Diets for commercial layers with 10% cassava root meal and fullfat soybeans.

	Control (corn)	10% cassava root meal
Ingredients (%)		
Corn	57.8	45.3
Cassava root meal	—	10.0
FFSB (toasted)	5.3	9.1
Soybean meal	16.2	15.0
Fish meal (65 % protein)	5.0	5.0
Wheat bran	3.5	3.5
DL-methionine	0.18	0.20
Calcium carbonate	9.71	9.64
Calcium phosphate	0.95	0.91
Salt	0.30	0.30
Vitamins and minerals	0.60	0.60
Nutritional composition		
Metabolizable energy, Mcal/kg	2.75	2.75
Protein, %	17.5	17.5
Methionine, %	0.44	0.44
Met + cystine, %	0.75	0.75
Lysine, %	0.91	0.91
Calcium, %	3.90	3.90
Available phosphorus, %	0.45	0.45
Linoleic acid, %	1.36	1.39

Table 27-61. Performance of commercial layers fed with 10% cassava root meal and fullfat soybeans[a].

	Control (corn)	10% cassava root meal
Daily feed consumption, g	102.6	103.2
Laying, %	89.2	89.5
Feed conversion (per dozen eggs)	1.4	1.4

a. 48 to 55-week laying period. La Esperanza Poultry Farm. Buga, Valle. 1,010 masl. 26 °C.

SOURCE: Gutiérrez and Martínez (1998).

Table 27-62. Diets for commercial layers with 15% cassava root meal and fullfat soybeans.

	Control (corn)	15% cassava root meal
Ingredients (%)		
Corn	41.1	34.1
Cassava root meal	—	15.0
Fullfat soybeans (extruded)	20.0	20.00
Soybean meal	8.1	11.60
Rice polishings	10.0	—
Wheat bran	9.1	7.60
DL-methionine	0.18	0.19
Calcium carbonate	9.60	9.30
Calcinated bone meal	1.30	1.50
Salt	0.35	0.35
Vitamins and minerals	0.30	0.30
Nutritional composition		
Metabolizable energy, Mcal/kg	2.75	2.75
Protein, %	17.0	17.0
Methionine, %	0.45	0.45
Met + cystine, %	0.70	0.70
Lysine, %	0.85	0.85
Calcium, %	3.90	3.90
Available phosphorus, %	0.42	0.42
Linoleic acid, %	1.74	1.37

Table 27-63. Performance of commercial layers fed with 15% cassava root and fullfat soybeans[a].

	Control (corn)	15% cassava root meal
Layers, No.	15,000	5,000
Daily feed consumption, g	114.0	115.0
Laying, %	78.3	79.0
Feed conversion (dozen eggs)	1.37	1.37

a. 55 to 61-week laying period. Santa Anita Poultry Farm. Pradera, Valle. 1.010 masl. 26 °C.
American Soybean Association (ASA), 2000.

SOURCE: Buitrago et al. (2002).

Table 27-64. Diets for commercial layers with 20% cassava root meal and fullfat soybeans.

	Control (corn)	20% cassava root meal
Ingredients (%)		
Corn	20.0	—
Sorghum	30.6	36.2
Cassava root meal	—	20.0
Fullfat soybean (toasted)	15.0	15.0
Soybean meal	12.3	16.5
Wheat bran	10.3	0.20
DL-methionine	0.23	0.23
Calcium carbonate	9.20	9.30
Calcium phosphate	1.40	1.60
Salt	0.35	0.35
Vitamins and minerals	0.60	0.60
Nutritional composition		
Metabolizable energy, Mcal/kg	2.70	2.70
Protein, %	17.0	17.0
Methionine, %	0.45	0.45
Met + cystine, %	0.70	0.70
Lisine, %	0.81	0.81
Calcium, %	3.90	3.90
Available phosphorus, %	0.42	0.42
Linoleic acid, %	1.54	1.25

Table 27-65. Performance of commercial layers fed with 20% cassava root meal and fullfat soybeans[a].

	Control corn	20% cassava root meal
Daily feed consumption, g	111.6	111.1
Laying, %	92.4	91.0
Feed conversion (per dozen eggs)	1.50	1.46

a. 39 to 46-week laying period. Avícola Montegrande Poultry Farm. Tuluá, Valle. 1,025 masl. 25 °C.

SOURCE: Gutiérrez and Martínez (1998).

Table 27-66. Diets for commercial white and brown layers with 10% and 20% cassava root meal and fullfat soybean.

	Control (corn)	10% cassava root meal	20% cassava root meal
Ingredients (%)			
Corn	41.1	34.1	23.0
Cassava root meal	—	10.0	20.0
Fullfat soybean (extruded)	20.0	20.0	20.0
Soybean meal	8.1	10.4	11.8
Rice polishings	10.0	10.0	10.0
Wheat bran	9.1	4.3	3.6
DL-methionine	0.18	0.19	0.21
Calcium carbonate	9.60	9.50	9.40
Calcinated phosphate	1.30	1.40	1.40
Salt	0.35	0.35	0.35
Vitamins and minerals	0.30	0.30	0.30
Nutritional composition			
ME, Mcal/kg	2.70	2.70	2.70
Protein, %	17.0	17.0	17.0
Methionine, %	0.45	0.45	0.45
Met + cystine, %	0.70	0.70	0.70
Lisine, %	0.85	0.85	0.85
Calcium, %	3.90	3.90	3.90
Available phosphorus, %	0.42	0.42	0.42
Linoleic acid, %	1.74	1.49	1.37

Table 27-67. Performance of commercial brown layers fed with 10% and 20% cassava root meal and fullfat soybeans[a].

	Control (corn)	10% cassava root meal	20% cassava root meal
Layers, No.	3,840	10,956	5,160
Daily feed consumption, g	115.1	115.8	114.8
Laying, %	69.3	65.7	65.1
Feed conversion (per dozen eggs)	2.00	2.12	2.11

a. 78 to 88-week laying period. Lohmann Brown layers. Avicauca Poultry Farm. Jamundí, Valle. 1,005 masl. 25 °C. American Soybean Association (ASA), 1999.

SOURCE: Buitrago et al. (2002).

Table 27-68. Swine diets totally based on cassava root meal, cassava foliage meal and fullfat soybean.

	Starting	Growing	Final	Gestation	Lactation
Ingredientes (%)					
Cassava root meal	45.2	50.5	53.4	57.1	51.7
Cassava foliage meal	—	4.0	8.0	8.0	8.0
Fullfat soybean	45.8	42.8	33.8	29.5	35.2
Soybean meal	6.0	—	—	—	—
Vegetable oil	—	0.4	2.8	3.0	2.8
Methionine	0.06	0.05	0.03	—	0.04
Dicalcium phosphate	1.2	0.8	0.5	1.1	1.0
Calcium carbonate	1.2	0.9	0.9	0.7	0.7
Salt	0.35	0.35	0.35	0.35	0.35
Vitamins and minerals	0.20	0.20	0.20	0.20	0.20
Nutritional composition					
Metabolizable energy, Mcal/kg	3.35	3.35	3.35	3.32	3.35
Protein, %	21.00	18.00	15.50	14.00	16.00
Lisine, %	1.20	0.95	0.75	0.58	0.95
Met + cystine, %	0.65	0.54	0.44	0.37	0.48
Calcium, %	0.90	0.90	0.88	0.90	0.86
Available phosphorus, %	0.40	0.32	0.25	0.35	0.35

Table 27-69. High levels of cassava root meal and fullfat soybeans in diets for growing-finishing pigs.

	Control diet		Cassava root meal + FFSB[a]	
	Growing	Finishing	Growing	Finishing
Ingredients (%)				
Corn	36.70	33.80	—	—
Cassava root meal	—	—	44.93	48.10
Fullfat soybean	20.00	18.60	20.00	20.00
Sorghum	16.00	16.00	—	—
Fish meal	—	0.50	—	—
Corn bran	8.00	12.00	—	—
Soybean meal	7.60	3.40	16.71	10.90
Wheat bran	8.00	12.00	12.00	15.00
Vegetable oil	—	—	3.70	3.30
Salt	0.39	0.39	0.39	0.39
Vitamins and minerals	3.31	3.31	2.27	2.31
Main nutrients				
ME, Mcal/kg	3.31	3.32	3.36	3.34
Protein, %	18.3	17.3	16.3	16.3

a. Fullfat soybean.

Table 27-70. Performance of finishing pigs with high inclusion of cassava root meal and fullfat soybean diets[a].

	Control diet	Cassava root meal + FFSB[b]
Initial weight, kg	48.10	49.29
Final weight, kg	96.00	96.41
Daily weight gain, kg	0.75	0.74
Daily consumption, kg	2.22	2.12
Feed conversion ratio	2.96	2.89

a. Granjas Paraíso – CLAYUCA – Nutribal. Palmira, Valle. 2002.
b. Fullfat soybean.

SOURCE: Buitrago et al. (2002).

References

To save space, the acronym "CIAT" is used instead of "Centro Internacional de Agricultura Tropical".

Agudu EW. 1972. Preliminary investigation on some unusual feedstuffs as yolk pigmenters in Ghana. Ghana J Agric Sci 5:33–38.

Buitrago JA. 1964. Utilización de yuca fresca en dietas para crecimiento y ceba de cerdos. Thesis MVZ. Universidad Nacional de Colombia, Bogotá. 114 p.

Buitrago JA. 1990. La Yuca en la Alimentación Animal. CIAT, Cali, Colombia. 446 p.

Buitrago JA; Gómez G; Portela R; Santos J; Trujillo C. 1978. Yuca ensilada para alimentación de cerdos. Instituto Colombiano Agropecuario (ICA) and CIAT, Cali, Colombia. 49 p. (Mimeo.)

Buitrago JA; Luckett L. 1999. Potencial de la yuca industrial para producción de alimentos animales. Reporte de trabajos demostrativos en Colombia. Bogotá, Colombia. 27 p.

Buitrago JA; Gil JL; Ospina B. 2002. Cassava in Poultry Nutrition. Cuadernos Avícolas 14. Consorcio Latinoamericano y del Caribe de Apoyo a la Investigación y al Desarrollo de la Yuca (CLAYUCA), Federación Nacional de Avicultores de Colombia (FENAVI), Fondo Nacional Avicola (FONAV), Cali, Colombia. (Also available at www.clayuca.org/PDF/cassava_poultry_nutrition.pdf.)

CIAT. 1973. Annual Report. Swine Production Systems. Cali, Colombia. p 119–144.

CIAT. 1974. Informe Anual. Sistemas de Producción de Ganado Porcino. Cali, Colombia. p 163–212.

CIAT. 1975. Annual Report. Swine Production Systems. Cali, Colombia. p D1–D20.

Chicco CF; Garbati ST; Muller-Haye B; Vecchionacce H. 1972. La harina de yuca en el engorde de cerdos. Agron Trop (Maracay, Venez.) 22(6):599–603.

Choo TL; Hutagalung RI. 1972. Nutritional value of tapioca leaf (*Manihot utilissima*) for swine. Malays Agric Res 1:38–47.

Chou KC; Muller Z; Nah KC. 1974. High levels of tapioca meal in poultry rations. Indian J Anim Sci 44(9): 697–702.

Contreras RE. 1973. Yuca fresca suplementada en la alimentación de cerdos en crecimiento. Thesis. Universidad de Oriente, Escuela de Zootecnia, Jusepín, Venezuela. 35 p.

Delgado ME; Coelho da Silva JF; Barbosa T. 1975. Substituição do milho desintegrado com palha e sabugo pela raspa de mandioca integral em rações para rumiantes. 2: Confinamento de bovinos. Experientiae 20(7):204–216.

Enríquez FQ; Ross E. 1972. Cassava root meal in grower and layer diets. Poul Sci 51(1):228–232.

Enríquez V, F; Arteaga F, C; Ávila G, E. 1977. Harina de yuca (*Manihot esculenta*) en dietas para pollos de engorde y gallinas de postura. Tec Pecu Mex 32:53–57.

Gil JL; Escobar G; Buitrago JA. 2001. Evaluación técnica y económica de cuatro dietas a base de harina de yuca y una dieta comercial para la alimentación de pollos de engorde. Informe Técnico Clayuca, Cali, Colombia. 14 p.

Gómez G; Buitrago JA. 1982. Effect of processing on nutritional content of feeds: root crops. In: Rechcigl M, ed. Handbook of nutritive value of processed foods. Vol II, p. 221–237. CRC Press, Boca Raton, FL, USA. 439 p.

Gómez G; Santos J; Valdivieso M. 1981. Utilización de la yuca en alimentación porcina. In: VII Curso Intensivo de Adiestramiento Posgrado en Investigación para la Producción de Yuca. CIAT, Cali, Colombia. 31 p.

Gutiérrez G; Martínez L. 1998. Efecto de utilizar harina de yuca y soya integral en dietas para aves ponedoras. Thesis. Universidad Nacional de Colombia, Palmira, Colombia.

Hennesey S; Ayala JC. 1986. Evaluación de soya integral cocida y harina de yuca en la alimentación de aves de postura. Thesis. Universidad Nacional de Colombia, Palmira, Colombia.

Lozada H; Alderete R. 1979. Efecto de la harina de raiz de yuca y nivel de urea sobre el comportamiento de becerros en pastos de baja calidad con libre acceso a melaza. Producción Animal Tropical 4:46–48.

Maner JH; Buitrago JA; Portela R; Jiménez I. 1978. La yuca en la alimentación de cerdos. Instituto Colombiano Agropecuario (ICA) and CIAT, Cali, Colombia. 113 p. (Mimeo.)

Mathur ML; Sampath SR; Gosh SN. 1969. Studies on tapioca: effect of 50 and 100 percent replacement of *vats* by tapioca in the concentrate mixture of dairy cows. Indian J Dairy Sci 22:193–199.

Méndez A; Zaragoza L. 1980. Sustitución del sorgo por harina de yuca en la alimentación de cerdos. Agric Tec Mex 6(2):83–91.

Moore CP. 1976. El uso del follaje de yuca en alimentación de rumiantes. In: Proc International seminar on tropical livestock. Acapulco, Mexico. p 47–62.

Muller Z; Chou KC; Nash K; Tan TK. 1972. Study of nutritive value of tapioca in economic rations for growing-finishing pigs in the tropics. United Nations Development Programme, UNDP/SF Project Sin 67/505. Pig and Poultry Research and Training Institute, Singapore. 35 p.

NRC (National Research Council). 1994. Nutrient requirements of poultry. 9th edition. Washington, USA.

NRC (National Research Council). 1998. Nutrient requirements of swine. 10th edition. Washington, USA.

Olaloku EA; Egbuiwe AM; Oyenuga BA. 1971. The influence of cassava in the production ration on the yield and composition of milk of White Fulani cattle. Nigerian Agric J 8(1):36–43.

Peixoto RR. 1973. Value of cassava flour as a calf starter component when fed to calves on a restricted milk diet. MSc thesis. Cornell University, Ithaca, NY, USA.

Pineda J; Rubio R. 1972. Un concepto nuevo en el levante de novillas para ganadería de leche. Revista ICA (Colombia) 17(4):405–413.

Ravindran V; Kornegay ET; Cherry JA. 1983. Feeding values of cassava tuber and leaf meals. Nutr Rep Int 28(1):189–196.

Ribeiro PJ; Moreira HA; Vitela H; Silva T. 1976. Melazo deshidrato e raspa de mandioca como sustitutos parciais do milho para producto de leite. Arq Esc Vet Univ Fed de Minas Gerais 28(2):193–200.

Ross E; Enriquez FQ. 1969. The nutritive value of cassava leaf meal. Poul Sci 48(3):846–853.

Stevenson M. 1984. The nutritional value of cassava root meal in laying hen diets. J Sci Food Agric 35:36–40.

Stevenson M; Jackson N. 1983. The nutritional value of dried cassava root meal in broiler diets. J Sci Food Agric 34:1361–1367.

Terleira HG; Ten Brinke HW; López W; Santisteban D. 1975. Uso de raíces de yuca, coronta de maíz y cáscara de algodón en el engorde de novillos en Tarapoto-San Martín. Ministerio de Alimentación. Dirección General de Investigación. Lima, Peru. 13 p. (Mimeo.)

Van Poppel J. 2001. Analyse uitslagen KB grondstoffen. [Analyses results of KB feed ingredients]. Hoofd Veevoeding en Kwaliteit, The Netherlands.

Zapata O; Sánchez L; Medrano J; Meza JH. 1985. Uso de algunos subproductos agrícolas en alimentación animal y lactoinducción en vacas lecheras. Instituto Colombiano Agropecuario (ICA). Boletín Técnico. Palmira, Colombia. 31 p.

APPENDIX 1

Acronyms, Abbreviations, and Technical Terminology

Entities

ABNT	Associação Brasileira de Normas Técnicas *[Brazilian Association for Technical Standards]*
ACCB	Asociación Colombiana de Ciencias Biológicas *[Colombian Association of Biological Sciences]*
ACOGRANOS	Asociación Colombiana Postcosecha de Granos *[Colombian Association for the Postharvesting of Grains]*
ACOPOR	Asociación Colombiana de Porcicultores *[Colombian Association of Pig Producers]*
AMCA	Air Movement and Control Association International, Inc., USA
ARS	Agricultural Research Service (of the USDA)
ASOMUDEPAS	Asociación Municipal para el Desarrollo Sostenible de los Pequeños Agricultores de San Jacinto *[San Jacinto Small Farmers' Municipal Association for Sustainable Development]*
ASOPROSA	Asociación de Mujeres Productoras de Santa Ana, Colombia *[Women Farmers' Association of Santa Ana]*
BioEuroLatina	Asociación para la Promoción de la Biotecnología en Latinoamérica en Cooperación con Europa *[Association for the Promotion of Biotechnology in Latin America in Cooperation with Europe]*
Biotecol	Biotecnología de Colombia *[Biotechnology of Colombia]*
CATIE	Centro Agronómico Tropical de Investigación y Enseñanza
CBN	Cassava Biotechnology Network
CECORA	Central de Cooperativas de la Reforma Agraria, Colombia *[Federation of Agrarian Reform Cooperative Associations]*
CENICAFE	Centro Nacional de Investigaciones del Café, Colombia *[National Coffee Research Center]*
CGIAR*	Consultative Group on International Agricultural Research
CGP	Cassava Genome Project
CIAT	Centro Internacional de Agricultura Tropical, Colombia *[International Center for Tropical Agriculture]*
CIMMYT	Centro Internacional de Mejoramiento de Maíz y Trigo *[International Maize and Wheat Improvement Center]*
CIP	Centro Internacional de la Papa *[International Potato Center]*
CITA	Centro Nacional de Ciencia y Tecnología de Alimentos, Costa Rica *[National Center for Food Science and Technology]*
CLAYUCA	Consorcio Latinoamericano y del Caribe de Apoyo a la Investigación y al Desarrollo de la Yuca *[Latin American and Caribbean Consortium to Support Cassava Research and Development]*
CNIA	Centro Nacional de Investigaciones Agropecuarias (of CORPOICA) *[National Center for Agricultural Research]*
CNPMF	Centro Nacional de Pesquisa de Mandioca e Fruticultura (of EMBRAPA) *also* Embrapa Mandioca e Fruticultura *[National Cassava & Fruits Research Center]*
CNRS	Centre national de la recherche scientifique, France *[National Center for Scientific Research]*
CONGELAGRO	Congelados Agrícolas S.A., Colombia *[Frozen Agricultural Products, p/c]*

* 'CGIAR' was originally the acronym for the 'Consultative Group on International Agricultural Research'. In 2008, CGIAR redefined itself as a global partnership. To reflect this transformation, and yet retain its roots, 'CGIAR' was retained as a name. CGIAR is now a global research partnership for a food secure future.

CORPOICA	Corporación Colombiana de Investigación Agropecuaria *[Colombian Corporation of Agricultural Research]*
CUNY	The City University of New York, USA
DGIS	Directoraat-Generaal Internationale Samenwerking, Netherlands *[Directorate-General for International Cooperation]*
DOE-JGI	U.S. Department of Energy-Joint Genome Institute
DRI	Fondo de Desarrollo Rural Integrado (of MADR) *[Fund for Integrated Rural Development]*
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária *[Brazilian Agricultural Research Corporation]*
ETH–Zurich	Eidgenössische Technische Hochschule Zürich *[Swiss Federal Institute of Technology Zurich]*
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FEDEARROZ	Federación Nacional de Arroceros, Colombia *[National Federation of Rice Growers]*
FEDEYUCA	Federación Nacional de Productores, Procesadores y Comercializadores de Yuca, Colombia *[National Federation of Cassava Producers, Processors, and Traders]*
FENAVI	Federación Nacional de Avicultores de Colombia *[National Federation of Poultry Producers]*
FIDAR	Fundación para la Investigación y Desarrollo Agrícola, Colombia *[Foundation for Agricultural Research and Development]*
IBPGR	International Board for Plant Genetic Resources (*now* Bioversity International)
ICA	Instituto Colombiano Agropecuario *[Colombian Institute of Agriculture]*
ICONTEC	Instituto Colombiano de Normas Técnicas y Certificación *[Colombian Institute for Technical and Certification Standards]*
IFAD	International Fund for Agricultural Development (of the International Monetary Fund)
IIT	Instituto de Investigaciones Tecnológicas, Colombia *[Technological Research Institute]*
IITA	International Institute of Tropical Agriculture
IPGRI	International Plant Genetic Resources Institute (*now* Bioversity International)
IPM Unit	Integrated Pest Management Unit (of CIAT)
IRD	Institut de recherche pour le développement, France *[Institute of Research for Development]*
ISAAA	International Service for the Acquisition of Agri-biotech Applications
LABIOTSA	Laboratorios de Biotecnología y Servicios Anexos, Ecuador *[Laboratories for Biotechnology and Annexed Services]*
LANUR	Laboratório de Nutrição de Ruminantes (of UFRGS) *[Ruminant Nutrition Laboratory]*
MADR	Ministerio de Agricultura y Desarrollo Rural, Colombia *[Ministry of Agriculture and Rural Development]*
OECD	Organisation for Economic Co-operation and Development
PRGA	CGIAR Systemwide Program on Participatory Research and Gender Analysis
RAD Project	Rural Agroenterprise Development Project (of CIAT)
SOCOLEN	Sociedad Colombiana de Entomología *[Colombian Entomology Society]*
UF	University of Florida, USA
UFRGS	Universidade Federal do Rio Grande do Sul, Brazil
UN	Universidad Nacional de Colombia *[National University of Colombia]*
UNDP	United Nations Development Programme
UNIANDES	Universidad de los Andes, Colombia
UNIVALLE	Universidad del Valle, Colombia
USDA	United States Department of Agriculture
USI	Usinas Sociais Inteligentes, Brazil

Other abbreviations and acronyms

AAI	alpha-amylose index
ABA	abscisic acid
AD	artificial drying (of cassava chips)
ADP	adenosine diphosphate (a nucleotide)
AFLP	amplified fragment length polymorphism
AGPase	ADP-glucose pyrophosphorylase (an enzyme)
AHAS	acetohydroxy acid synthase
a.i.	active ingredient
AN	available nitrogen (i.e., usable by plants)
ANA	α-naphthaleneacetic acid (used in plant tissue culture media)
ATIS	automated immersion systems
BAC	bacterial artificial chromosome
BamHI	restriction enzyme derived from *Bacillus amyloliquefaciens*
BAP	benzylamino purine (hormone used in plant tissue culture media)
BIRUS	biorefinerias rurales sociales *(rural social biorefineries)*
BOD	biological oxygen demand
BSA	bulk segregant analysis
Bt	*Bacillus thuringiensis* (used for biological control)
BU	Brabender units (these measure viscosity of a liquid)
^{14}C	*also* carbon-14 or radiocarbon, a radioactive isotope of carbon
C_3	pathway for capturing carbon dioxide during photosynthesis, involving a 3-carbon molecule, typical of cool-season plants
C_4	pathway for capturing carbon dioxide during photosynthesis, involving a 4-carbon molecule, typical of warm-season plants
C_i/C_a	ratio of intercellular CO_2 to atmospheric CO_2
CAM	*also* CAM photosynthesis, crassulacean acid metabolism, which is a carbon fixation pathway that occurs at night
cDNA	complementary DNA (synthesized from a mature mRNA template in a reaction catalyzed by the enzyme reverse transcriptase and the enzyme DNA polymerase)
CEC	cation exchange capacity
c.f.	conversion factor (for quantity of dried chips from a given batch of fresh cassava roots)
CFM	cassava foliage meal
cfu	colony-forming unit (of microorganisms)
Chl	chlorophyll
CM	controlled pollination (used for coding cassava lines developed at CIAT)
cmg	centimilligram (10^{-2} of a gram)
CN group	cyano group
CNP	cyanogenetic potential (of a cassava variety)
COD	chemical oxygen demand
cP	centipoise (a measure of viscosity)
CP	commercial product
CRM	cassava root meal
cv., cvs	cultivar, cultivars
CW	controlled wild (refers to controlled pollination in wild × cassava crosses)
Da	dalton (measure of atomic mass)
DAP	days after planting
DAP	diammonium phosphate
db	dry basis
DC	dried cassava chips
DDT	dichlorodiphenyltrichloroethane (pesticide)
DE	digestible energy
dm	decameter (10 meters)
DM	dry matter
DNA	deoxyribonucleic acid
DNCP	degree of nutrient element in the commercial product
DS	dry soil
dS/m	deciSiemens per meter (used to measure salinity)
dw	dry weight
E	efficiency of fertilizer application
E	egg (insect)
EC	electrical conductivity
ECR	ensiled cassava root
ECZ	edaphoclimatic zone
EDTA	ethylene diamine tetraacetic acid
ELISA	enzyme-linked immunosorbent assay
EM	effect as mulch (of green manures)
ESTs	expressed sequence tags

F and V	fixed and variable costs
F_1, F_2, etc.	first filial generation, second filial generation, etc.
FC	fresh cassava chips
FEC	friable embryogenic callus
FFSB	fullfat soybean
FN	fixed nitrogen (in humus)
FOB	free on board (a shipping term)
FRWA	fresh root weight in air
FRWW	fresh root weight in water
FRY	fresh root yield (of cassava)
FU	farinograph units
fw	fresh weight
GA	gibberellic acid (hormone used in plant tissue culture media)
GBSS	granule-bound starch synthase (an enzyme)
GDC	glycine decarboxylase (a photorespiratory enzyme)
gfw	grams (fresh weight)
GM	green matter
HA	high adaptation index to low soil K
HCN	hydrocyanic acid (content indicates cyanogenic potential of cassava roots)
HI	harvest index
hL	hectoliter
HMA	hot-melt adhesive
hp	horsepower
HPR	host-plant resistance
HQ	headquarters
IA	intermediate adaptation index to low soil K
IPDM	integrated pest-and-disease management
IPM	integrated pest management
ISA	measured in percentage, refers to physicochemical characteristic of flour
IVAG	*in vitro* active genebank
IVBG	*in vitro* base genebank
IVDMD	*in vitro* dry matter digestibility
kPa	kilopascal (a measure of force per unit area)
kVA	kilovolt-ampere (a unit of electrical power equal to 1000 volt-amperes)
L	larva (insect)
L	liter
LA	low adaptation index to low soil K
LAC	Latin America and the Caribbean
LAI	leaf area index
LAR	local area report
LSF	liquefaction, saccharification, and fermentation
L/T	cassava chip load per sloping tray
MAP	months after planting
masl	meters above sea level
Mcal	megacalories
MCP	maximum capacity for processing (of cassava chips)
mdh	malate dehydrogenase maize probe
me	malic enzyme maize probe
ME	metabolizable energy
MHD	maximum level of humidity accepted
MLO	mycoplasma-like organism
MPa	megapascal (a measure of force per unit area)
mRNA	messenger RNA (an RNA molecule encoding a chemical "blueprint" for a protein product)
mS	millisiemens
MS	Murashige and Skoog culture medium
MVAG	micro-viscoamylograph
NAD-ME	a C_4 photosynthetic pathway, subtype nicotinamide adenine dinucleotide malic enzyme
NADH	nicotinamide adenine dinucleotide (reduced form)
NADP-ME	a C_4 photosynthetic pathway, subtype nicotinamide adenine dinucleotide phosphate malic enzyme
NBR	normas brasileiras (*usually followed by corresponding numbers, as established by the ABNT*) *(Brazilian standards)*
ND	natural drying (of cassava chips)
NE	State of Nebraska, USA
NF	need for fertilizer application
NP	not planted
NTC	Norma Técnica Colombiana *[Colombian Technical Standard]*
OA	osmotic adjustment
OCD	oxygen chemical demand
OM	organic matter

OW	open wild (refers to open pollination in wild × cassava crosses)
P	pupa (insect)
P_n	photosynthetic rate (measured as μmol CO_2 per m^2/s)
P-protein	phloem protein
PAR	photosynthetically active radiation (referring to solar radiation for plants)
p.c.	paste concentrate
PCR	polymerase chain reaction (*see also* RT-PCR)
PDA	potato dextrose agar
PEPC	*also* PEP carboxylase, phospho*enol*pyruvate carboxylase (an important enzyme in photosynthesis)
pH	pouvoir hydrogène *[hydrogen power]* (unit to express the degree of acidity or alkalinity of a solution)
PIB	post-illumination burst of CO_2
ppc	phospho*enol*pyruvate carboxylase maize probe
PPD	postharvest physiological deterioration (of harvested cassava roots)
PTO	power takeoff (a drive shaft found on a tractor)
pv.	pathovar (bacterial strain)
PVA	polyvinyl acetate
PW	polycross of cassava with a wild *Manihot* species
QPM	quality-protein maize
QR	quantitative resistance
QRLs	quantitative resistance loci
QTLs	quantitative trait loci
RDA	recommended dietary allowance, *now* RDI or reference daily intake, *also* recommended daily intake (USA)
RFLP	restriction fragment length polymorphism
RGAs	resistance gene analogs
r.h.	relative humidity
RITA®	récipient à immersion temporaire automatique *[automatic temporary immersion device]*
RN	recommended nutrient
RNA	ribonucleic acid
RNAi	RNA interference technology
rpm	revolutions per minute
RT-PCR	real-time polymerase chain reaction (*see also* PCR)
rubisco	ribulose biphosphate carboxylase (enzyme found in chloroplasts)
RVA units	Rapid Visco Analyzer units (for flour quality)
sat.	saturation
SBE	starch-branching enzyme
SBM	soybean meal
SCARs	sequence characterized amplified regions
SCP	single-cell protein, *also known as* unicellular protein
SE	standard error
SG	specific gravity
SHF	simultaneous hydrolysis and fermentation
SLA	specific leaf area
S_N	nutrient in the soil
SSRs	simple sequence repeats
STET	compound of sucrose, Triton X-100, EDTA, and tris-HCl
SW	self-pollinated cross between cassava and a wild *Manihot* species
TDN	total digestible nutrients
Tgel	gelatinization temperature
TILLING®	targeting induced local lesions in genomes
TN	total nitrogen
tris-HCl	tris(hydroxymethyl)aminomethane-hydrochloride
tRNA	transfer RNA (a small RNA molecule that transfers a specific active amino acid to a growing polypeptide chain at the ribosomal site of protein synthesis during translation)
TTSS	type III secretion system
UE	use efficiency (referring to plant use of water or nutrients)
USLE	universal soil loss equation
VPD	vapor pressure deficit(s)
Vs	volume of soil
W	watts
wb	wet basis
WF^R	whitefly resistance
WRC	weighted requirement of crop
Ws	weight of soil

WUE	water-use efficiency
w/w	weight by weight

Cassava diseases and pests

ACMD, ACMV	African cassava mosaic disease, African cassava mosaic virus
CBB	cassava bacterial blight, *also* vascular bacteriosis of cassava
CCMV	cassava common mosaic disease
CCSpV	cassava Colombian symptomless virus
CFSD	cassava frogskin disease
CGM	cassava green mite (*see also Mt*)
CMD	cassava Caribbean mosaic disease
CsCMD, CsCMV	cassava common mosaic disease, cassava common mosaic virus
CsXV	cassava X virus
CVMD, CVMV	cassava vein mosaic disease, cassava vein mosaic virus
EPNs	entomopathogenic nematodes
Mc	*Mononychellus caribbeanae*
Mt	*Mononychellus tanajoa* (cassava green mite; *also* CGM)
Tu	*Tetranychus urticae* (green spotted mite)
VAM	vesicular arbuscular mycorrhizae
Xam	*Xanthomonas axonopodis* pv. *manihotis*

Soil textures

C	clay
CL	clay loam
L	loam
S	sandy
SC	sandy clay
SCL	sandy clay loam
Si	silt
SiC	silty clay
SiCL	silty clay loam
SiL	silt loam
SL	sandy loam

Chemical elements and compounds

Elements

Al	aluminum
B	boron
C	carbon
Ca	calcium
Cl	chlorine
Cu	copper
Fe	iron
K	potassium
Mg	magnesium
Mn	manganese
Mo	molybdenum
N	nitrogen
Na	sodium
O	oxygen
P	phosphorus
S	sulfur
Zn	zinc

Compounds

$CaCO_3$	calcium carbonate
CN^-	cyanide radical (*also* cyanide anion)
CaO	calcium oxide
CO_2	carbon dioxide
ETOH	hydrated ethanol (at 96%, v/v)
$H_2BO_3^-$	boric acid ion
H_2O	water vapor
$H_2PO_4^-$	dihydrogen phosphate ion
$Hg(NO_3)$	mercury (II) nitrate (*also* mercuric nitrate *or* mercury dinitrate)
KCl	potassium chloride
K_2O	potassium oxide
$MgCO_3$	magnesium carbonate
MgO	magnesium oxide (*also* magnesia)
MoO_4^{2-}	molybdenum oxoanion
N_2O	nitrous oxide (*also* laughing gas)
NaCl	sodium chloride
NaClO	sodium hypochlorite
NH_2^-	amine
NH_3	ammonia
NH_4^+	ammonium cation
NO_3	nitrate
P_2O_5	phosphorus pentoxide
SeO_4^{2-}	selenate ion
SO_4^{2-}	sulfate ion

CIAT Publication No. 377

Corporate Communications, CIAT

and

Latin American and Caribbean Consortium to Support Cassava Research and Development (CLAYUCA)

Translation:	Elizabeth L. McAdam Lynn Menéndez Damian & Bibi Hager
Editing:	Elizabeth L. McAdam
Production editing:	Gladys Rodríguez Claudia Marcela Calderón
Production:	Oscar Idárraga (layout) Julio César Martínez (cover design)
Printing:	Impresora Feriva S.A., Cali, Colombia

ISBN (CIAT): 978-958-694-112-9

ISBN (CTA): 978-92-9081-503-7