principal) and a borrower (the agent), stockholders and management, and landlords and tenants. In the lender-borrower case, the lender has entrusted the borrower with the use of loan funds in return for the borrower's promise of a safe and timely return of the funds, plus interest, according to the terms of the loan contract. However, due to the agent's self-interest, informational asymmetries, and uncertain expectations, both contracts and incentive alignments between the principal and agent generally are incomplete. Agency costs attributable to monitoring, bonding, and residual losses then are incurred in structuring, administering, enforcing, and adapting contracts in order to align incentives, resolve informational problems, and respond to uncertainties [Jensen and Meckling (1976); Barry et al. (1992)].

The lender-borrower and landlord-tenant relationships are especially important in agricultural finance. In a credit relationship, two basic concerns of the agricultural lender are (1) whether the borrower/agent is riskier than believed when the loan was originated (an adverse selection problem), and (2) whether the borrower will take on greater risks during the term of the loan than were originally anticipated (a moral hazard problem). These conditions are attributable to asymmetries in both incentives and information between the lender and the farm borrower. The borrower is motivated by profitability and wealth accumulation, because he or she shares directly in the returns (favorable or unfavorable) earned by the loan proceeds. In contrast, the lender is restricted to the fixed returns of the loan funds plus interest, as established in the loan contract, although additional benefits may come from growth over time in a successful borrower's financing needs. Thus, in evaluating a borrower's creditworthiness, the lender emphasizes loan repayability and safety – that is, self-liquidating and asset-generating loans – while the borrower focuses on profitability and wealth.

Asymmetric information is also directly involved in the agency relationship because the lender may lack information about the borrower's goals and actions, as well as about the risks of the projects being financed. Farm borrowers should know more about their productivity, business characteristics, financial position, and repayment intentions than do lenders, and much of financial planning and loan documentation is intended to convey this information from borrowers to lenders. Lenders do specialize in lending and related information processing, and they may have a broader perspective on credit transactions than do borrowers. However, the intentions, abilities, and experiences of individual borrowers are what motivate loan performance.

Adverse incentives for borrowers may also arise because they do not bear the full consequences of their actions. As leverage increases, the consequences of more of the borrower's actions that lead to default are borne by the lender [Stiglitz (1985)]. A borrower, then, has an increasing incentive to take riskier actions and to employ a go-for-broke attitude [Robison et al. (1987); Foster and Rausser (1991)] that increases the cost of financing for the lender and increases the lender's likelihood of becoming an owner of the borrower's assets. The lender, in turn, has an increasing incentive to control the borrower's actions.

These insights from finance theory have helped to guide the research agenda in agricultural finance. Studies have focused closely on the information-intensive, personalized relationships that characterize the arrangements between agricultural lenders and their borrowers, including the lender's procedures for evaluating and monitoring creditworthiness. Rationalizing the specialization of many lenders in financing agriculture is a natural outgrowth of the sector's sources of risk, small business orientation, and capital intensity. Similarly, studies that consider the changing motivations of farmers as debt levels and financial adversities increase have helped to explain tendencies toward go-for-broke behavior, stringency in loan contracts, and intense monitoring arrangements by agricultural lenders. These issues and related studies are further developed below.

3.2. *Resolving information and incentive problems*

Lenders and borrowers may utilize extensive practices to improve incentive alignments and resolve information problems [Miller et al. (1993)]. Differential loan pricing based on risk-adjusted interest rates is one lender response to the adverse selection problem [Stiglitz and Weiss (1983)]. Credit rationing, institutional adversities, and market failure are possible results of severe credit rationing. Using risk-adjusted interest rates would yield a more dispersed distribution of risky borrowers and lower lending risks on average, thus reducing the adverse selection problems. Adjusting interest rates for risk presumes that sufficient information is available to effectively distinguish among the risk classifications. Thus, information collection, processing, and monitoring by lenders are important contributions to the resolution of agency cost problems before and after the loan contract is established.

Market signaling is another mechanism whereby borrowers and lenders respond to the problems of asymmetric information. Market signaling suggests that one or more of the market participants (the lender or the borrower) convey additional information to other market participants (the borrower or the lender) about the levels of and value placed on creditworthiness. Effective financial accounting systems maintained by creditworthy borrowers provide a distinguishing signal between high and low credit risks, and they provide for monitoring of business performance over time. Because certified or audited accounts are used relatively little in agriculture, lenders must employ their own expertise in distinguishing among farmers' financial performance. Agricultural borrowers may also undertake management practices that distinguish them from their peers and highlight unique skills and levels of productivity. Examples include the use of futures and options contracts to manage risks, producing specialty crops, adopting new production and telecommunication technologies, advanced levels of education, and leadership reputations in local communities.

Extensive financial contracting by lenders involves provisions in a loan contract intended to address potential adverse selection and moral hazard problems [Smith and Warner (1979)]. These non-price methods include collateral requirements, loan repayment upon demand provisions, reporting requirements, performance standards, sales restrictions, constraints on additional borrowing, insurance requirements, default penalties, and foreclosure conditions. Because the contracting costs generally are borne by the borrower, his or her responses tend to reduce asymmetric information problems and align the borrower's actions with the goals of the lender. In addition, the financial market disciplines borrowers through the risk of non-renewal of loans if agency costs are excessive [Stiglitz and Weiss (1983)].

The creation of markets for exchange of financial information is another mechanism for responding to the problems of asymmetric information. Credit-rating companies, for example, specialize in collecting and disseminating information about part of the creditworthiness of agricultural borrowers. Collateral control companies will monitor, control, and validate the status of specific assets (e.g., stored grain, animals in large cattle feedlots) pledged to secure a loan agreement. Field servicing companies, which may include banks or other financial institutions, will service agriculture real estate loans, manage repayments, and monitor loan performance. Written or oral references provided by individuals about others are a commonly used form of market information, and lenders often are willing to exchange at least some information about their customers in order to facilitate the functioning of their respective markets.

If information problems are severe enough, public policies and institutional regulations may be developed to enhance market performance. Such actions might be justified if the market in question serves the public interest and if non-government resolutions to information deficiencies are ineffective. Examples include financial reporting requirements for corporate farms, disclosures of public offerings to financial regulators, truth-in-lending and advertising requirements, and government sponsorship of financial institutions and loan programs.

3.3. Incomplete contracting, property rights, and financial structure

A firm's financial structure can also be examined using the incomplete contracting approach in which the allocation of risk and control among alternative classes of investors is a key focus [Hart (1988); Berglof (1990); Aghion and Bolton (1992)]. Debt and equity are the standard financial instruments, but they are distinguished not only by their relative claims on the firm's assets and earnings, but also by the control rights associated with each type of financial claim – where the residual rights of control (those not designated by the financial contract or by law) are synonymous with ownership. More specifically, the allocations of control and ownership under this approach are state-dependent – under normal conditions, equity holders own and control the firm's assets, although ultimate control is determined by the type of equity (e.g., voting versus non-voting stock, preferred versus common stock, limited versus general partners). Under extreme adversity, however, financial contracts are designed so that ownership and control revert to the debt holders (according to seniority and size of claims). Debt capital, thus, represents a form of contingent ownership of the firm.

Under the property rights approach, the terms of the respective types of financial claims logically must represent more than the need for external funds and the level of compensation for the use of these funds. Unanticipated contingencies raise open questions about who will control the firm under alternative performance conditions and how cases of dispute and financial distress are ultimately resolved. Such contingencies are too numerous and too varied to fully anticipate in a written contract. Thus, contracts are necessarily incomplete in that they do not stipulate the contracting parties' obligations and actions in every eventuality. Incompleteness gives rise to the need to allocate control in situations not covered by the initial contract – that is, the allocation of the residual rights of control.

In effect, the incomplete contracting approach suggests that the parties to the contract must determine at the outset who is best suited to control the firm in various situations and what performance levels will signal the need for a transfer of control. Given this contingent allocation of control, the sharing of return streams is designed to provide the appropriate incentives for the exercise of effort by the parties commensurate with their respective ranges of control [Berglof (1990)]. That is, the party holding residual control rights over a specified range of states should bear the risk and reap the expected returns associated with decisions in these states. This party (the equity holder) will exercise effort commensurate with the anticipated rewards. In less favorable states, however, the rewards to such efforts dissipate, and go-for-broke actions by the equity holder, whose financial claims are substantially diminished, may yield adverse effects that accrue more to the debt holder. Thus, it is logical at this point for the residual rights of control, associated with ownership, to shift to the lender so that he or she can exert appropriate effort to protect the debt claims. It is also logical for the lender to exercise more stringent provisions of financial contracts that increasingly constrain the range of managerial choices available to the equity holder.

3.4. Transaction cost economics

Elements of transaction cost economics also apply to a firm's anticipated financial structure and relationships with suppliers of financial capital. According to Williamson (1996), transaction costs are incurred in drafting, negotiating, governing, safeguarding, and adapting the terms of agreements. The transaction costs are closely related to agency costs, although placing more emphasis on ex-post governance structures versus the ex-ante focus of agency theory and on transaction characteristics versus the characteristics of principals and agents [Williamson (1996)]. The choice of governance structure for coordinating a vertical system and determining the boundaries of firms then focuses on the minimization of transaction costs, based on the characteristics of the transactions and the work efforts of the respective parties.

Within this transaction cost framework, Williamson (1996) suggests that the degree to which assets are specialized to various activities is an important determinant of a firm's financial structure. In his view, investments with low asset specificity are more suitable for debt financing because of their easier redeployment (or re-marketability). Re-marketability is a preferred attribute of assets pledged as collateral to secure a loan. In contrast, equity financing is more likely for relationship-specific assets. Re-marketability of such assets is lower and the returns to specialized assets are more vulnerable to opportunistic rent-seeking by other contracting parties. Thus, Williamson (1996) asserts that a firm's use of debt relative to equity capital is inversely related to the degrees of specificity of assets owned or controlled by the firm. These transaction cost concepts match well with the tendency for highly specialized agricultural assets (e.g., buildings, confinement production technologies, irrigation systems) to have higher equity capital requirements than is the case for more marketable machines, livestock, commodities, and perhaps even farmland.

3.5. Free cash flow concept

Jensen's (1986) free cash flow concept also has applicability to agricultural finance. The free cash flow concept suggests that managers (agents) of firms with excess cash flows and abundant financial assets may exercise managerial laxness, devote insufficient attention to detail, squander resources in non-business uses, and otherwise engage in self-serving behavior that is counter to the objectives of principals. The general effects of such opportunistic behavior are a diminution in the firm's financial performance and increased vulnerability to mergers, acquisitions, or other losses of business independence. A possible solution to these maladies is the creation of leverage-induced, external financial obligations that will stimulate increased efforts by agents to satisfy these obligations, and thus bring closer alignment with the goals of principals.

The free cash flow concept is much more general than Jensen's (1986) application to corporate control and finance. It applies to many types of agency relationships in which obligations may lead to stronger incentive compatibility between principals and agents. In an agricultural setting, the concept suggests that farmers could be induced to exert greater effort on behalf of lenders and landlords as their obligations to these principals increase. Along these lines, Nasr, Barry, and Ellinger (1998) utilized farm-level data to test the free cash flow hypothesis and found a positive statistical relationship between a farm's technical efficiency and its ratio of current debt to total assets. This result suggests that greater reliance by farmers on current debt to finance their operations is consistent with the hypothesis that they will work harder to meet these financial obligations.

4. Liquidity prefereuce theory

A major implication of the principal-agent problem in credit relationships is that the preferences of the lender, as expressed by the interest rate and non-interest rate terms of the loan contract, may influence the rate of firm growth, risk management practices, resource allocations, and enterprise choices of the borrower. The influences of interest rate and non-interest rate terms of loans were observed in agricultural finance by Baker (1968) in the 1960s and tested in a number of empirical studies. Baker's study of principal-agent problems predated by nearly 10 years the landmark principal-agent and agency cost work in finance by Jensen and Meckling in the late 1970s. Baker's approach was motivated by liquidity and incentive alignment issues, however, while Jensen and Meckling emphasized information and incentive issues.

Baker recognized that optimal resource allocation and enterprise choices of agricultural borrowers would change to reflect lenders' preferences, as manifested in differential financing costs. Baker's conceptual approach was to acknowledge the traditional production economics relationship in which a firm's optimal combination of resources is achieved when the marginal rate of resource substitution equals the inverse of the price ratio. When borrowing is considered as a means of financing inputs, the economic equilibrium is modified to incorporate the financing cost that includes both interest costs and the value (liquidity premium) of borrowing capacity or credit surrendered in the transaction. Given the discrepancy between the preferences of the lender and of the borrower, as reflected by varying loan limits and potentially erroneous borrower expectations of lender behavior, optimal resource allocation can be influenced. This influence can take place whether or not borrowing occurs, through changes in the size and composition of the credit reserve, given its liquidity value to the borrower.

Subsequent empirical work focused on both the liquidity premium concept and the interest rate and non-interest rate responses of agricultural lenders to the managerial actions and business characteristics of farm borrowers. In 1971, Barry and Baker developed a modeling approach for estimating the levels of liquidity premiums that agricultural borrowers with different levels of risk aversion would associate with credit reserves. Related studies by Vandeputte and Baker (1970) and Baker and Bhargava (1974) provided more general specifications of functional relationships between liquidity premiums and sizes of reserves for both cash and multiple sources of credit. Chhikara (1986) then showed how liquidity premiums associated with cash and credit reserves could be derived from the expected utility model, and Barry and Robison (1987) and Gwinn, Barry, and Ellinger (1992) showed how debt capacity and liquidity are related to different levels of risk aversion, thus combining elements of external and internal credit rationing.

Accompanying these studies of how agricultural producers value various sources of liquidity was a companion set of studies that evaluated the credit responses of lenders to numerous strategies in borrowing, debt management, and risk management. Included were measures of credit responses associated with a farmer's choice of lender; sequence and source of borrowing and repayment; financing instrument; asset structure; enterprise mix of farming operations; and degrees of vertical coordination [Baker (1968); Baker and Hopkin (1969); Barry and Baker (1977); Sonka et al. (1980); Barry et al. (1981); Barry et al. (1997)]. Empirical measures were developed for lender responses to many such strategies and situations. The effects of these strategies and situations on farm business performance often are evaluated using mathematical programming or simulation models in which the credit components are based on the lender responses.

Observational techniques used in these studies for estimating lenders' credit responses are based on simulated borrowing requests in which a sample of lenders respond through a survey (mail, personal, or workshop-administered) to case loan requests for representative farms. The case loan typically involves a fully documented loan request over an array of purposes and terms, set high enough to anticipate the lender's rejection and designed for deletion of individual items (usually capital items) until loan approval is obtained. The result is an estimate of the firm's total credit, conditioned by the particular set of circumstances surrounding the loan request. The objective of the approach is a set of functional relationships between the credit responses and the characteristics of the loan situation that would hold as reliable predictors of lender response over a wide range of loan conditions.

Two examples of the simulated loan request approach to measuring lender credit responses are studies by Barry and Willmann (1976) and Pflueger and Barry (1986). Barry and Willmann focused on the relationship between credit availability and forward contracting of commodity sales by farmers as a risk management tool. Using a simulated borrowing approach to evaluate the responses of a sample of lenders to alternative levels of forward contracting by crop farmers, they found that the most preferred levels of contracting generated about 17 percent more total credit and about 53 percent more operating credit than the least preferred levels. When these credit responses were evaluated in a multi-period risk programming model, the risk efficient growth plans included contracting due to both the favorable effects on credit and the lower price risks. The model results indicated contracting even for farmers with little or no risk aversion, and even though expected profits were higher for the non-contract sales, reflecting the misalignment of incentives between the borrower and the lender.

Pflueger and Barry (1986) considered how a sample of non-real-estate lenders would respond to a farmer's use of crop insurance as a risk management tool. The results of the survey, also based on simulated loan requests, indicated a positive credit response by about 60 percent of the lenders, with little changes in interest rates and loan maturities. A stochastic, multi-period simulation model was used to evaluate the effects of the lenders' credit responses and the use of crop insurance on the farm's profitability, solvency, liquidity, and survivability. The simulation results, which modeled an early 1980s farm situation already experiencing financial stress, indicated that crop insurance and the credit responses improved farm survival and liquidity, but additional borrowing occurred to sustain the firm under adverse profit conditions. Thus, reductions in the representative farm's business risk were largely offset by increases in financial risk (see Section 7.2 below).

5. Relationships in agricultural finance

Relationships may involve two important characteristics: information and sympathy. Relationships may arise from close and continued exchanges between two economic agents including suppliers and users of financial capital. Some of the information acquired in these exchanges may involve economic data relating to cash flows, debt obligations, assets, and investment plans. Other kinds of data acquired may include the preferences, values, and character traits shared by the parties to the exchange.

For the most part, financial relationships have been examined in the presence of incomplete information and agents motivated by self-interest [Petersen and Rajan (1994, 1995)]. Most recently, the influence of relationships that include both information and sympathy has been examined using the newly developed social capital paradigm

[Schmid and Robison (1995)]. Social capital represents a different approach to the principal-agent analysis in which sympathy redefines externalities.

An externality is created when one agent creates an outcome for another agent without permission from the affected agent. When social capital exists, what otherwise might be considered an externality is internalized with favorable economic outcomes. Transactions and monitoring costs are reduced because relationships reduce the incentive for exploitive behavior that produces negative externalities, and increase the incentive to meet contracted obligations. Social capital may help explain why family businesses rich in social capital appear to dominate other types of business organizations. To illustrate, family businesses account for 75 percent of Oregon's small companies [Nelton (1990)], and 75 percent of U.S. companies are family-owned or controlled [Calonius (1990)].

In agricultural finance, the key issues and research initiatives have responded to these questions: How have the major attributes of relationships changed over time, and how do relationships respond to changes in market competition? What is the nature of the relationships between agricultural borrowers and their lenders? In what ways do farmers' investments, financial performance, risk management, and other business practices influence the cost, availability, and other terms of financial capital? How is credit scoring applicable to financial relationships in agriculture? How do agricultural lenders manage credit risks? How do relationships between lenders, borrowers, and other parties influence leasing, agribusiness lending, and other business practices? These questions are addressed in the following sections.

5.1. *Relationship concepts*

Relationships develop through interactions between parties over time and/or across multiple financial products and services. Relationships directly involve the generation of reliable and accurate information about the parties to a financing transaction, the use of such information in evaluating and monitoring creditworthiness, and the impacts information has on the reduction of agency costs and on the resolution of adverse selection and moral hazard problems. The anticipated results of effective relationships are improved availability of financial capital and reduced costs of financing transactions. Increases in competition, however, may work against the benefits of relationships and result in less favorable access to financial markets for newer firms or financially stressed firms.

5.2. *Evolving nature of relationships*

The nature of relationships has changed over time as financial markets were deregulated, financial market conditions became more volatile, and financial institutions evolved from primarily commercial banks and other depository institutions to broader financial services companies. Hodgman (1961) introduced the customer relationship concept in banking by showing the importance of customers' demand deposits as a source of a bank's capacity to lend and invest, and the resulting importance of a bank's relationship to loan customers who hold demand deposits. Wood (1975) extended Hodgman's customer-deposit relationship to multi-periods by showing how a liberal lending policy may induce increases in future deposits that can, in turn, be loaned or invested. Wood also added the customer loan relationship which suggests that a bank's current lending policy influences its future loan demands. Barry (1978) applied these deposit relationship concepts to estimate the rate of loan-deposit feedback in rural banking at a time when banks were still subject to stringent regulations on deposit rates, ranges of products and services, and geographic scope of operations. His results showed a relatively high rate of loan-deposit feedback that contributed to the bank's profitability of bringing non-local sources of funds into local lending markets.

Sharpe (1990) considered asymmetric information as a determinant of customer relationships attributable to a bank's monopoly power over its established, higher-performing borrowers who become "informationally captured" by the bank. The adverse efficiency consequences of this informational imperfection are reduced by implicit contracts arising from the institution's efforts to create a reputation as a reliable lender. The terms of such contracts depend on the institution's degree of informational advantage, reputational perceptions, and other determinants of customer profitability. Sharpe contrasts his ex-post, information-driven relationship theory to an alternative justification suggested by Wachter and Williamson (1978), based on the existence of ex-ante, relationship-specific capital investment created by the pre-loan evaluation.

More recently, Petersen and Rajan (1994, 1995) considered the interactions between lenders, borrowers, and financial market performance. Their 1994 article uses data from a national survey of small, non-farm businesses to determine that information-based relationships may have significant, positive effects on credit availability, and less significant reductions in credit costs. Their 1995 article uses the same database to test the interactions between lending competition and the availability and cost of credit for young or financially stressed borrowers, both of whom were found to benefit from stronger relationships in more concentrated markets. Less competitive markets may better enable lenders to grant short-run concessions to disadvantaged firms, while adjusting financing terms in more favorable times to share in the future surplus of the borrowing firm.

Barry, Ellinger, and Moss (1997) applied the Petersen and Rajan concepts to evaluate the influence of the competitiveness of agricultural lending markets on lender-borrower relationships. Their findings clearly indicate an inverse relationship between competition and borrower loyalty, which serves as a proxy for the lender-borrower relationship. Bankers in more competitive farm real estate and non-real-estate lending markets tend to have less loyal customers, irrespective of other institutional and market characteristics. Nonetheless, evidence [Barry and Ellinger (1997)] still suggests that rural financial markets are more concentrated and less competitive than their urban counterparts. Agricultural and rural business lending, thus, represents niche markets for many local lenders in which specialization is conducive to relationship-building, targeted skills in financial analysis, and the types of informational advantages cited by Sharpe (1990).

Turvey and Weersink (1997) extend the analysis of the lender-borrower relationship to provide empirical evidence about loan demand/contract curves for agricultural loans. Using explicit linkages to credit-scoring models in estimating loan demand parameters, they find evidence of backward-bending loan demand curves, reflecting the properties of asymmetric incentives and information in agricultural lending. These results, in turn, suggest some degree of credit rationing in agricultural lending.

5.3. Credit evaluation procedures

Previous studies of credit relationships in agriculture have shown that the responses of lenders to the business characteristics, managerial actions, and other agency costs of financing agricultural firms influence the cost, availability, and other terms of financial capital, including the magnitude and composition of liquid credit reserves (see the section on liquidity preference, Section 4 of this chapter). In turn, these cost effects may influence the optimal financial structure (leverage) and financial performance of farm businesses as well as the composition of their assets, risk management practices, and other income-generating activities. These studies do not, however, directly consider the agricultural lender's processes of credit evaluation, including the relative importance of the major variables affecting creditworthiness.

In contrast, a growing set of studies (e.g., Lufburrow et al. (1984); Dunn and Frey (1976); Hardy and Weed (1980); Fischer and Moore (1987); Stover et al. (1985); Miller and LaDue (1989); Turvey (1991); Turvey and Brown (1990); Miller et al. (1994); Novak and LaDue (1994); Chhikara (1989); Splett et al. (1994); and Aguilera-Alfred and Gonzalez-Vega (1993)] have focused on the credit evaluation process, including the development and validation of various types of credit-scoring models, and on predicting financial stress and bankruptcy problems of farmers [Shepard and Collins (1982); Franks (1998)]. Agricultural lenders themselves have accelerated the development and use of more formal methods of credit evaluation [Miller et al. (1993)], in light of growing concerns about loan quality, increased competition in agricultural lending, efforts to control lending costs, and improvements in data quality and loan information systems. These lender-based models have many similarities to one another, although model comparisons indicate a large degree of disparity in model design and use across lenders [Ellinger et al. (1992)].

Credit-scoring and risk-rating models provide systematic, comprehensive ways in which to assess the borrower's financial data and, along with the lender's judgment and other relevant information, reach a valid assessment of the borrower's creditworthiness. The basic steps in model development are to (1) identify key variables that best distinguish among borrowers' creditworthiness, (2) choose appropriate measures for these variables, (3) weight the variables according to their relative importance to the lender, (4) score each loan as a weighted average of the respective variables, and (5) assign the credit scores to the appropriate class [Barry et al. (1995)].

Considerable attention has focused on appropriate statistical methods for evaluating credit-scoring models [Turvey and Brown (1990)]. Moreover, evidence suggests that statistically based models and judgment-based models developed by lenders can yield similar credit evaluations [Splett et al. (1994)]. Recent models have moved beyond estimating the ability to replicate subjective loan classifications by lenders, to concentrate on the borrower's actual loan performance as the validation criterion [Miller and

LaDue (1989); Miller et al. (1994); Turvey (1991)]. Financial planning models of farm businesses have also endogenized farm investment decisions, credit evaluations, and loan pricing based on the credit-scoring procedures of agricultural lenders [e.g., Barry and Ellinger (1989)]. Less is currently known, however, about whether credit-scoring models should be tailored to the structural and/or demographic characteristics of farm borrowers, or whether a single model can effectively do the job.

5.4. Managing borrowers' credit risks

Lenders' management of an individual borrower's credit risks depends significantly on the size and structural characteristics of the borrower's business, and on the characteristics of the financial institution. Larger, industrialized agricultural production units generally seek financing from larger lending institutions, and tend to be treated like other large commercial borrowers. Financial reporting, specialized collateral control, telecommunications, and automated information systems play important roles in lender-borrower relationships for these larger operations. On the other hand, small, part-time farm operations in developed economies are increasingly treated as consumer borrowers, where loan acceptance is determined by credit- scoring, and loan transactions occur with credit cards. Interest rates to small borrowers are higher than on commercial or agricultural loans, and contact between borrower and lender is minimal.

In contrast, informal finance provided to small farms in developing countries by money lenders or peer monitoring in group borrowing relies heavily on personal observations and individual monitoring [Carter (1988); Hoff and Stiglitz (1990)]. The informal closeness of relationships between money lenders, for example, and their borrowers contributes to the resolution of asymmetric information problems, perhaps more effectively than the financial contracting and monitoring arrangements employed in larger-scale commercial finance. Similarly, extended family linkages, which provide opportunities for lending to smooth consumption in developing economies, also reflect the resolution of informational problems.

Between the small farms and the industrialized units are the commercial scale family farms. Their small business scale, geographic remoteness, informal accounting practices, and relatively high business and financial risks create intensive information needs to allow lenders to successfully manage credit risks. Frequent monitoring, periodic farm and office visits, reputations, specialized and experienced loan officers, and a localized community orientation of many agricultural lenders have long characterized key elements of credit risk management for commercial-scale family farms.

Lenders are placing greater reliance on risk-adjusted interest rates to distinguish among borrowers with different credit risks [Miller et al. (1993)]. Differential collateral requirements are also a significant non-price response to credit risk. Timeliness of loan payments and periodic financial reports are relied on heavily to monitor business performance. According to Miller et al. (1993), information about past financial performance is the dominant signal agricultural borrowers can provide to distinguish their credit risks. Projected financial performance, collateral offered, borrower experience, production efficiency, and risk management ability have medium to high importance. Borrower education and reputation in the community have lesser importance.

5.5. *Real estate leasing arrangements*

Farmers' use of share rent or cash rent leasing is a major financing mechanism for controlling the use of farmland. Despite the high capital investment tied up in the leased land, many leasing contracts have involved informal arrangements in which leases are oral rather than written and/or the contract terms are annual or three to five years in length, despite the long-lived nature of farmland. Even with annual, oral leases, however, it is common to observe long-term relationships between the landlord and the farm operator.

In applying information and transactions costs concepts to leasing arrangements, Allen and Lueck (1992) tested and confirmed that reputation and common law may explain the high incidence of use of short-term and often oral contracts in the leasing of farmland. The information conveyed by reputation and experience has been sufficient to solidify the landlord-tenant relationship in many instances, and transform a short-term legal arrangement into a longer-term financial relationship.

5.6. *Agribusiness and trade financing*

Agribusiness or trade financing of farmers is a long-standing practice that is especially significant for many operating inputs and for farm machinery. In many countries, the local merchant served as a credit source long before the presence of specialized financial institutions. The modern-day trade firm can compete effectively in the financial markets because it may operate a branch or dealer system efficiently over widely diverse geographic areas, have cost-effective access through the parent company to national financial markets for loan funds, experience low delivery costs, and rely on consistently applied credit evaluation procedures and scoring models. Offering credit or leasing arrangements complements the trade firm's merchandising activities.

Trade firms also develop important, yet different customer relationships with farmers than do specialized lenders [Sherrick and Lubben (1994)]. The trade firm's customer relationship primarily involves the merchandising activity, but it may yield extensive information about a farmer's management ability, business practices, and financial performance. This customer information, in turn, contributes importantly to the evaluation of creditworthiness and, thus, augments the trade firm's management of the credit risk.

5.7. *The role of social capital*

Agricultural finance is also related to social capital. The traditional economic model is based on individual utility maximization, assuming that individuals are self-motivated. Actions that appear to contradict a preference-based model are often explained away by the emergence of new tastes. For example, gifts to charity that reduce one's own wealth might be explained in a way consistent with self-serving preferences by identifying a taste for philanthropy. Concern for the environment has been described as motivated by the taste for diversity.

While few, if any, would disagree that behavior often may be explained by self-interest, much of human behavior seems inconsistent with selfishness. Social capital emphasizes that an individual's well-being is altered by changes in the well-being of others with whom a relationship exists. Moreover, when one person's accomplishments are the object of another person's caring, he/she has access to advantages (disadvantages) not available to those who lack the vicarious caring. One definition that recognizes the social capital content of caring follows:

> Social capital is the sympathy (antipathy) one person has toward another person, idealized self, or object. The sympathetic (antipathetic) person is said to supply social capital while the person or object of sympathy (antipathy) is said to possess social capital. The persons or objects of social capital may expect benefits (harm), advantages (disadvantages), and preferential (discriminatory) treatment from the providers of social capital. Social capital may be culturally dependent, environmentally influenced, and responsive to a wide range of stimuli including the perceived social capital claimed by others. [Robison and Siles (1997, p. 10)]

Other definitions of social capital include (1) the social obligations or "connections" which are convertible into economic capital under certain conditions [Bourdieu (1986)]; (2) a resource of individuals that emerges from their social ties [Coleman (1988)]; (3) mutually beneficial activities that promote and reinforce a sense of the common good; (4) the ability to create and sustain voluntary associations [Putnam (1995)]; (5) trust [Fukuyama (1995)]; (6) the expectations for action within a collectivity that affect the economic goals and goal-seeking behavior of its members, even if these expectations are not oriented toward the economic sphere [Portes (1995)]; and (7) friends, colleagues, and more general contacts through whom you received opportunities to use other forms of capital [Burt (1992)].

Several applications to agricultural finance are suggested by social capital theory. Social capital changes the relationship between a principal and his or her agent. If the principal has social capital with his agent, as in the case of a landlord and tenant who are related or are close friends, the tenant might act in the interest of the landlord without the need for special contracts to alter incentives or monitoring costs to prevent cheating. As a result, one might expect to find a preference for landlords to lease to close friends and family. Supporting this conclusion was Gwilliams (1993), who pointed out that 81 percent of the participants in share leases were close friends or family, and 89 percent of those entering into cash leases were close friends or family.

Various studies have concluded that social capital alters the terms of trade compared to arm's-length transactions. To examine the extent to which social capital (relationships) influence lenders' loan approval decisions, a mail survey was conducted of bankers in Michigan, U.S.A. [Siles et al. (1994)]. The study concluded that social capital is not likely to change significantly the probability of a very good loan or a very bad loan being approved or disapproved. However, for those loans in between, social capital can increase the probability of loan approval by as much as 60 percent in the U.S. These findings are especially applicable to agricultural finance in light of the important roles played by small, community-oriented banks and the information-intensive nature of lender-borrower relationships in agricultural lending.

Social capital may also influence savers. A survey of 1,000 people 18 years or older, drawn randomly from Michigan zip code areas with populations of 10,000 or less, was conducted in 1992 to find the effect of social capital on one's choice of bank [Hanson et al. (1996)]. The survey results found that a friendly relationship with the bank and its personnel increases the likelihood that customers will stay with their financial institution; an unfriendly relationship results in a large decrease in the probability that the financial institution will retain the customer's business in the future. The survey results suggest that having a friendly relationship with the bank customer increases the interest rate on certificates of deposit that would entice the customer to switch institutions by 74 basis points over the cases when the relationship with the bank customer is unfriendly. Again, the community orientation of smaller banks in rural markets makes social capital considerations important in these markets.

An individual's social capital may lead him or her to develop attachment value towards objects such as farmland, occupations, and ideas. As a result of one's social capital, a farmer may take financial actions to preserve his or her ownership of farmland or make investments in assets to gain the approval of peers that appear to be irrational when considered against the profit-maximizing motive.

One important dimension of social capital involves transaction costs. Because social capital increases the value of trade between social capital-endowed trading partners, trade between these partners is more likely to occur than between the estranged and strangers. Therefore, in economies with high transaction costs associated with limited information and enforcement ability, trading between the social-capital-endowed will be more prevalent. This tendency is especially true in financial markets. Adams (1992) reports that despite tens of billions of dollars committed to establishing sustainable agricultural credit programs in developing countries, there are few successes. They have failed largely because of loan recovery problems, chronic dependency on outside funds, and excessive transaction costs.

In contrast to the formal credit system, Adams (1992) cites informal finance systems in Bolivia and the Philippines that recovered most of their loans while formal lenders were awash in default. The informal finance systems in these countries mobilized and allocated large amounts of voluntary savings while banks had trouble attracting deposits.

The apparent difference between the formal and informal financial systems was relationships. Adams and Canavesi (1992) report that 90 percent of the *pasanakus* (an informal finance organization in Bolivia) were composed largely of friends or fellow workers (p. 316). Esguerra and Meyer (1992) provide similar evidence from the Philippines. And Graham (1992) reports from Niger that loans from family, friends, and relatives constituted a majority of the informal finance activity.

In general, social capital has the capacity to internalize consequences that otherwise might be considered externalities. In light of social capital's ability to internalize externalities, a policy other than one based on an individual's self-interests may be important to consider.

6. Financial growth and intertemporal analysis

The smaller scale, concentrated ownership, and capital intensity of agriculture has placed considerable emphasis on the financial management function of farm businesses. Research and analysis in financial management has a rich and lengthy history, especially in focusing on the financial dimensions of firm growth in agriculture. Key questions and issues have considered static versus dynamic analysis, optimal investment and firm growth patterns, financial leveraging and capital structure, optimization versus simulation models, life cycle consumption and financing plans, and the relationships among a farm's financial, production, and marketing components in influencing its performance over time. Underlying these application areas are the concepts of firm growth.

6.1. Growth concepts

A study of the growth process for agricultural firms requires a shift away from perceiving the firm in a static environment to a dynamic setting [Dorfman (1969); Boussard (1971); Barry (1977)]. For a firm, dynamics deals with deriving an optimal time path from its state in any period to a terminal state – if, in fact, a desired terminal state can be defined. The path is optimal with respect to the firm's objectives. The time path implies the sequential nature of decision making in that decisions in the respective time periods depend on preceding events and on expectations of succeeding events.

Some firm growth and investment studies [Schnitkey et al. (1989); Collins and Karp (1993); Boussard (1971)] have formally cast their empirical analysis in a dynamic setting, although the extent of empirical detail achievable in dynamic analysis is limited. Most studies, however, have been willing to trade off the intertemporal precision of dynamic analysis to allow a more extensive focus on the empirical characteristics of the problem under study. For the most part, a static or comparative static framework is utilized in the following discussion.

The core of the firm growth process is acquiring the control of additional resources that generate returns in excess of their costs and, thereby, add to the value of the firm. In turn, reinvested earnings also add to wealth and increase future income-generating capacity. The relationship between financial structure and firm performance can be expressed in a simple conceptual model, developed first under conditions of certainty and timelessness [Barry (1994)]. In this linear profitability model, a farm's rate of return on equity capital is a weighted average of the difference between the return on assets and the cost of debt, where the weights are the ratios of assets to equity and debt to equity, respectively, and the profit measure is net of withdrawals for taxation and family consumption [Barry et al. (1995)].

The model clearly shows some of the key alternatives for influencing the rate of return on equity capital. That is, the net return on equity will increase as the rate of return on assets is higher, and the rates of interest, taxation, and consumption are lower. Those effects grow stronger as financial leverage increases. That is, an increase in the rate of return on assets by one unit will increase the rate of return on equity by the product of the net rate of savings times the asset-to-equity ratio. Similarly, the effect on the rate of return to equity of a change in the cost of debt is to decrease the rate of return on equity by the product of the net rate of savings times the debt-to-equity ratio. Finally, the effect of a change in leverage on profitability, with the return on assets and the cost of debt held constant, is to increase the rate of return on equity by the product of the net rate of savings times the difference between the rate of return on assets and the cost of debt.

6.2. Empirical modeling

The firm growth concepts cited above have been operationalized in a large number of deterministic firm-level models employed over the years to study the effects of alternative financial strategies and constraints on capital accumulation and growth in income-generating capacity for agricultural firms [Barry (1977)]. These micro-level, intertemporal models of farm firms generally utilize either optimization [Ellinger et al. (1983); Featherstone et al. (1988)] or simulation as the conceptual framework.

Simulation [Mapp and Helmers (1984)] offers considerable flexibility for expressing relationships among variables, handling unique characteristics of decision situations, and for specifying performance measures (e.g., financial ratios) that are widely used in financial analysis. Generally, the decision process in simulation is formulated by the model builder and will vary from model to model. An objective function does not inherently guide the decision process as it does in mathematical programming.

In contrast, the optimization approach involving mathematical (i.e., linear, quadratic, etc.) programming offers the opportunity to observe financial performance, investment patterns, financing activities, and consumption effects that arise from the firm's efforts to push against its resource limits and operating requirements in order to maximize the stipulated objectives. Constrained optimization offers a clear framework in which to present and describe important relationships among variables, resource limits, inter-period transfers, and their data implications. Shortcomings of mathematical programming include the linearity conditions, inability to handle financial ratios, validity of the specified objectives, and reduced flexibility in model specifications relative to simulation.

Both modeling approaches have allowed analysts to identify and evaluate the effects of alternative growth strategies and to better understand how such key attributes as management ability, risk, resource costs, financial position, and reinvestment rates affect the firm growth process. Some models have emphasized the financial components of firm growth, while others focus on production or market considerations. A strong attribute of firm growth models is their ability to link the financial, production, and market components of agricultural businesses, and account for important interactions among these business functions, both over time and under conditions of uncertainty.

6.3. *Objective functions*

The objective function in optimization models can represent those objects of a decision maker's goals judged relevant to the situation being analyzed. Because managers of agricultural firms may exhibit a wide range of managerial objectives, a variety of objective functions have been evaluated in deterministic growth models. One commonly used approach is to maximize the net worth of the firm at the end of the planning horizon. This formulation is analogous to a comprehensive future value, capital budgeting problem in which the effects of compounding are represented by reinvestment opportunities for each year's earnings among the various investment and production activities in following periods. Other commonly used formulations of objective functions in farm-level multi-period optimization have included (1) maximization of the firm's future net worth plus the sum of annual consumption expenditures, (2) maximization of the present value of annual consumption expenditures plus ending net worth, and (3) maximization of the present value of annual net income [Cocks and Carter (1968); Boehlje and White (1969); Irwin (1968a); Martin and Plaxico (1967); Patrick and Eisgruber (1968); and Barry (1977)].

6.4. *Time attitudes and life cycle models*

More recent studies by Phimister (1995a, 1995b), Langemeier and Patrick (1993), Lifran (1994), and Barry, Robison, and Nartea (1996) have addressed intertemporal firm-level analysis in the context of life cycle planning and performance models of farm businesses, where production and consumption are linked through the close household-farm relationships that characterize family farming in most countries. Under this approach, intertemporal analysis is expressed as the maximization of the utility of multi-period consumption, constrained by the present value of wealth (and the related consumption opportunities) and the available investment alternatives, including both productive investments and lending and borrowing in a perfect or imperfect financial market.

Time attitudes are explicitly considered by introducing a time attitude function, $w(t)$. This function weights the utility of alternative consumption levels in period t, and identifies the separate roles of the investor's time attitude and the utility of consumption (i.e., tastes) at a specific time.

The time-weighted utility function is

$$\operatorname{Max} U = \sum_{t=1}^{T} v(c_t)w(t), \tag{1}$$

where $w(t)$ is the time weight and $v(c_t)$ is the utility of consumption at time t. Under dynamic conditions where time is expressed as distance to the future, Strotz (1956) argued that the function $w(t)$ must take the form $1/(1+n)^t$, where n is a constant in order for individuals to make consistent consumption choices over time (i.e., where actual equals planned consumption). Subsequently, Barry, Robison, and Nartea (1996) generalized Strotz's analysis to allow changes in time attitudes, under a calendar date concept of time, in which the time attitude function $w(t)$ has the form

$$w(t) = \frac{1}{\prod_{t=1}^{T}[1+n(i)]}. \tag{2}$$

Expression (2) allows changes in the values of time attitudes over time while retaining equality between planned and actual consumption as time passes, as long as no new information would lead to rational changes in the timing of consumption plans. The merits of the time weighted function in (1) are the clear distinction between the time attitude and the utility of consumption at specific points in time, and the theoretical distinction between optimal investment and financing decisions under perfect financial market conditions. At the same time, however, this approach complicates empirical analysis because it requires explicit and accurate information about the investor's time-specific utility functions and about their time attitude function. The complexity is compounded when risk attitudes are considered along with time attitudes. Maximizing terminal net worth is a much easier, although less theoretically satisfying, approach for the close household-farm relationships that characterize the agricultural sectors of many countries.

Phimister (1995a, 1995b) used the life cycle model to address the important policy question of whether the level and form of borrowing constraints influence the ability of farm households to consume, invest, and grow over time. His findings (1995a) indicate that a life cycle model without borrowing restrictions was rejected by data for Dutch dairy farms, although the statistical results for selected financial variables representing lenders' non-price credit responses were inconclusive. Additional results by Phimister (1995b) based on a farm-level optimization model suggest that the form of the borrowing constraint may have an important effect on intertemporal performance.

Phimister employed the time-weighted utility function in his analysis, although a constant time attitude was implied. In reference to Phimister's approach, Barry, Robison, and Nartea (1996) observed that changes over time in farmers' behavioral attributes could affect consumption and financing decisions. In particular, plausible changes in time attitudes (and risk attitudes) could lead to an "internal" constraint on borrowing that yields effects resembling those of lender-induced external borrowing constraints. Allowing the model to accommodate intertemporal changes in time attitudes would address this possibility.

6.5. Dynamic analysis

Most of the deterministic firm growth analyses have represented static situations, without explicitly accounting for the passage of time. The static models can accommodate considerable empirical detail, but they do not reflect potentially important dynamic relationships among major variables (e.g., prices of land and other state variables). Thus, static models may overstate or understate the true profit and growth potential for the business situations being modeled. The degree of difference could be sizeable relative to a comparably specified dynamic analysis.

Schnitkey, Taylor, and Barry (1989) examined farmland investment returns using dynamic programming. Consideration was given to optimal purchase and sale decisions for farmland under dynamic linkages between farmland returns and farmland prices, and the effects of these dynamic factors on a farm's financial structure. Comparisons between the decisions obtained from the dynamic programming model and a static capital budgeting model (i.e., net present value) indicated a clear tendency for over-responsive transactions by the static model, resulting in a larger range of investment/disinvestment decisions relative to the dynamic model results.

A similar approach to stochastic dynamic programming was employed by Novak and Schnitkey (1994) who explored how bankruptcy risks may influence farm financial performance. The key insight, enabled by the dynamic properties of their analysis, was that explicit consideration of bankruptcy risks tended to moderate farm investment behavior especially when financial conditions are less favorable. The related reductions in probabilities of bankruptcy and increases in expected terminal wealth were not surprising, but the dynamic specifications yielded the more plausible results.

Dynamic analysis appears especially appropriate in investment situations where lengthy time periods are involved and where the absence of extensive empirical detail is not a major concern. In the latter cases, the static approaches to intertemporal analysis may prove more effective to use, perhaps in combination with key elements of the dynamic models.

6.6. Life cycle and intergenerational effects

The close household-business relationship of most agricultural production units results in a strong relationship between the life cycle of the business and the life cycle of the manager. Financial performance, efficiency attainment, and other business characteristics may significantly reflect whether a firm is becoming established, growing, consolidating, or engaged in transferring its resources to new owners [Barry et al. (1995)]. In many cases, the establishment and transfer stages of agricultural firms' life cycles are tied to each other through family relationships [Guinnane (1992); Rosenzweig and Wolpin (1985)]. Optimal timing of a farm's transfer from parent to child then becomes an important issue [Kimhi (1994)].

Estate management is a long-term process that encompasses all of the stages of the life cycle [Boehlje and Eisgruber (1972)]. Included are all of the activities that go into building an estate, generating retirement income, planning an equitable distribution of property among heirs, and minimizing the cost of transferring assets. When substantial holdings of real estate are included in farm estates, the effects of a country's estate and inheritance taxes, liquidation expenses, and other transfer costs may be high. Farm estates generally have low liquidity and limited capacity for generating easily the funds needed to pay such costs, without selling the farm. Tax concessions for qualifying farm estates often occur. In addition, various estate planning strategies have been studied and utilized in order to facilitate the estate transfer process. Such strategies include the form of property ownership, and the use of wills and gifts [Boehlje and Eisgruber (1972)], life insurance [Tauer (1985)], reverse mortgages [Gibson and Barry (1994)], trusts, and others [Harl (1992); Looney and Uchtmann (1994); Thomas and Boehlje (1983)].

7. Portfolio theory and financial analysis

Risk considerations have long played important roles in agricultural finance. Included among the questions addressed are: How does a farm's financial structure influence its overall risk position? How are business and financial risks related to one another? How risky are agricultural investments compared to non-agricultural investments? Do agricultural policies increase or decrease financial risks in agriculture? Do risk attitudes matter? How effective are farmers' financial responses to risk compared to other methods of risk management? These questions have frequently been addressed using portfolio theory, as summarized in the following discussion.

7.1. Portfolio model

Portfolio theory based on mean-variance analysis has received extensive use in agricultural finance, especially in delineating the properties of business risk and financial risk for agricultural firms [Robison and Barry (1977); Barry (1994); Barry and Robison (1987); Robison and Brake (1979)]. Recent theoretical support for the mean-variance criterion has also encouraged its use [Meyer (1987); Meyer and Rasche (1992)]. Portfolio theory includes financial activities by introducing a risk-free asset that can be combined with portfolios of risky assets.[2] Positive and negative holdings of the risk-free asset represent lending and borrowing, respectively, at the risk-free interest rate. Combining the risk-free asset with the efficient portfolios of risky assets enlarges the risk efficient set, makes it more risk efficient, and under normality, yields the stochastic separation property in which the investment decision in risky assets is independent of the financing decision involving the desired combination of the risky assets and the risk-free asset. Movement along the risk-efficient set clearly indicates the risk-return trade-off associated with different levels of financial leverage.

[2] See Barry and Robison (1987), Pinches (1992), or other financial management and investment textbooks for a standard treatment of portfolio theory.

7.2. Business and financial risks

For financial analysis, it is helpful to distinguish between the effects of business risk and financial risk on the agricultural investor's total risk. Business risk arises from the variability of returns to risky assets. It is independent of the financial structure of the portfolio. Financial risk arises from the composition and terms of the financial claims on assets. Any fixed obligation financing, as in borrowing and leasing, is considered a form of financial leveraging.

Business and financial risks in portfolio theory can be modeled in an additive or multiplicative way [Gabriel and Baker (1980); Barry (1983); Collins (1985)]. Following the multiplicative approach and maintaining the assumption of a deterministic interest rate, it can be shown [Barry (1983); Barry and Robison (1987)] that total risk (*TR*), business risk (*BR*), and financial risk (*FR*) are expressed as

$$TR = (BR)(FR) \tag{3}$$

or as

$$\frac{\sigma_e}{\bar{r}_e} = \left(\frac{\sigma_a}{\bar{r}_a}\right)\left(\frac{(\bar{r}_a)(A/E)}{(\bar{r}_a)(A/E) - (i)(D/E)}\right), \tag{4}$$

where $\bar{r}_e$ and σ_e are the expected rate of return to equity and its standard deviation, respectively, $\bar{r}_a$ and σ_a are the expected return and standard deviation of risky assets, i is the cost of debt, and A/E and D/E are the respective ratios of assets and debt-to-equity.

From (4), total risk, expressed as a coefficient of variation ($\sigma_e/\bar{r}_e$) for returns to equity, is the product of business risk and financial risk. In turn, business risk is expressed as the coefficient of variation for returns on risky assets, $\sigma_a/\bar{r}_a$. And financial risk is represented by a flow measure of financial leverage in the investor's portfolio. That is, the second term to the right of the equal sign in (4) relates the returns on risky assets in the numerator to the returns on equity in the denominator. This flow measure of leverage is analogous to a stock measure expressed by the asset-to-equity ratio. As leverage increases, so does the measure of financial risk in (4), thus magnifying total risk while *BR* remains constant.

Equation (4) can be evaluated in terms of possible adjustments in *BR*, *FR*, or both as changes occur in one or more of the model's parameters [Barry and Robison (1987)]. If, for example, the investor's risk attitude were expressed as a constant level of *TR*, then an increase in *BR* may be offset by a decrease in *FR*, or vice versa. The specific form and magnitude of the portfolio adjustments will vary with the structural and operating characteristics of farm businesses, with the risk attitude of the investor, and with the possible responses of lenders and other financial claimants.

Featherstone et al. (1988) employ a similar approach to risk balancing in exploring the relationship between farmers' leverage positions and the reductions in business risk attributable to participation in government stabilization programs for agricultural commodities. They demonstrate that farm policies could result in an increase in financial leverage that offsets the policy-induced reductions in business risks, thus increasing total risk when the opposite effect is the intended policy goal. Ahrendsen, Collender and Dixon (1994) also tested financial structure issues for dairy farms using the risk-balancing concept and could not confirm the concept's ability to explain financial structure, although matters of data quality, variable formulations, cost/size relationships, and others were cited as areas needing further study.

7.3. Risk and financial structure

Under conditions of risk, an investor's objective function is modified to directly account for sources and magnitudes of risk, and the investor's attitudes toward risk. The risk attitude may then become an important variable influencing portfolio decisions, including the investor's preferred relationship between debt and equity capital–that is, optimal financial structure. Barry, Baker, and Sanint (1981) and Barry and Robison (1987) illustrate this effect analytically by expressing the investor's objective function in terms of expected utility maximization, utilizing the mean-variance approach and deriving the optimal financial structure.

Under a deterministic interest rate condition, the Barry, Baker, and Sanint result for optimal debt (D) is

$$D = \frac{\bar{r}_a - i - 2\lambda\sigma_a^2 E}{2\lambda\sigma_a^2}, \tag{5}$$

where λ is the level of risk aversion, $\bar{r}_a$ and σ_a^2 are the expected return to and variance of risky assets, i is the cost of debt, and E is equity capital. Rearranging (5) algebraically will give the optimal debt-to-equity ratio. The optimal financial structure under risk-free borrowing, thus, depends upon the risk attitude as well as on the financial data [see Collins (1985), and Featherstone et al. (1988), for an alternative yet identical portrayal of optimal financial structure].

When the borrowing cost is stochastic (σ_i^2) and correlated (covariance σ_{ai}) with the return on risky assets, Barry, Baker, and Sanint (1981) show that optimal debt is

$$D = \frac{\bar{r}_a - \bar{i} - 2\lambda E(\sigma_a^2 - \sigma_{ai})}{2\lambda(\sigma_a^2 + \sigma_i^2 - \sigma_{ai})}. \tag{6}$$

In both (5) and (6), the optimal financial structure is inversely related to changes in the risk attitude. That is, greater levels of debt are associated with lower levels of risk aversion while other factors remain constant. [See Leatham and Baker (1988), for an empirical analysis, using discrete stochastic programming of a farmer's choice between fixed and adjustable interest rate loans under alternative risk specifications.]

Barry, Baker, and Sanint (1981) use this analytical framework to show how unanticipated variations in the cost and availability of credit combine with other financial and business risks to determine total risks. Consideration of stochastic costs and availability of credit generally lead to lower leverage by farmers, although in selected circumstances high correlations between borrowing costs and assets returns could warrant greater leverage. Their empirical evidence works against this response, however, by showing a strongly positive relationship between credit availability and level of farm income, implying a negative relationship between borrowing costs and levels of income. Moreover, a tendency for capital credit to be more volatile than operating credit suggests that the financing capacity for firm growth is more unstable than financing capacity for annual operations.

Gwinn, Barry, and Ellinger (1992) consider the optimal financial structure of cash grain farms under conditions of risk and for various levels of risk aversion by farmers, as motivated by the debt and equity relationship derived in Equations (5) and (6). They developed a multi-period risk programming model that contained a wide range of investment and financing alternatives, credit specifications, family consumption, and tax relationships. The objective function yielded a risk-return trade-off between the expected value of the farm's terminal net worth and variance-covariance measures on terminal asset and liability values and on annual gross margins of production and sale activities.

The risk programming results were validated by comparisons with performance data for farm businesses from the Illinois Farm Business Farm Management Association. The results indicated substantial differences in financial structure, farm size, and liquidity over a wide range of risk aversion levels. The risk-neutral solution had the largest farm size, the highest financial leverage, the least asset diversity, the fastest rate of financial growth, and the greatest total risk. Increases in risk aversion yielded slower growth, smaller farm sizes, lower financial leverage, larger liquidity, and greater diversity in resource control over ownership and leasing of farmland. Thus, a range of optimal financial structures for family-oriented cash grain farms is plausible to expect, based on differences in levels of risk aversion among farmers.

In studying the theories of capital structure for proprietary firms, Collins and Karp (1993, 1995) draw comparisons between the static, risk-averse expected utility approach [Barry et al. (1981); Collins (1985)] and their stochastic, risk-neutral optimal control approach. Different assumptions about risk attitudes, risk concepts (variability vs. ruin), planning horizons, functional forms, and other decision attributes, together with data deficiencies, hamper the comparisons. The ability to handle multi-period horizons is a strength of the dynamic approach, while accounting for possible changes over time in risk attitudes is a strength of the other. The insights offered by these comparisons are interesting, although the principal contributions to date likely involve identifying the range of variables influencing capital structure, rather than the validity of any particular modeling approach.

8. Aggregate investment analysis

In contrast to the micro-level orientation of much of the financial management work of the past, a substantial literature has addressed aggregate or sector-level financial analysis. Answers have been sought to questions such as: What determines farmers' investment behavior? Are farm investments reversible? How are the investment and capital structure of agriculture related to each other? Do financing terms, credit policies, and taxation affect the aggregate structure of the farm sector? Answers to these questions generally involve micro-foundations, although the possible relationships may be tested econometrically with the use of aggregate data.

8.1. Investment analysis concepts

Consider, first, the determination of farmers' investment behavior. A micro-foundation to this question might express a farmer's investment decision in terms of the net present value model:

$$NPV = -V_0 + \sum_{n=1}^{N} \frac{R_0(1-t)(1+g_p)^n}{(1+i)^n} + \frac{V_N - (V_N - V_0)(t)}{(1+i)^N}, \tag{7}$$

where

$$i = (i_d)(1-t)(D/A) + (i_e)(E/A) \tag{8}$$

and

$$V_N = V_0(1+g_v)^N. \tag{9}$$

Variable V_0 is the asset's initial investment requirement; V_N is the asset's terminal value, reflecting growth or decline at periodic rate g_V; t is the income tax rate; R_0 is the base level of net cash flow per period; g_v is a growth rate (positive, negative or zero) for net cash flows; and i is the weighted after-tax cost of capital, where i_d and i_e are the costs of debt and equity, respectively, and D/A and E/A are the respective ratios of debt and equity to assets.

Investment profitability, thus, depends on the magnitude of discounted returns, including the after-tax terminal value of the assets, compared to the asset's initial investment requirements, using the weighted average cost of financial capital as the discount rate. A positive (negative) net present value signifies profitability (unprofitability) relative to the cost of financial capital. The internal rate of return (IRR), an alternative investment criterion, is the discount rate that yields a net present value of zero [Barry et al. (1995)]. Profitability, then, is based on a comparison of the IRR to the weighted average cost of financial capital.

Comparative statics indicate that investment profitability is inversely related to the initial asset price (investment requirement) and to the cost of capital, and positively related to the level of net cash flows and the growth rates of cash flows and the terminal value. Changes in tax rates have an ambiguous relationship to investment profitability, depending on the nature of the tax (e.g., ordinary income vs. capital gains) and how taxation jointly affects the asset returns and the cost of capital [Robison and Barry (1996)].

The net present value concept is extended when, as is frequently the case, investments are irreversible and/or postponable [Pindyck (1991); Ross (1995)]. Irreversibility occurs when investments result in sunk costs for industry or firm-specific assets or for situations when the lemons problem, government regulations, and institutional arrangements hamper asset redeployability. Postponability gives the prospective investor the opportunity to wait for new information about prices, costs, technology, legal issues, and other market conditions before he or she commits resources to the investment.

The benefits of new information from waiting could enhance investment profitability, but the waiting process incurs costs as well. Included in the costs are foregone returns from making the investment earlier, possible increases in investment expenditures, and adverse profit effects resulting from comparable investments by competitors.

The valuation issues associated with postponing an investment resemble an option valuation problem. In this case, the value added to a net present value model by postponing the investment decision is equal to the value of an options contract for the right to purchase the investment in the future. When a firm makes an irreversible investment, it exercises or nullifies the option to make this investment at a later time. The lost option value is a potentially important opportunity cost that is part of the investment cost.

The present value of the investment's net cash flows must now exceed the initial expenditures by an amount equal to the value of keeping the investment option open [Pindyck (1991)]. In this sense, a project may not only compete with other possible projects, but it competes with itself delayed in time [Ross (1995)]. Option values, thus, represent the maximum price that could be paid to guarantee the right to purchase the investment at its investment cost (exercise price) at a designated time in the future.

Most of the aggregate investment analysis in agricultural finance is consistent with the general specification of the net present value model. Numerous studies have sought to measure and test the relative importance of the respective variables, and the speed with which capital adjustments occur. Similarly, asset replacement models, which represent a special case of investment analysis, have sought to determine optimal holding periods for depreciable assets, based on the key variables affecting profitability [Perrin (1972); Robison and Barry (1996)]. More recent studies have employed the information and incentive arguments of modern finance theory to focus on the linkage between investment and financing [Hubbard (1998)].

8.2. Early investment and tax policy studies

Studies investigating the aggregate demand for one or more farm assets begin to appear in the late 1950s. Cromarty (1959), Griliches (1960), Heady and Tweeten (1963), Fox

(1966), and Rayner and Cowling (1968) all utilized a partial stock-adjustment approach incorporating lag terms which permitted adjustment over time to an optimal stock level. Positive but small coefficients for the lag term were consistently obtained.

Similar behavioral assumptions pertaining to investments were made in these studies: Farmers sought to maximize profits and, thus, achieve a desired level of investment and related service flows. A commonly used variable was the ratio of machinery prices to commodity prices, which was a consistently important explanation of investment behavior. Griliches (1960) was the only one of the above studies to conclude that interest rates significantly explained investment, perhaps reflecting the relatively low and stable interest rates during these times. Rayner and Cowling (1968) found that the farm wage rate relative to tractor prices was a significant explanatory variable for machinery investments in Great Britain. They attributed this finding to structure of the labor force, farm size, and agricultural policy in Great Britain relative to the United States. These studies were completed during the same period of time, and each employed ordinary least squares regression. They achieved similar results, which remained unchallenged for a considerable period of time.

Early work in this area also considered how various forms of market imperfections influenced investment and disinvestment in the agricultural sector. G.L. Johnson (1956), Edwards (1959), G.L. Johnson and Quance (1972), and D.G. Johnson (1950) addressed the concept of asset fixity in agriculture based on the relationship between an asset's marginal productive value to a firm and the spread between the asset's acquisition cost and its salvage value in the marketplace. The wider the spreads between acquisition cost and salvage value, the greater the fixity of assets and the more sluggish are resource adjustments in response to changing market signals. These concepts and the related empirical studies helped to explain the seemingly slow adjustments of resources in agriculture and the tendency for an apparent overinvestment in the sector.

8.3. Investment, capital structure, and taxation

In 1981, Penson, Romain, and Hughes developed an econometric approach to investment analysis that reflected the joint effects of capital structure, taxation, and capacity depreciation patterns on the implicit rental price of durable capital. The capital structure formulation directly reflected the combined use of debt and equity capital employed by farmers when they finance purchases of durable inputs. Their estimating equation related net investment to variables depicting the ratio of farm output to the implicit rental price of capital, the desired capital stock, and lagged net investment.

The findings by Penson, Romain, and Hughes (1981) indicate statistical significance and correct signs for each of the major variables, thus providing good explanations for annual net investment in tractors. In particular, their results are supportive of the engineering-data capacity depreciation patterns for delineating net investment from gross investment and replacement expenditures [see Ball and Witzke (1993), for a recent application]. The conventional geometric decay pattern did the poorest job among those tested of explaining the real annual net investment in farm tractors. The elasticities, computed at the mean, between net investment and the output to capital cost ratio were 2.64 for the engineering data pattern, 2.53 for a one hoss shay pattern, 4.33 for straight line, and 6.59 for geometric decay, suggesting a substantial over-estimate of farmers' investment responses to changes in prices, interest rates, taxes, and other relevant variables under the geometric decay pattern.

Dynamic specifications of investment behavior account for the effects of asset adjustment costs on movements from one capital stock equilibrium to another. The relative fixity of inputs causes such adjustments to take time. The accelerator concept becomes important to the process by which net investment closes the gap between desired and actual levels of capital stock. Under dynamic conditions, the agricultural firm's long-run dynamic problem is to choose time paths for variable inputs and quasi fixed inputs that maximize the present value of net earnings. Especially important to aggregate investment analysis are the difference equations and functional forms for the profit and cost of adjustment functions.

Using the dynamic investment framework, LeBlanc and Hrubovcak and colleagues undertook a series of studies beginning in the 1980s that included examining the effects of interest rates and tax policies on investment in agriculture. Their 1985 study focused on the relationship between agricultural machinery investments, interest rates, and several other important variables. They report three general conclusions from their analysis. First, changes in interest rates had a minor direct effect on the optimal level of agricultural machinery. The response of the optimal capital stock to changes in the interest rate is highly inelastic, less than −0.01 in 1978. Second, interest rates do affect investment by altering the rate of adjustment to new levels of optimal capital stock–higher rates delay investments, and vice versa. Third, the ratio of machinery price to output price is a more important determinant of the adjustment rate than is the real interest rate.

Subsequent studies focused on the investment implications of tax policy using a broader concept of rental rates of capital than interest rates alone. The investment equations in the 1986 study by LeBlanc and Hrubovcak are functions of variable input and output prices, technological change, rental rates of capital, and lagged capital stock. The rental rate is a function of asset price, capacity depreciation, tax variables, the discount rate (weighted average costs of debt and equity capital), and the rate of inflation. Tax policies affect investment by altering the implicit rental price of capital.

Results for their 1986 base model indicate significant inverse relationships between investment and the rental price of capital, dynamically stable adjustment rates, and plausible values for other key variables affecting investments. Specific tax policy effects focused on the impacts of investment tax credit, interest deductibility, and other tax changes during the 1954–1978 period. The results of the tax analysis indicated that nearly 20 percent of net investment in agricultural equipment during the 1956–1978 period was attributed to tax policy, with the investment tax credit and liberalized depreciation allowance having the largest and smallest effects, respectively.

An extension of the tax policy effects by LeBlanc et al. (1992) utilized a similar conceptual framework together with a stochastic coefficient econometric methodology to estimate how the Tax Reform Act of 1986 altered the cost of capital and net investment in agriculture. Their base model results indicated that land price, rental rates of capital, energy price, and lagged capital stock were the most important determinants of net investment, and wages and chemical prices were the least important. The provisions of the 1986 Act were estimated to substantially increase (12.7 percent overall) rental prices of capital, and thus decrease the optimal long-run capital stock in the agricultural sector by an estimated $4 billion or nearly a 25 percent reduction from prior law. These results provide clear evidence of the importance of tax policy on the capital position of agriculture.

Weersink and Tauer (1989) contrast the dynamic optimization approach to estimation of investment functions with a traditional approach in which ad hoc adjustments (e.g., finite distributed lags) are imposed on the time structure of investment. Their traditional model, applied to dairy farms, included variables for capacity utilization, cattle inventories, costs of capital, farm size, external debt, farm income, time, and operator age. All of the variables except size and age were statistically significant. Both the dynamic and traditional models tracked the actual expenditures of dairy farmers reasonably well, although the traditional model was judged to perform better. Both models suggested a significant delay between changes in the determinants of desired capital stock and the actual investment expenditure.

An alternative data-generating approach to machinery investment analysis by Gustafson, Barry, and Sonka (1989) utilized experimental and simulation procedures with a panel of cash grain farmers to test the effectiveness of the approach and to observe the effects on investment expenditures of selected structural, performance, and environmental conditions. While limited in generality due to the small size of the farmer panel, the results show investment levels statistically related to the tenure and leverage position of farm operator, the economic conditions they face, and the age of existing machinery. Alternative public policies of lower commodity price supports, tax reforms, and reductions in interest rates influence the timing of purchases, but do not alter total investment levels.

Elhorst (1993) makes a special effort in his traditional approach to farm investment analysis to utilize farm-level data in the Netherlands and to tailor the econometric approach to differences in investment frequencies among farmers. His "infrequency purchase model" yielded a substantial improvement in estimation results, but still left unexplained substantial portions of the farmers' investments. Elhorst speculates that a greater emphasis on the linkages between investment and financing might be promising to consider.

8.4. Investment and financing relationships

Asymmetric information concepts have also played an important, recent role in analyzing investment behavior in the agricultural sector. Under this approach, credit rationing triggered by asymmetric information, as demonstrated by Stiglitz and Weiss (1981), may serve as a constraint on business investment. Testing whether financial variables become significant in empirically estimated investment equations, when investment is known to be profitable or unprofitable, provides evidence of financial constraints attributable to asymmetric information [Fazzari et al. (1988); Hubbard (1998)].

Jensen, Lawson, and Langemeier (1993) build upon the earlier study of Weersink and Tauer (1989) by using farm-level data to estimate a composite model of agricultural investment that includes variables suggested by the accelerator, neo-classical, and asymmetric information models. Their internal finance variables included real net farm income, interest commitments, real total depreciation, and real off-farm income. Their results indicate that the addition of the internal cash flow variables significantly improved the explanatory power of their agricultural investment model, and that investment was more responsive to the internal cash flow variables than to either the accelerator or neo-classical variables.

Hubbard and Kashyap (1992) also applied asymmetric information concepts to the agricultural sector in exploring the relationship between investment in agricultural equipment and internal finance represented by farmers' net worth positions. A key factor for many models, in which asymmetric information is important, is that the cost of external finance varies inversely with the level of "inside finance". Thus, lenders may become more willing to lend when farmers' net worth improves, and adverse incentive problems should be less important at sufficiently high levels of net worth. The empirical results obtained by Hubbard and Kashyap clearly indicate that the standard perfect-capital-market approach fails to adequately explain investment, due to systematic correlations between the unexplained component of investment and movements in farmers' net worth positions. The correlation is strongest during periods of low net worth. Extending the model to accommodate net worth improves the explanation of farmers' investments, although the effects are significantly more important during deflationary periods than during boom times.

Several studies have considered whether credit rationing affects production levels in the agricultural sector, under asymmetric information concepts. Calomiris, Hubbard, and Stock (1986) evaluated the relationships between state-level farm output and farmers' collateral positions, debt-servicing burdens, and bank failures. They find strong evidence that disruptions in agricultural credit markets can have real effects on farm output, especially through deteriorating collateral positions and institutional failures.

Belongia and Gilbert (1990) use a model of credit rationing to determine whether farmers receive more of their credit from federal agencies when the aggregate supply of credit declines, and whether credit availability is strongly related to the level of farm output. Their empirical results for the 1947–1986 period are consistent with non-price credit rationing from private sector lenders, by showing a higher proportion of government-sponsored lending to agriculture as the growth rate of total agricultural credit declines. The government-sponsored credit, thus, fills the gap when private sector rationing increases. However, further empirical work suggested that government-sponsored non-real-estate credit is not significantly related to agricultural output. The authors suggest that these results fail to indicate an important role of subsidized credit in facilitating agricultural production, and question whether farmers divert such credit to higher- valued opportunities. Belongia and Gilbert (1990) do not, however, consider the credit effects on farmers' financial performance.

In a developing economy setting, Feder et al. (1990) considered the extent to which production credit programs for farm households in China stimulate production or are used for other purposes. Their results indicate that a significant proportion of the short-term credit provided by rural credit cooperatives as "production credit" may actually be utilized for consumption and investment, especially in light of the absence of informal lenders and of medium- and long-term credit for the households in their study. The likely output effect, thus, will be smaller than anticipated. These results clearly highlight the fungibility of credit problem in institutional development lending and its adverse implications for building borrower and lender discipline in credit programs.

8.5. *Investment, sunk costs, and risk*

Sunk costs, irreversibilities, and risk may interact to influence the likelihood of investment and disinvestment, the mobility of resources, and potential over- or under-investment in agriculture. Following G. Johnson's early work, Tweeten and Quance (1969), Houck (1977), and Traill, Colman, and Young (1978) tested for irreversible supply and demand equations, generally based on separate equations for periods of increasing and decreasing investments. More recently, Vasavada and Chambers (1986) used an asset adjustment cost model to determine that agricultural investments have high degrees of irreversibility. Nelson, Braden, and Roh (1989) also tested for asymmetries in investment and disinvestment periods, finding some evidence that periods of disinvestment are more persistent than periods of investment.

The dynamic properties of sunk costs, irreversibilities, and asset fixity have also received increasing attention in economics research. Part of the focus has been on understanding how these factors influence the role of competitive markets in achieving an efficient allocation of resources [Chavas (1994); Hsu and Chang (1990)]. Also important are the influences on technology adoption, productivity growth, and the structure of agriculture [e.g., Saha et al. (1994); Purvis et al. (1995)].

The adverse effects of sunk costs have important implications for public policies, institutional innovations, and firm-level decision making. Barham and Chavas (forthcoming), for example, illustrate how sunk costs and risk may lead to such response strategies as investments in human capital, public infrastructure, information dissemination, insurance, and other risk management strategies. The intended effects of such actions are to improve resource mobilization, encourage investments and disinvestments, stimulate trade, enhance productivity, and add to welfare outcomes.

9. Finance, economic growth, and the structure of agricultnre

Theory and empirical evidence indicate that the sophistication of financial systems and an economy's growth and development are strongly related to one another [Levine (1997); Gertler and Rose (1996)]. Levine argues that the development of financial markets and institutions is a critical and inextricable part of the growth process. In the absence of financial markets, the effects of high information and transaction costs (including the costs of acquiring information, enforcing contracts, and exchanging goods and financial claims) would tend to immobilize savings, stifle risk-taking, constrain investment decisions, hamper technological innovations, and dampen rates of economic growth. High-return, technologically intensive projects generally require long-run commitments of capital, but savers are reluctant to concentrate their funds for lengthy periods in risky investments where good information is lacking. Financial markets, with their liquidity, diversity, and information-providing roles, enable the mobilization and channeling of these savings to their highest payoff uses.

The financial intermediary, thus, provides the service of identifying and monitoring the most promising firms, managers, and prospective investments. The result is a heightened pace of economic growth and development. Levine (1997) cites "... a growing body of empirical analyses, including firm-level studies, individual country studies, and broad cross-country comparisons that demonstrate a positive link between the functioning of the financial system and long-run economic growth" (p. 720). A linkage, however, does not necessarily imply causation.

Is credit a causal factor or a facilitating factor in the structural change and economic growth of agricultural sectors? Agricultural finance clearly is linked to changes in farm structure [Gustafson and Barry (1993); Lins and Barry (1980)]. Past practices in farm lending, which have included more liberal lending in favorable times and more conservative lending in less favorable times, have strongly influenced the size, profitability, and well-being of family farms. Gains in agricultural productivity, the mechanization and modernization of farming operations, more orderly marketing of farm commodities, and liquidity management have benefited considerably from ready availability of agricultural credit.

These benefits of credit in particular, and financial services more generally, are considered to be accommodating, rather than causal, in that the financial capital responds to underlying economic incentives. Availability of credit may often be a necessary condition for capital investments. It is not, however, a sufficient condition. Profit incentives are needed as well. Thus, readily available credit likely has facilitated, but not necessarily caused, many of the changes occurring in agriculture – fewer and larger farms, greater specialization, adoption of new technology, greater capital intensity, and stronger market coordination. Moreover, as the prospects for economic development increase, financial market development becomes more essential. In turn, the enhanced capabilities of financial markets also become predictors of future rates of growth, capital accumulation, and technological change. In this perspective, as observed by Levine, financial markets are endogenous to economic growth and development. They evolve over time, and are essential to economic growth.

Sometimes, however, swings in credit conditions can magnify changes in the financial well-being of agricultural producers. In the U.S., for example, the boom times of the late 1970s were fueled by readily available, low-cost credit, only to be met by the credit management and loan repayment problems of the early 1980s, and the significant stresses faced by many financial institutions, especially those that specialized in agricultural lending.

Credit policies may also have conflicting effects. The historic institutional developments in agricultural finance (i.e., creation of government-sponsored agricultural lenders, direct government loan programs, laws targeted to agricultural loans) have assisted many countries to maintain a pluralistic, smaller-scale, family-oriented, largely non-corporate farming structure. Concurrently, however, credit policies intended to sustain this pluralistic structure of agriculture can also slow resource adjustment, build excess production capacity, create excessive debt, and counter the effects of new technologies and market focuses in agriculture [Lee and Gabriel (1980)]. Emergency or disaster-related public credit can have the effect of substituting for income, thus perpetuating adverse incentives by borrowers. Weak monitoring and enforcement problems in public credit can create moral hazards by both agricultural borrowers and their lenders in seeking to continue use of the public safety net. These actions go well beyond the intended roles of credit markets and undermine their integrity and soundness (see the discussion about public credit in Section 10 of this chapter).

10. Suppliers of financial capital

10.1. Introduction

Suppliers of financial capital include savers with investable funds and financial intermediaries who specialize in the transmission of funds from savers through financial markets to those with need for external sources of funds. The financial institution performs the intermediation process more efficiently and safely than would individual savers and investors, while still earning an acceptable rate of return on the institution's equity capital. Efficient collection and processing of information about the creditworthiness of borrowers, loan performance, and financial market conditions are major services provided by financial intermediaries. Diversity in their holdings of assets and liabilities reduces credit risk, interest rate risk, and liquidity risk, and helps to reconcile liquidity differences between savers and investors. Thus, economic theories of the firm and of markets, along with the informational concepts of modern finance theory, apply to financial intermediaries, similar to their applications to other types of organizations. In the cases of market gaps or major market imperfections, public loan programs or publicly sponsored institutions may emerge as important participants in the intermediation process. This section of the chapter addresses the application of these financial market concepts to agricultural finance.

10.2. Financing the agricultural sector

The historically strong reliance by farmers on debt capital to operate their farms, capitalize their asset bases, and respond to liquidity pressures requires a responsive, modern financial market. Ideally, agricultural borrowers would prefer a financial market that offers competitive interest rates; ready, low-cost access to credit; reliable availability of financial capital through all phases of the business cycle; versatile uses of funds; credit terms tailored to the characteristics of the activities being financed; and effective access to financially related products and services. The financing of agriculture, however, presents special challenges to the financial markets.

As indicated in Section 2, farms typically are capital-intensive, geographically dispersed, limited in scale and scope, and characterized by lengthy production periods. They are subject to significant business risks and to cyclical swings in economic conditions, often resulting in liquidity problems at specialized lending institutions serving agriculture. Imbalances in needs for and availability of local market funds require reliable access to non-local sources of funds. However, non-local funding is challenged because relationships between agricultural borrowers and their lenders typically are characterized by strong reliance on reputations, personal familiarity, and social closeness. Skills in farmers' financial management and the quality of their financial information also are more limited in agricultural lending. In light of these characteristics, the availability of competitively priced, dependable credit for agricultural borrowers has long been an important policy issue, and public credit programs often play significant roles in enhancing market development and ensuring credit availability.

10.3. Types of agricultural lenders

Most countries have several types of financial intermediaries and other entities that provide loans and financial services to the agricultural sector. Included are [Barry et al. (1995)]:

- A commercial banking system that relies heavily on deposits as a source of loanable funds.
- Specialized agricultural lending institutions, with corporate or cooperative organizations, that depend primarily on financial market sources of funds.
- Government programs at the federal, provincial, and/or state levels that rely on financial markets or taxation for sources of funds.
- Credit unions composed of members with a common bond.
- Farm-related trade or agribusiness firms.
- Intermediaries that perform important fiduciary or trust functions, such as insurance firms, pension funds, and trust companies.
- Individuals such as family members, sellers of farmland, neighbors individually or in groups, and money lenders in the case of developing countries.
- Originators who channel loans into well-diversified loan pools funded by asset-backed securities.

These sources of financial capital differ in their organizational structures, operational characteristics, degrees of specialization, sources of funds, relative importance, and relationship to the public sector. They each participate, with varying degrees, in providing the basic services of financial intermediation: (1) origination of loans, (2) funding of loans, (3) risk bearing, (4) provision of liquidity, and (5) monitoring, payment collection, and other servicing of loans. Each of these services generates a source of profits to the intermediary and, as financial markets develop and become more competitive, different financial institutions may tend to specialize in the provision of one or more of these services.

10.4. Regulation of financial markets

Public involvement in financial markets is inherently extensive and changes in form as the financial markets of countries experience greater maturity and development. Even the most sophisticated financial markets experience strong public regulation. The need for such regulation is attributed to several factors. Included are the intangible nature of financial assets (promises to repay for debt and ownership titles for equity); the significant importance of information generation, transmission, and processing in the intermediation process; aggregate monetary stability; and safety and soundness for investors in securities issued by government-sponsored institutions. As a result, considerable confidence, trust, and stability are required among market participants in order for financial markets to develop and function effectively. The resulting regulatory environment is intended to safeguard savers and investors, foster competition, respond to market imperfections, facilitate effective monetary policy, and achieve other specific social goals.

Governmental regulation of financial markets may take many forms:

- Restraints on geographic expansion of financial institutions, as with branching and holding company regulations.
- Mandatory specialization in some services (e.g., farm, student, or housing loans; transaction accounts).
- Portfolio diversification through reserve and capital requirements, legal lending limits, and asset allocations.
- Public reporting and examination requirements.
- Special borrowing privileges.
- Fair trade practices.
- Public programs for credit and insurance.
- Laws affecting the design, security, negotiability, and trade of financial instruments.

The extent of regulation varies substantially among types of financial institutions and credit sources. Examples include complete public sponsorship in the case of government loan programs; chartering of government-sponsored, yet privately owned agricultural credit institutions; and comprehensive regulatory oversight of depository institutions and insurance protection for depositors. In contrast, agricultural lending by agribusinesses and trade firms, individuals, and money lenders is largely unregulated, except for the discipline provided by the marketplace. This regulatory mosaic contributes to the effective operation of heterogeneous financial markets, but can also create periodic imbalances in credit markets that raise concerns by market participants about "leveling the regulatory playing field".

10.5. Evolution of financial markets

Financial markets have experienced lengthy, accelerating transition. Innovations in information processing and electronic communications technologies have allowed the breaking-down of geographic barriers, and have led to substantial integration between national and international financial markets. Globalization is common in the trading of many types of financial assets, in the financing of international trade, and in sourcing various types of funds. Deregulation of interest rates and of the range of products and services financial institutions may offer has led to the emergence of broadly based, highly competitive financial services companies, offering a combination of transactions, credit, savings, investments, insurance, counseling, and related services to their customers. At the same time, specialized service providers can still fill well-defined market niches, often through partnering arrangements with other financial services companies.

Securitization is becoming widespread in the financing of residential housing, automobiles, accounts receivable, commercial properties, and other types of assets. In the U.S., the Federal Agricultural Mortgage Corporation (Farmer Mac) provides securitization services for farm real estate loans. Packaging loans into pools, adding credit enhancements, and selling asset-backed securities to investors have proven effective in the reallocation, and management, of credit risks and interest rate risks from financial institutions to financial market investors. The creation and trading of derivative securities in financial risk management is in the vanguard of financial innovations, although subject to strong demands for trader expertise in order for derivative markets to function safely and effectively.

Financial reforms have played an important role in the evolution of financial markets. These reforms have been widespread in recent decades, motivated in part by ideological factors, technological developments, and changing financial market conditions. The reform process usually involves a set of actions taken to ease portfolio controls, target credit to selected borrowers, and limit government intervention in the determination of interest rates [Caprio et al. (1996)]. Relying more on market forces has been viewed as a promising way to enhance the intermediation process and improve the allocation of resources. The evidence [Caprio et al. (1996); Herring and Litan (1995)] suggests that the reform process can be successfully managed, although the timing and degree of success are strongly influenced by a country's financial condition, the sequence of reforms, and the linkages between the country's financial and non-financial sectors.

Reforms have opened domestic financial markets to greater international influences. Integration among markets is especially strong in the wholesaling of funds and financial services [Herring and Litan (1995)]. Integration is less complete, however, in retail markets, including agricultural finance, in which smaller firms and individuals primarily patronize financial service providers in their own locality, region, or country. Interacting with local personnel remains a strong customer preference in agricultural finance, although new telecommunications and transport technologies are making inroads on these preferences.

10.6. Implications for agricultural lending

This evolutionary financial market environment has not excluded the financing of agriculture. Large-scale commercial lenders (including money center and regional banks, and large specialized agricultural lending systems) are meeting the credit and financial services needs of larger, industrialized agricultural production units that have varying types of contractual arrangements with food companies and other agribusiness firms. These industrialized units neither need nor use subsidized credit programs, except perhaps when younger, inexperienced agricultural families become contract growers in integrated poultry, livestock, or dairy operations.

Commercial-scale family farms also tend to be financed by commercial banks and specialized agricultural lenders, perhaps with government sponsorship and/or financing assistance. These credit sources have either acquired, or have access to, the modern financial market technology, although their approach to agricultural lending is gravitating away from the information-intensive, traditional-relationship style toward a price-driven style typical of commercial lending in other sectors. In response, agricultural borrowers must upgrade their skills in financial and risk management, accounting, and financial reporting, consistent with those of other commercial borrowers, in order to compete effectively for loan funds.

Small, part-time, or limited-resource farms remain large in numbers, but relatively small in terms of economic contributions. In developed countries, small farms often rely heavily on non-farm employment as sources of income. In developing countries, small farms often operate at subsistence levels. The financing needs of small farms in developed countries are increasingly treated as consumer-type loans by commercial lenders, with credit-scoring and higher interest rates used to offset the high servicing costs of small loans. Small farmers rely heavily on targeted, public credit programs with concessionary lending terms to meet their financing needs. Individuals, money lenders, trade firms, and other local sources are other credit sources for small farms. For this type of borrower, public credit serves the multiple purposes of facilitating resource adjustments, providing liquidity in times of adversity, and assisting in meeting the creditworthiness requirements of commercial lenders.

10.7. Agricultural finance markets and institutions

Professional studies in agricultural finance have coincided closely with the transition in financial markets cited above. Included are aggregate projections of capital and credit needs in agriculture [Hughes and Penson (1981)], financial market analyses, policy studies, and structural change of financial institutions. Impacts of regulatory changes on the availability, cost, and other financing terms for agricultural borrowers have received considerable attention [e.g., Barry (1981)]. The results of optimization models, simulation, and econometric analyses of financial institutions have highlighted the combined effects of interest rate deregulation and financial stress of agricultural borrowers on the performance and management strategies of different types of financial institutions [Barry (1981); Barnard and Barry (1985); Barry and Lee (1983); Pederson (1992); Robison and Barry (1977)].

During the stress times of the 1980s in the U.S., some institutional responses to risk (e.g., floating interest rates, larger risk premiums in loan rates) had the unintended effects of transmitting credit risk and interest rate risk to healthy agricultural borrowers, thus widening and deepening the adversities. Other strategies (broader loan diversification, expanded geographic markets, gap and duration gap management, insurance) have enhanced the risk-bearing capacities of financial institutions, and have led to more efficient management of credit, interest rate, and liquidity risks [Ellinger and Barry (1989); Barry et al. (1995, 1996)]. Differential loan pricing based on competitive types of loans, borrowers' credit risks, loan sizes, costs of funds, and degrees of financial stress is also an effective element of asset-liability management by financial institutions [Barry (1995); Barry and Calvert (1983); Schmiesing et al. (1985); Bottomley (1975); Lee and Baker (1984)]. These pricing strategies respond to the adverse selection and moral hazard problems of agricultural lending, and are often tied to the growing use of credit-scoring techniques.

Designing flexible repayment programs through variable amortization, debt reserves, graduated payments, shared appreciation loans, and other mechanisms, similar to the flexibility provided by share rent obligations in farm real estate leasing, formalizes the role of financial institutions and credit reserves in accommodating random fluctuations in the financial conditions of agricultural borrowers [Lee and Baker (1984); Rahman and Barry (1981); Khoju et al. (1993); Ellinger et al. (1983); Buffier and Metternick-Jones (1995)]. Lenders, however, have largely refrained from designing loan contracts with these elements of flexibility, preferring instead to implement flexibility when needed through loan extensions, refinancing, deferred payments, workouts, and other means of forbearance.

Impacts of geographic liberalization on the costs and availability of agricultural loans and on institutional performance have been substantially addressed. Restructuring of the Farm Credit System in the U.S., for example, has expanded risk-carrying capacities of system institutions, modestly enhanced operating efficiencies, and altered the management of intra-system agency costs [Barry and Barnard (1985); Lee and Irwin (1996); Collender (1996); Barry et al. (1993)]. Bank structure has been a significant variable in explaining differences in changing market shares [Wilson and Barkley (1988)] and relative lending capacities [Barry and Pepper (1985)] of commercial banks across states in the U.S., as evidenced by studies of bank mergers and acquisitions [Neff and Ellinger (1996)]. Affiliation with multi-bank holding companies was found to significantly reduce the ratio of agricultural loans to total loans for the rural subsidiaries of large bank-holding companies [Belongia and Gilbert (1988)]. The subsidiaries of large bank- holding companies have greater opportunities to diversify risk by lending to businesses in a variety of industries, thus reducing the supply of agricultural credit through commercial banks. An offsetting factor, when statewide branching is permitted, was observed by Laderman, Schmidt, and Zimmerman (1991), who found that rural banks hold higher non-agricultural loan portfolio shares and urban banks hold higher agricultural loan portfolio shares. These more recent studies of the local market effects of structural change in banking are consistent with the mixture of effects found by earlier studies [Board of Governors of the Federal Reserve System (1977); Barry (1995)].

Long-term farm real estate lending by depository institutions can be especially problematic to their risk positions. Reliance on relatively short term sources of funds to finance longer-term loans increases institutional vulnerability to interest rate risks and hampers the availability of fixed-rate long-term loans to agricultural borrowers [Barry and Ellinger (1997)]. The longer-term funding sources available to government-sponsored agricultural lenders, through sales of bonds in financial markets, allow reductions in their vulnerability to interest rate risk, to offset in part the relatively high concentrations of credit risk in these lenders' agricultural loan portfolios. Important policy issues remain concerning the access to longer-term sources of funds by depository institutions and other localized agricultural lenders.

10.8. Public credit policies

Agricultural credit markets are especially vulnerable to the benefits and costs of public intervention. Public credit programs are intended to either correct a market imperfection, fill a gap in the workings of credit markets, or achieve a public purpose through the re-allocation of resources or redistribution of income in the economy [Barry (1995); Bosworth et al. (1987)]. In the U.S., for example, the cooperative Farm Credit System was created beginning in 1916, primarily to fill a gap in farm real estate lending; the Federal Agricultural Mortgage Corporation was created in 1987 to improve the workings of farm real estate lending through the provision of a secondary market for these loans; and the Farm Services Agency (formerly the Farmers Home Administration) was created in the 1940s to provide direct loans to young farmers and other potentially viable farmers who could not qualify for commercial credit. Finally, commodity credit programs were developed as a part of the U.S. government's farm price support and income stabilization policies, and subsidized export credit (loan guarantee) programs [Yang and Wilson (1996)] are intended to enhance the competitive position of U.S. farm products in international markets.

Credit programs that aim to correct market imperfections need not require much, if any, subsidization; they are considered the more successful government programs in credit markets [Bosworth et al. (1987)]. In contrast, efforts to achieve public purposes do involve subsidization, with significant questions raised about the form, magnitude, length, measurability, and recipients of the subsidies. The Federal Credit Reform Act of 1980 in the U.S., for example, fundamentally changed the budgetary treatment of direct loans and loan guarantees. The Act has required explicit measurement of the costs and subsidy elements of federal credit programs. To illustrate, the estimated 1995 subsidy rates for the federal government's Farm Services Agency loans were 13.03 percent for direct loans and 2.49 percent for guaranteed loans [Barry (1995)]. Earlier estimates of subsidy rates were in the range of 7.1 percent to 10.0 percent for Farm Service Agency loans and 0.0 percent to 0.5 percent for Farm Credit System loans [Hughes and Osborne (1987)].

In agricultural development lending, the adverse effects of government intervention have been extensively analyzed [Adams (1971); Adams and Graham (1981); Buttari (1995); Adams and Fichett (1992); Adams and Von Pischke (1992); Von Pischke (1991)]. Among the effects of government intervention are limited assistance to farmers, high default rates, high public costs, non-viable commercial lenders, regressive income effects, weak mobilization of savings, and disincentives to commercial lenders who must comply with subsidy requirements. Interest rate subsidies are especially problematic, creating excess demand for loans and unintended structural consequences [Meyer (1990)]. Even then, however, removals of interventions and regulations can yield high adjustment costs and further unintended structural consequences [Anderson (1990)].

Credit subsidies also create adverse incentives for borrowers who view loans as a gift or grant, and for lenders who become lax in screening loan applicants and monitoring loan performance. Little respect is gained for the obligation to repay and for the integrity of public credit programs [LaDue (1990)]. High delinquency and default rates typically characterize concessionary credit programs in both developed and developing countries [Karmajou and Baker (1980)]. These programs are especially vulnerable to the political hazards of public credit programs, as discussed below.

Key conclusions about government intervention, summarized by Buttari (1995), are that agricultural and rural borrowers need reasonable access to financial services from viable lenders, rather than subsidized credit, and that public policy should be directed to this end. Financial sustainability for both borrowers and lenders is the plausible policy goal. Such a goal will contribute to overall economic growth, to the benefit of both borrowers and lenders. Nonetheless, subsidized credit programs remain widespread and play important roles in international lending programs.

Major questions also concern the appropriateness of credit programs relative to other mechanisms for providing the subsidy [Barry (1995)]. Credit programs have weaknesses in transmitting subsidies because the loan funds may be used for unintended purposes, the borrowers may have had access to credit from other sources, the subsidy benefits may accrue to private lenders rather than to borrowers, and favorable terms of credit may be capitalized into the value of the assets being financed [Lee and Gabriel (1980); Stam (1995); Shalit and Schmitz (1982, 1984)]. Moreover, using credit markets to transmit subsidies undermines the integrity of inherently fragile financial markets. A financial market's primary function is to facilitate financial intermediation by adjusting the liquidity and risk positions of savers and investors. Extensive government regulation contributes to market effectiveness by fostering confidence, trust, and discipline among market participants. Adding a subsidy, however, is counterproductive to market effectiveness. Thus, the larger the subsidy needed to achieve the public purpose, the less the assistance should be channeled through public credit programs.

Among the forms of public credit, the emphasis in the U.S. has clearly shifted away from direct public loans toward publicly guaranteed loans by commercial lenders. As shown above, loan guarantees provide lower subsidies than direct loans, especially since direct loans are seldom priced to cover the government's full cost of funding, administering, and risk-bearing. Pricing for risk through fees and premiums is more explicit with a loan guarantee. Loan guarantees also displace fewer financial market resources, offer greater liquidity for loan sales by institutions, and provide greater use of private lender's knowledge and experience for loan origination, servicing, and management. Coupled with guarantees, time limitations on borrowers' use of guarantee programs also help to reduce moral hazard behavior and encourage timely graduation of borrowers to commercial sources of credit [Barry (1995)].

Credit programs are also vulnerable to political incentives. From a policymaker's perspective, credit programs are a popular, politically expedient policy instrument (Barry (1994, 1995); Hughes et al. (1986)]. They are relatively easy and cost effective to administer, as long as program demands are not growing too fast. While the administrative and risk-bearing costs often are difficult to measure and obscure to taxpayers, the programs are highly visible to a politician's constituents. They can be targeted to specific groups, quickly developed for responding to ad hoc crises, and do not directly influence commodity and input markets, although the secondary effects on asset values, incomes, and risk can be significant. Moreover, credit programs give the impression of financial soundness because loan repayment with interest is intended, although seldom is loan performance totally consistent with this intention.

10.9. Financial stress in agriculture

Periodic episodes of widespread financial stress in agriculture provide insightful case studies about the implications and effectiveness of public credit interventions intended to mitigate the effects of adversity. Evidence from the Depression era of the 1930s, for example, clearly indicates the costly, longer-run effects of debt moratoria and related policies [Rucker (1990); Rucker and Alston (1987); Alston (1984)]. Faced with foreclosure moratoria, commercial lenders tend to curtail future credit availability because they fear that a recurrence of future moratoria could exacerbate repayment problems.

The 1980s in the U.S., Canada, Australia, and other countries was another time of severe financial adversity for many farmers and their lenders [Harl (1990); Peoples et al. (1992)]. High debt loads (accumulated during the favorable times of the 1970s), volatile interest rates, and sharp declines in farm income and land values fueled farmers' financial problems. Farm bankruptcies and farm sales under stress increased substantially and the financial conditions of agricultural lenders deteriorated significantly [Barry and Lee (1983)].

As the crisis times widened and deepened, policy responses in the U.S. also became extensive [Pederson et al. (1987)]. Special bankruptcy laws for farmers were enacted [Dixon et al. (1995); Harl (1992)]. Public credit programs at federal and state levels emphasized debt restructuring, principal and interest buy-downs, and concessionary interest rates. Foreclosure moratoria on government loans were temporarily in effect. Lender bail-outs occurred, and major restructuring of the Farm Credit System was initiated [Lee and Irwin (1996)].

Public support was essential to the financial recovery of many agricultural borrowers and their lenders. The effects are demonstrated vividly by the loan loss experiences of the primary U.S. farm lenders. Between 1980 and 1997, the farm loan losses of commercial banks and the Farm Credit System totaled \$4.57 billion and \$3.82 billion, respectively, with most of these losses occurring from 1984 to 1988 [Economic Research Service (1998)]. In contrast, the last-resort lending program of the U.S. government experienced loan losses of \$20.18 billion, spread widely over the 14-year time period. Without the government support, the losses of farmers, input suppliers, and commercial lenders would have been much greater.

The problems of the 1980s also brought positive, longer-run improvements in lending programs, and further demonstrated the capacity of financial markets to absorb major increases in credit risk by spreading the adverse effects over numerous market participants. Included among the improvements in lending programs were the adoption of more conservative lending practices, greater emphasis on risk management, better financial accounting by agricultural firms, risk-based loan pricing systems, and more formal methods of credit evaluation. The U.S. Farm Credit System was subject to stronger government regulations, institutional restructuring, creation of an insurance program for bond holders, and establishment of several new risk- monitoring and loss-sharing arrangements [Collender and Erickson (1996)]. Public credit programs also shifted away from direct lending to guarantees of loans made by participating commercial lenders, and established more stringent conditions for borrower eligibility. For the most part, these improvements responded directly to the information and incentive problems leading to the high costs of adverse selection and moral hazards in credit relationships between agricultural borrowers and their lenders.

11. Conclnding comments

The theory and methods of analysis employed in studies of agricultural finance draw substantially on modern finance concepts, but with significant tailoring to the unique financial characteristics of the agricultural sectors of the world. Farms typically are capital-intensive, geographically dispersed, limited in scale and scope, and characterized by lengthy production periods. They are subject to significant business risks and to cyclical swings in economic conditions. Some are very large in size with complex organizations and financing arrangements. Many others are extremely small and barely subsist. Close relationships to family households predominate, and outside equity capital seldom is employed.

In light of these characteristics, financial management studies at both firm and aggregate levels have given substantial attention to issues associated with firm growth, investment analysis, financial structure, risk and liquidity management, performance measurement, and the role of "relationships" between borrowers and lenders. Other market-related studies have responded to the emergence of specialized agricultural lenders and lending programs targeted to the unique informational and monitoring requirements for financing farm businesses. Designing financing programs commensurate with the risky cash flow patterns of farm businesses, especially patterns attributed to farm real estate and other depreciable assets, has been especially challenging.

Evaluations of public credit programs are prominent as well. Government ownership, sponsorship, or back-up support (i.e., guaranteed or insured loans) has enabled many lenders to cope with the risks of specialized lending. Many government loan programs also provide targeted assistance to young, small, or disadvantaged farmers to help them gain financial viability. Studies have consistently shown, however, that attempts to convey significant subsidies through financial markets are largely ineffective.

Does financing matter in farmers' investment, financial, and business planning? The evidence clearly supports a positive answer to this question. Farmers' use of debt capital is widespread. Moreover, lenders will adjust the cost, availability, and other terms of the debt capital in response to a host of risk characteristics, business practices, and performance results of agricultural producers. These adjustments may often reflect the effects of differing incentives between the lender and borrower, as well as the problems of adverse selection and moral hazard attributable to asymmetric information. The localized, personal nature of lender-borrower relationships in agricultural finance suggests, however, that farm borrowers learn about lenders' preferences rather quickly and can choose whether to adjust their business practices accordingly.

Does external credit rationing occur in agricultural finance? Under normal economic conditions, there is little evidence of widespread, chronic credit rationing in developed countries. Cases where credit is rationed generally involve borrowers with weak creditworthiness. The availability of both specialized and non-specialized agricultural lenders, together with financial reforms that let interest rates respond freely to market conditions, help to ensure the ready availability of loan funds to creditworthy borrowers. In times of financial stress, credit may become more constraining as borrowers' creditworthiness weakens, but such risk responses by lenders can logically be expected. Credit rationing by commercial lenders may be greater in developing countries in which both lenders and borrowers have questionable viability. The small size and subsistence nature of many farms in these settings hamper their development of creditworthiness.

Rather than external rationing, internal rationing of credit is more likely the case. Under internal rationing, farmers' credit decisions reflect their own risk attitudes, time preferences, and other aspects of behavior. Even then, however, lenders still determine and influence the total borrowing capacity of farm businesses, regardless of whether this capacity is used fully, partially, or not at all in actual borrowings. Thus, lenders may ration total borrowing capacity and credit reserves, but not necessarily the portion that is borrowed.

References

Adams, D.W. (1971), "Agricultural credit in Latin America: A critical review of external funding policy", American Journal of Agricultural Economics 53:163–172.

Adams, D.W. (1992), "Taking a fresh look at informal finance", in: D.W. Adams and D.A. Fitchett, eds., Informal Finance in Low-Income Countries (Westview Press, Boulder, CO).

Adams, D.W., and M.L. Canavesi (1992), "Rotating savings and credit associations in Bolivia", in: D.W. Adams and D.A. Fitchett, eds., Informal Finance in Low Income Countries (Westview Press, Boulder, CO).

Adams, D.W., and D.A. Fichett, eds. (1992), Informal Finance in Low-Income Countries (Westview Press, Boulder).

Adams, D.W., and D. Graham (1981), "A critique of traditional agricultural credit projects", Journal of Development Economics 8:347–366.

Adams, D.W., and J.D. Von Pischke (1992), "Micro enterprise credit programs: Deja vu", Paper prepared for SAID (Agricultural Finance Program, Ohio State University, Columbus, Ohio, USA).

Aghion, P., and P. Bolton (1992), "An incomplete contracts approach to financial contracting", Quarterly Journal of Economics 89:488–500.

Aguilera-Alfred, N., and C. Gonzalez-Vega (1993), "A multinominal logit-analysis of loan targeting and repayment at the agricultural development bank of the Dominican Republic", Agricultural Finance Review 53:55–64.

Ahrendsen, B.L., R.N. Collender and B.L. Dixon (1994), "An empirical analysis of optimal farm capital structure decisions", Agricultural Finance Review 54:108–119.

Allen, D.W., and D. Lueck (1992), "The 'Back Forty' on a handshake: Specific assets, reputation, and the structure of farmland contracts", Journal of Law, Economics, and Organization 8:366–376.

Alston, L.J. (1984), "Farm foreclosure moratorium legislation", American Economic Review 74:445–457.

Anderson, J. (1990), "Rural credit and the mix between permanent and temporary wage labor contracts in Pernamburo, Brazil", American Journal of Agricultural Economics 72:1139–1145.

Arthur, L., C. Carter and F. Abizadeh (1988), "Arbitrage pricing, capital asset pricing, and agricultural assets", American Journal of Agricultural Economics 70:359–365.

Baker, C.B. (1968), "Credit in the production organization of the firm", American Journal of Agricultural Economics 49:507–521.

Baker, C.B., and V. Bhargava (1974), "Financing small farm developments in India", Australian Journal of Agricultural Economics 18:101–118.

Baker, C.B., and J.A. Hopkin (1969), "Concepts of finance for a capital-using agriculture", American Journal of Agricultural Economics 51:1055–1065.

Ball, V.E., and H.P. Witzke (1993), "The stock of capital in European community agriculture", European Review of Agricultural Economics 20:437–450.

Barham, B.L., and J.-P. Chavas (1998), "Sunk costs and resource mobility: Implications for economic and policy analysis", Agricultural Economics (forthcoming).

Barnard, F.L., and P.J. Barry (1985), "Interest rate deregulation and agricultural banking: A risk programming analysis", Agricultural Finance Review 45:100–112.

Barnard, C.H., and J. Grimard (1995), "Financial structure of Canadian and U.S. farms, 1989–1991", Canadian Journal of Agricultural Economics 43:79–90.

Barry, P.J. (1977), "Theory and methods in firm growth research, economic growth of the agricultural firm", Tech. Bull. 86 (College of Agriculture Research Center, Washington State University).

Barry, P.J. (1978), "Rural banks and farm loan participations", American Journal of Agricultural Economics 60:214–224.

Barry, P.J. (1980), "Capital asset pricing and farm real estate", American Journal of Agricultural Economics 62:41–46.

Barry, P.J. (1981), "Impacts of regulatory change on financial markets for agriculture", American Journal of Agricultural Economics 63:905–912.

Barry, P.J. (1983), "Financing growth and adjustment of farm firms under risk and inflation", in: K.L. Baum, ed., Modeling Farm Decisions for Policy Analysis (Westview Press, Boulder, CO).

Barry, P.J., ed. (1984), Risk Management in Agriculture (Iowa State University Press, Ames, IA).

Barry, P.J. (1985), "Needed changes in farmers home administration lending programs", American Journal of Agricultural Economics 67:341–344.

Barry, P.J. (1994), "Financial management of family farms: Modeling and empirical research", in: Family Economics and Agricultural Household Models (Elsevier, New York).

Barry, P.J. (1995), The Effects of Credit Policies on U.S. Agriculture (The AEI Press, Washington, D.C.).

Barry, P.J. (1996), "Fund availability at rural banks", Paper presented to annual meeting of regional research project NC-207 (Center for Farm and Rural Business Finance, University of Illinois).

Barry, P.J., and C.B. Baker (1971), "Reservation prices on credit use: A measure of response to uncertainty", American Journal of Agricultural Economics 53:222–227.

Barry, P.J., and C.B. Baker (1977), "Management of financial structure: Firm level", Agricultural Finance Review 37:50–63.

Barry, P.J., C.B. Baker and L.R. Sanint (1981), "Farmers' credit risks and liquidity management", American Journal of Agricultural Economics 63:216–227.

Barry, P.J., and F.L. Barnard (1985), "Interaction effects on rural financial intermediaries of financial stress and deregulation", American Journal of Agricultural Economics 67:1191–1195.

Barry, P.J., J.R. Brake and D.K. Banner (1993), "Agency relationships in the farm credit system: The role of the farm credit banks", Agribusiness: An International Journal 9:233–246.

Barry, P.J., and J.D. Calvert (1983), "Loan pricing and profitability analysis by agricultural banks", Agricultural Finance Review 43:21–29.

Barry, P.J., and P.N. Ellinger (1989), "Credit scoring, loan pricing and farm business performance", Western Journal of Agricultural Economics 14:45–55.

Barry, P.J., and P.N. Ellinger (1997), "Liquidity and competition in rural credit markets" (Federal Reserve Bank of Kansas City, Financing rural America, Kansas City, MO).

Barry, P.J., P.N. Ellinger, J.A. Hopkin and C.B. Baker (1995), Financial Management in Agriculture, 5th edn. (The Interstate Printers and Publishers, Danville, IL).

Barry, P.J., P.N. Ellinger and L.M. Moss (1997), "Lending relationships, customer loyalty, and competition in agricultural banking", Agricultural Finance Review 57:17–28.

Barry, P.J., and W.F. Lee (1983), "Financial stress in agriculture: Implications for agricultural lenders", American Journal of Agricultural Economics 65:945–952.

Barry, P.J., and H.A. Pepper (1985), "Impacts of holding company affiliation on loan/deposit relationships in agricultural banking", North Central Journal of Agricultural Economics 7:65–74.

Barry, P.J., and L.J. Robison (1986), "Economic versus accounting rates of return on farm land", Land Economics 62:388–401.

Barry, P.J., and L.J. Robison (1987), "Portfolio theory and financial structure: An application of equilibrium analysis", Agricultural Finance Review 47:142–151.

Barry, P.J., L.J. Robison and G. Nartea (1996), "Changing time attitudes in intertemporal analysis", American Journal of Agricultural Economics 78:972–981.

Barry, P.J., S.T. Sonka and K. Lajili (1992), "Vertical coordination, financial structure, and the changing theory of the firm", American Journal of Agricultural Economics 74:1219–1225.

Barry, P.J., B. Roberts, M. Boehlje and T. Baker (1997), "Financing capacities of independent versus contract hog production", Journal of Agricultural Lending 10:8–14.

Barry, P.J., B.J. Sherrick, D.A. Lins, D. Banner, B. Dixon and J.R. Brake (1996), "Farm credit system insurance risk simulation model", Agricultural Finance Review 56:68–84.

Barry, P.J., and D.R. Willmann (1976), "A risk programming analysis of forward contracting with credit constraints", American Journal of Agricultural Economics 58:62–70.

Barzel, Y. (1997), Economic Analysis of Property Rights, 2nd edn. (Cambridge University Press, New York).

Belongia, M., and A. Gilbert (1988), "The effects of affiliation with large bank holding companies on commercial bank lending to agriculture", American Journal of Agricultural Economics 70:69–78.

Belongia, M., and A. Gilbert (1990), "The effects of federal credit programs on farm output", American Journal of Agricultural Economics 72:769–773.

Berglof, E. (1990), "Capital structure as a mechanism of control: A comparison of financial systems", in: M. Aoki, B. Gustafson and O. Williamson, eds., The Firm as A Nexus of Treaties (Sage Publications, London).

Board of Governors of the Federal Reserve System (1977), Improved fund availability at rural banks (Washington, DC).

Boehlje, M.D., and L. Eisgruber (1972), "Strategies for the creation and transfer of the farm estate", American Journal of Agricultural Economics 54:461–472.

Boehlje, M.D., and T.K. White (1969), "A production-investment decision model of farm firm growth", American Journal of Agricultural Economics 51:546–564.

Bosworth, B., A. Carron and E. Rhyne (1987), The Economics of Federal Credit Programs (Brookings Institutions, Washington, D.C.).

Bottomley, A. (1975), "Interest rate determination in underdeveloped rural areas", American Journal of Agricultural Economics 57:279–291.

Bourdieu, P. (1986), "The forms of capital", in: J.G. Richardson, ed., Handbook of Theory and Research for the Sociology of Education (Greenwood Press, New York) 241–258.

Boussard, J.M. (1971), "Time Horizons, objective function, and uncertainty in a multiperiod model of firm growth", American Journal of Agricultural Economics 53:467–477.

Brake, J.R., and P.J. Barry (1971), "Flow of funds for the farm sector: Comment", American Journal of Agricultural Economics 53:665–667.

Buffier, B.D., and M.A. Metternick-Jones (1995), "Income equalization deposits: Enhancing farm viability", Review of Marketing and Agricultural Economics 63:191–199.

Burt, R.S. (1992), Structural Holes: The Social Structure of Competition (Harvard University Press, Cambridge).

Buttari, P.J. (1995), "Subsidized credit programs: Theory, record, and alternatives", SAID Evaluation Study No. 75 (U.S. Agency for International Development, Washington, D.C.).

Calomiris, C.W., R.G. Hubbard and J.H. Stock (1986), "The farm debt crisis and public policy", Brookings Papers on Economic Activity 2:441–478.

Calonius, E. (1990), Blood and money, Newsweek Special Edition, The 21st Century Family, Winter/Spring, p. 82. (Source of numbers used in the article: Family Business Magazine "Buchholz and Crane's Corporate Bloodlines".)

Caprio, G., I. Atiyas and J.A. Hanson (1996), Financial Reform: Theory and Practice (Cambridge University Press, New York).

Carter, M.R. (1988), "Equilibrium credit rationing of small farm agriculture", Journal of Development Economics 28:83–103.

Chambers, R., and U. Vasavada (1983), "Testing asset fixity for U.S. agriculture", American Journal of Agricultural Economics 65:761–769.

Chavas, J.-P. (1994), "On sunk costs and the economics of investments", American Journal of Agricultural Economics 76:114–127.

Chhikara, R.K. (1986), "Liquidity management hypothesis: Theoretical foundations, empirical tests and applications", Ph.D. Thesis (University of Illinois, Urbana-Champaign, Illinois).

Chhikara, R. (1989), "The state of the art in credit evaluation", American Journal of Agricultural Economics 71:1138–1144.

Cocks, K.D., and H.O. Carter (1968), "Micro goal functions and economic planning", American Journal of Agricultural Economics 50(2):400–411.

Coleman, J.S. (1988), "Social capital in the creation of human capital", American Journal of Sociology Supplement 94:S95–S120.

Collender, R. (1996), "Can federal action improve efficiency in the market for farm loans?", Agr. Info. Bull. 724-01 (Economic Research Service, U.S. Department of Agriculture, Washington, D.C.).

Collender, R.N., and A. Erickson (1996), "Farm credit system safety and soundness", Agricultural Information Bulletin No. 722 (Economic Research Service, U.S. Department of Agriculture, Washington, D.C.).

Collins, R.A. (1985), "Expected utility, debt-equity structure, and risk balancing", American Journal of Agricultural Economics 67:627–629.

Collins, R.A., and L.S. Karp (1993), "Lifetime leverage choice for proprietary farmers in a dynamic stochastic environment", Journal of Agricultural and Resource Economics 18:225–138.

Collins, R.A., and L.S. Karp (1995), "Static vs. dynamic models of proprietary capital structure: Discussion and preliminary empirical evidence", Agricultural Finance Review 55:1–9.

Cromarty, W.A. (1959), "The farm demand for tractors, machinery, and trucks", Journal of Farm Economics 41:323–331.

Dixon, B.L., E.M. Flynn and J.A. Flaccus (1995), "The chapter 12 experience in the U.S.: Regional comparisons and analysis of filing, discharge, and failure rates", Agricultural Finance Review 55:38–53.

Dorfman, R. (1969), "An economic interpretation of optimal control theory", American Economic Review 59:817–831.

Dunn, D., and T. Frey (1976), "Discriminant analysis of loans for cash grain farmers", Agricultural Finance Review 36:60–66.

Economic Research Service (1994), U.S. Department of Agriculture, AREI Updates, Farmland Tenure (Washington, D.C.) Number 7.

Economic Research Service (1998), U.S. Department of Agriculture, Annual Series, Agricultural Finance, Situation and Outlook (Washington, D.C.).

Edwards, C. (1959), "Resource fixity and farm organization", American Journal of Agricultural Economics 41:747–759.

Elhorst, J. (1993), "The evaluations of investment equations at the farm level", European Review of Agricultural Economics 20:167–182.

Ellinger, P.N., and P.J. Barry (1987), "The effects of tenure position on farm profitability and solvency: An application to Illinois farms", Agricultural Finance Review 47:106–118.

Ellinger, P.N., and P.J. Barry (1989), "Interest rate risk exposure of agricultural banks: A gap analysis", Agricultural Finance Review 49:9–21.

Ellinger, P.N., P.J. Barry and D.A. Lins (1983), "Farm financial performance under graduated payment mortgages", North Central Journal of Agricultural Economics 5:47–53.

Ellinger, P.N., N.S. Splett and P.J. Barry (1992), "Conency of credit evaluations at agricultural banks", Agribusiness: An International Journal 8:517–536.

Esguerra, F., and R.L. Meyer (1992), "Collateral substitutes in rural informal financial markets in the Philippines", in: D.W. Adams and D.A. Fitchett, eds., Informal Finance in Low Income Countries (Westview Press, Boulder, CO).

Fazzari, S.M., R.G. Hubbard and B. Petersen (1988), "Financing constraints and corporate investment", Brookings Papers on Economic Activity 4:141–195.

Featherstone, A.M., C.B. Moss, T.G. Baker and P.V. Preckel (1988), "The theoretical effects of farm policies on optimal leverage and the probability of equity losses", American Journal of Agricultural Economics 70:572–579.

Feder, G., L. Law, J. Lin and X. Luo (1990), "The relationship between credit and productivity in Chinese agriculture: A microeconomic model of disequilibrium", American Journal of Agricultural Economics 76:1151–1157.

Fischer, M., and K. Moore (1987), "An improved scoring function for the St. Paul bank for cooperatives", in: Financing Agriculture in a Changing Environment: Macro, Market, Policy and Management Issues (Southern Illinois University, Carbondale, IL).

Foster, W.E., and G.C. Rausser (May 1991), "Farmer behavior under risk of failure", American Journal of Agricultural Economics 73:276–288.

Fox, K.A. (1966), "Demand for farm tractors in the united states – A regression analysis", Agricultural Economics Report, 103 (United States Department of Agriculture, Washington, DC).

Franks, J.R. (1998), "Predicting financial stress in farm businesses", European Review of Agricultural Economics 25:30–52.

Freshwater, D. (1989), "Canadian agricultural finance in the 1980s and 1990s", Canadian Journal of Agricultural Economics 37:1–27.

Freund, R.J. (1956), "Introduction of risk into a risk programming model", Econometrica 24:253–263.

Fukuyama, F. (1995), Trust: The Social Virtues and the Creation of Prosperity (The Free Press, New York).

Gabriel, S.C., and C.B. Baker (1980), "Concepts of business and financial risk", American Journal of Agricultural Economics 62:560–564.

Gertler, M., and A. Rose (1996), "Finance, public policy, and growth", in: G. Caprio, I., Atiyas and J.C. Hanson, eds., Financial Reform: Theory and Experiences (Cambridge University Press, New York).

Gibson, S., and P. Barry (1994), "Estate planning and the reverse mortgage", Journal of the American Society of Farm Managers and Rural Appraisers 58:13–22.

Giraro, J.A., W.G. Tomek and T.D. Mount (1974), "The effect of income instability on farmers' consumption and investment", Review of Economics and Statistics 56:141–150.

Graham, D.H. (1992), "Informal rural finance in Niger: Lessons for building formal institutions", Chapter 6, in: D.W. Adams and D.A. Fitchett, eds., Informal Finance in Low Income Countries (Westview Press, Boulder, CO).

Griliches, Z. (1960), "The demand for a durable input: Farm tractors in the United States, 1921–57", in: A.C. Harberger, ed., The Demand for Durable Goods (University of Chicago Press, Chicago).

Grossman, S., and O. Hart (1986), "The costs and benefits of ownership: A theory of vertical and lateral integration", Journal of Political Economy 94:691–719.

Gu, D. (1996), "Capital asset pricing and agricultural assets in England and Wales", Journal of Agricultural Economics 47:99–108.

Guinnane, T.W. (1992), "Intergeneration transfers, emigration, and the rural Irish household system", Explorations in Economic History 29:456–476.

Gustafson, C.R., and P.J. Barry (1993), "Structural implications of agricultural finance", in: A. Hallam, ed., Size, Structure and the Changing Face of American Agriculture (Westview Press, Boulder, CO) 383–411.

Gustafson, C., P.J. Barry and S.T. Sonka (1989), "Machinery investment decisions: A simulated analysis for cash grain farms", Western Journal of Agricultural Economics 13:244–253.

Gwilliams, K. (1993), "Farmland leasing and contract choice in Michigan: The influence of social distance", Ph.D. Thesis (Michigan State University).

Gwinn, A.S., P.J. Barry and P.N. Ellinger (1992), "Farm financial structure under uncertainty: An application to grain farms", Agricultural Finance Review 52:43–56.

Hanson, S.D., L.J. Robison and M.E. Siles (1996), "Impacts of relationships on customer retention in the banking industry", Agribusiness: An International Journal 12:27–36.

Hardy, W., and J.B. Weed (1980), "Objective evaluation of agricultural lending", Southern Journal of Agricultural Economics 12:159–164.

Harl, N.E. (1990), The Farm Debt Crisis of the 1980s (Iowa State University Press, Ames, Iowa).

Harl, N. (1992), Agricultural Law: Estate, Tax, and Business Planning (Matthew Bender and Company, New York).

Harl, N.E. (1992), "Chapter 12 bankruptcy: A review and evaluation", Agricultural Finance Review 52:1–11.

Hart, O. (1988), "Incomplete contracts and the theory of the firm", Journal of Law, Economics, and Organization 4:119–139.

Hart, O. (1995), Firms, Contracts, and Financial Structure (Oxford University Press, New York).

Heady, E.O., and L.G. Tweeten (1963), Resource Demand and Structure of the Ag Industry (Iowa State University Press, Ames).

Herendeen, J.B., and W. Grisley (1988), "A dynamic q model of investment, financing, and asset pricing", Southern Economics Journal 55:360–373.

Herring, P.J., and R.E. Litan (1995), Financial Regulation in the Global Economy (The Brookings Institution, Washington, D.C.).

Hochman, E., and G.S. Rausser (1997), "Firm growth policies under different pollution abatement, production, and financial structure", Economic Growth of the Agricultural Firm, Technical Bulletin 86 (College of Agriculture Research Center, Washington State University).

Hodgman, D.R. (1961), "Commercial bank loan and investment policy" (Bureau of Economic and Business Research, University of Illinois).

Hoff, K., and J. Stiglitz (1990), "Introduction: Imperfect information and rural credit markets: Puzzles and policy perspectives", The World Bank Economic Review 4:235–250.

Houck, J. (1977), "An approach to specifying and estimating an irreversible function", American Journal of Agricultural Economics 59:570–572.

Hsu, S., and C. Chang (1990), "An adjustment cost rationalization of asset fixity theory", American Journal of Agricultural Economics 72:298–308.

Hubbard, R.G. (1998), "Capital-market imperfections and investment", Journal of Economic Literature 36:193–225.

Hubbard, R.G., and A.K. Kashyap (1992), "Internal net worth and the investment process: An application to U.S. agriculture", Journal of Political Economy 100:506–534.

Hughes, D., and N. Osborne (1987), "Measuring federal farm credit subsidies", Agricultural Finance Review 47:125–134.

Hughes, D.W., and J.B. Penson (1981), "An overview of farm sector capital and credit needs", Agricultural Finance Review 41:1–19.

Hughes, D.W., S.C. Gabriel, P.J. Barry and M.D. Boehlje (1986), Financing the Agricultural Sector: Future Challenges and Policy Alternatives (Westview Press, Boulder, CO).

Hughes, D., J. Penson, J. Richardson and D. Chen (1987), "Policy responses to financial stress", Agricultural Finance Review 47(Special Issue):100–113.

Irwin, G.D. (1968a), "A comparative review of some firm growth models", Agricultural Economics Research 20:82–100.

Irwin, G.D. (1968b), "Three myths about the balance sheet: The changing financial structure of farming", American Journal of Agricultural Economics 50:1596–1599.

Jensen, M.C. (1986), "Agency costs of free cash flow, corporate finance, and takeovers", American Economic Review 76:323–329.

Jensen, M., and W. Meckling (1976), "Theory of the firm: Managerial behavior, agency costs, and ownership structure", Journal of Finance Economics 3:305–360.

Jensen, F.E., J.S. Lawson and L.N. Langemeier (1993), "Agricultural investment and internal cash flow variables", Review of Agricultural Economics 15:295–306.

Johnson, C. (1990), "Farmland as a business asset", Journal of Agricultural Economics 41:135–148.

Johnson, D.G. (1950), "The nature of the supply function for agriculture", American Economic Review 40:539–564.

Johnson, G.L. (1956), "Supply functions – some facts and notions", in: E.O. Heady, et al., eds., Agricultural Adjustment Problems in a Growing Economy (Iowa State University Press, Ames).

Johnson, G.L., and L. Quance (1972), The Overproduction Trap in U.S. Agriculture (John Hopkins University Press, Baltimore).

Johnson, J., M. Morehart and K. Erickson (1987), "The financial condition of the agricultural sector", Agricultural Finance Review 47(Special Issue):1–18.

Karmajou, F., and C.B. Baker (1980), "Reforming Cameroon's government credit program: Effects on liquidity management by small farm borrowers", American Journal of Agricultural Economics 62:709–718.

Khoju, M.R., C.H. Nelson and P.J. Barry (1993), "Debt service reserve fund as a response to repayment risk", Review of Agricultural Economics 15:217–232.

Kimhi, A. (1994), "Optimal timing of farm transferal from parent to child", American Journal of Agricultural Economics 76:228–236.

Laderman, E., R. Schmidt and G. Zimmerman (1991), "Location, branching, and bank portfolio diversification: The case of agricultural lending", Economic Review, Federal Reserve Bank of San Francisco, 24–37.

LaDue, E. (1990), "Moral hazard in federal farm lending", American Journal of Agricultural Economics 72:774–779.

Langemeier, M.R., and G.F. Patrick (1993), "Farm consumption and liquidity constraints", American Journal of Agricultural Economics 75:479–484.

Leatham, D.J., and T.G. Baker (1988), "Farmers choice of fixed and adjustable interest rate loans", American Journal of Agricultural Economics 70:803–812.

LeBlanc, M., and J.A. Hrubovcak (1985), "The effects of tax policy on aggregate agricultural investment", Agricultural Economics Research 37:12–20.

LeBlanc, M., and J. Hrubovcak (1986), "The effects of interest rates on agricultural machinery investment", American Journal of Agricultural Economics 68:767–777.

LeBlanc, M., J. Hrubovcak, R. Durst, and R. Conway (1992), "Farm machinery investment and the tax reform act of 1986", Journal of Agricultural and Resource Economics 17:66–79.

Lee, H., and R.G. Chambers (1986), "Expenditure constraints and profit maximization in U.S. agriculture", American Journal of Agricultural Economics 68:857–865.

Lee, J., and S. Gabriel (1980), "Public policy toward agricultural credit, future sources of funds for agricultural banks" (Federal Reserve Bank of Kansas City, Kansas City).

Lee, W., and C.B. Baker (1984), "Agricultural risks and lender behavior", in: P.J. Barry, ed., Risk Management in Agriculture (Iowa State University Press, Ames, Iowa).

Lee, W., and G. Irwin (1996), "Restructuring the farm credit system: A progress report", Agricultural Finance Review 56:1–21.

Lee, W., and N. Rask (1976), "Inflation and crop profitability: How much can farmers pay for land?", American Journal of Agricultural Economics 58:984–990.

Levine, R. (1997), "Financial development and economic growth: Views and agenda", Journal of Economic Literature 35:688–726.

Lifran, R. (1994), "Credit constraints in a life-cycle model with self-employment: Empirical evidence for finance", in: F. Caillavet, H. Guyomard and R. Lifran, eds., Agricultural Household Modeling and Family Economics (Elsevier Science, Amsterdam).

Lins, D.A., and P.J. Barry (1980), "Availability of financial capital as a factor of structural change in the U.S. farm production sector, farm structure Committee on Agriculture, United States Senate (U.S. Government Printing Office, Washington, D.C.).

Lins, D.A., and P.J. Barry (1984), "Agency status of the farm credit system", American Journal of Agricultural Economics 66:601–606.

Looney, J., and D.L. Uchtmann (1994), Agricultural Law: Principles and Cases (McGraw-Hill, New York).

Lufburrow, J., P.J. Barry and B.L. Dixon (1984), "Credit scoring for farm loan pricing", Agricultural Finance Review 44:8–14.

Mapp, H., and G. Helmers (1984), "Methods of risk analysis for farm firms", in: P.J. Barry, ed., Risk Management in Agriculture (Iowa State University Press, Ames, Iowa).

Martin, J.R., and J.S. Plaxico (1967), "Polyperiod analysis of capital accumulation of farms in the rolling plains of Oklahoma and Texas", USDA Technical Bulletin 1381.

Melichar, E. (1979), "Capital gains vs. current income in the farming sector", American Journal of Agricultural Economics 61:1082–1092.

Melichar, E.O. (1984), "A financial perspective on agriculture", Federal Reserve Bulletin 70:1–13.

Meyer, J. (1987), "Two moment decision models and expected utility maximization", American Economic Review 77:421–430.

Meyer, J., and R.H. Rasche (1992), "Sufficient conditions for expected utility to imply mean-standard deviation rankings: Empirical evidence concerning the location and scale condition", The Economic Journal 102:91–106.

Meyer, R.L. (1990), "Analyzing the farm-level impact of agricultural credit: Discussion", American Journal of Agricultural Economics 72:1158–1160.

Miller, L.H., and E.L. LaDue (1989), "Credit assessment models for farm borrowers: A logit analysis", Agricultural Finance Review 49:22–36.

Miller, L., P. Barry, C. DeVuyst, D. Lins and B. Sherrick (1994), "Farmer mac credit risk and capital adequacy", Agricultural Finance Review 54:66–79.

Miller, L.H., P.J. Ellinger, P.N. Barry and K. Lajili (1993), "Price and non-price management of agricultural credit risk", Agricultural Finance Review 53:28–41.

Moss, L., P.J. Barry and P.N. Ellinger (1997), "The competitive environment for agricultural bankers in the U.S", Agribusiness: An International Journal 13:431–444.

Nasr, R., P.J. Barry and P.N. Ellinger (1998), "Financial structure and efficiency of grain farms", Agricultural Finance Review 58:33–48.

Neff, D.L., and P.N. Ellinger (1996), "Participants in rural bank consolidations", American Journal of Agricultural Economics 78:721–727.

Nelson, C.H., J.B. Braden and J. Roh (1989), "Asset fixity and investment asymmetry in agriculture", American Journal of Agricultural Economics 71:970–979.

Nelton, S. (1990), "We could use a few good numbers", Nation's Business, p. 53.

Novak, F.S., and G.D. Schnitkey (1994), "The effects of including bankruptcy on dynamic investment decisions", Journal of Agricultural and Resource Economics 19:255–266.

Novak, M., and E. LaDue (1994), "An analysis of multiperiod agricultural credit evaluation models for New York dairy farms", Agricultural Finance Review 54:55–65.

Patrick, G.F., and L.M. Eisgruber (1968), "The impact of managerial ability and capital structure on growth of the farm firm", American Journal of Agricultural Economics 50:491–507.

Patrick, G.F., P.N. Wilson, P.J. Barry, W.G. Boggess and D.L. Young (1985), "Risk perceptions and management responses: Producer-generated hypotheses for risk modeling", Southern Journal of Agricultural Economics 17:231–238.

Pederson, G.D. (1992), "Agricultural bank portfolio adjustments to risk", American Journal of Agricultural Economics 74:672–681.

Pederson, G., M. Boehlje, D. Doye and R. Jolly (1987), "Resolving financial stress in agriculture by altering loan terms: Impacts on farmers and lenders", Agricultural Finance Review 43:123–137.

Penson, J.B. (1987), "Evaluating financial trends in agriculture", Agricultural Finance Review 47:14–20.

Penson, J.B., R.F.J. Romain and D.W. Hughes (1981), "Net investment in farm tractors: An econometric analysis", American Journal of Agricultural Economics 63:629–635.

Peoples, K., D. Freshwater, G. Hanson, P. Prentice and E. Thor (1992), Anatomy of an American Agricultural Credit Crisis (Rowman and Littlefield Publishers, Lanham, MD).

Perrin, R. (1972), "Asset replacement principles", American Journal of Agricultural Economics 54:60–67.

Petersen, M., and R. Rajan (1994), "The benefits of lending relationships: Evidence from small business data", Journal of Finance 45:3–37.

Petersen, M., and R. Rajan (1995), "The effects of credit market competition on lending relationships", The Quarterly Journal of Economics 110:407–443.

Pflueger, B.W., and P.J. Barry (1986), "Crop insurance and credit: A farm level simulation analysis", Agricultural Finance Review 46:1–14.

Phimister, E. (1995a), "Farm consumption behavior in the presence of uncertainty and restrictions on credit", American Journal of Agricultural Economics 77:952–959.

Phimister, E. (1995b), "The impact of borrowing constraints on farm households: A life cycle approach", European Review of Agricultural Economics 22:61–86.

Pinches, G.E. (1992), Essentials of Financial Management (Harper Collins Publishers, New York).

Pindyck, R.S. (1991), "Irreversibility, uncertainty, and investment", Journal of Economic Literature 29:1110–1148.

Portes, A. (1995), "Economic sociology and the sociology of immigration: A conceptual overview", The Economic Sociology of Immigration: Essays on Networks, Ethnicity and Entrepreneurship (Russell Sage Foundation, New York).

Purvis, A., W.G. Boggess, C.B. Moss and J. Holt (1995), "Technology adoption under irreversibility and uncertainty", American Journal of Agricultural Economics 77:541–551.

Putnam, R.D. (1995), "Bowling alone: America's declining social capital", Journal of Democracy 6:65–78.

Rahman, M.L., and P.J. Barry (1981), "Financial control and variable amortization under uncertainty: An application to Texas rice farms", Southern Journal of Agricultural Economics 13:99–104.

Rayner, A.J., and K. Cowling (1968), "Demand for farm tractors in the United States and the United Kingdom", American Journal of Agricultural Economics 50:896–912.

Robison, L.J., and P.J. Barry (1977), "Portfolio adjustments: An application to rural banking", American Journal of Agricultural Economics 59:311–320.

Robison, L.J., and P.J. Barry (1996), Present Value Models and Investment Analysis (Michigan State University Press, East Lansing, MI, USA).

Robison, L.J., and J.R. Brake (1979), "Application of portfolio theory to farmer and lender behavior", American Journal of Agricultural Economics 61:158–164.

Robison, L.J., and S.D. Hanson (1997), "Analyzing firm response to risk using mean-variance models", in: R.B.M. Huirne, J.B. Hardaker and A.A. Dijkhuizen, eds., Risk Management Strategies in Agriculture: State of the Art and Future Perspectives (Backhuys Publishers, The Netherlands).

Robison, L.J., and A.A. Schmid (1996), "Can Agriculture prosper without increased social capital?", in: H.W. Ayer, ed., The Best of Choices, 1986–1996 (American Agricultural Economics Association, Ames, Iowa).

Robison, P.J., and M.E. Siles (1997), "Social capital and household income distributions in the United States: 1980, 1990", Department of Agricultural Economics Report No. 595 and the Julian Zamora Research Institute Research Report No. 18 (Michigan State University, East Lansing, Michigan).

Robison, L.J., P.J. Barry and W.G. Burghardt (1987), "Borrowing behavior under financial stress by the proprietary firm: A theoretical analysis", Western Journal of Agricultural Economics 12:144–151.

Rosenzweig, M.R., and K.I. Wolpin (1985), "Specific experience, household structure, and intergenerational transfers: Farm family land and labor arrangements in developing countries", Quarterly Journal of Economics 100:961–987.

Ross, S.A. (1995), "Uses, abuses, and alternatives to the net present value rule", Financial Management 24:96–102.

Rucker, R. (1990), "The effects of state farm relief legislation on private lenders and borrowers: The experience of the 1930s", American Journal of Agricultural Economics 76:24–34.

Rucker, R., and L. Alston (1987), "Farm failures and government intervention: A case study of the 1930s", American Economic Review 77:724–730.

Saha, A., H.A. Love and R. Schwart (1994), "Adoption of emerging technologies under output uncertainty", American Journal of Agricultural Economics 76:836–846.

Schmid, A.A., and L.J. Robison (1995), "Applications of social capital theory", Journal of Agricultural and Applied Economics 27:59–66.

Schmiesing, B., M. Edelman, C. Swanson and D. Kolner (1985), "Differential pricing of agricultural loans by commercial banks", Western Journal of Agricultural Economics 10:192–204.

Schnitkey, G.D., C.R. Taylor and P.J. Barry (1989), "Evaluating farmland investments considering dynamic stochastic returns and farmland prices", Western Journal of Agricultural Economics 14:143–156.

Scott, J.T., and E.O. Heady (1967), "Regional demand for farm buildings in the United States", Journal of Farm Economics 49:184–198.

Shalit, H., and A. Schmitz (1982), "Farmland accumulation and prices", American Journal of Agricultural Economics 64:710–719.

Shalit, H., and A. Schmitz (1984), "Farmland price behavior and credit allocation", Western Journal of Agricultural Economics 9:303–313.

Sharpe, S.A. (1990), "Asymmetric information, bank lending, and implicit contracts: A stylized model of customer relationships", Journal of Finance 45:1069–1087.

Shepard, L., and R. Collins (1982), "Farm bankruptcy 1910–1978", American Journal of Agricultural Economics 62:609–615.

Sherrick, B., and R. Lubben (1994), "Economic motivations for vendor financing", Agricultural Finance Review 54:120–131.

Siles, M., S.D. Hanson and L.J. Robison (1994), "Socio-economics and the probability of loan approval", Review of Agricultural Economics 16:405–414.

Smith, C.W. (1987), "Agency costs", in: J. Eatwell, M. Milgate and P. Newman, eds., The New Palgrave, a Dictionary of Economics (Macmillan Press, London).

Smith, C., and J. Warner (1979), "On financial contracting: An analysis of bond covenants", Journal of Financial Economics 7:117–161.

Sonka, S., B.L. Dixon and B.L. Jones (1980), "Impact of farm financial structure on the credit reserve of the farm business", American Journal of Agricultural Economics 62:565–570.

Splett, N., P. Barry, B. Dixon and P. Ellinger (1994), "A joint experience and statistical approach to credit scoring", Agricultural Finance Review 54:39–135.

Stam, J. (1995), "Credit as a factor influencing farmland values", Staff Paper No. 9504 (Economic Research Service, U.S. Department of Agriculture).

Stensland, J., and G. Pederson (1997), "The benefits and costs of fee-income generation in small banks", Agricultural Finance Review 57:1–16.

Stiglitz, J.E. (1985), "Credit markets and the control of capital", Journal of Money, Credit, and Banking 17:133–152.

Stiglitz, J.E., and A. Weiss (1981), "Credit rationing in markets with imperfect information", American Economic Review 71:393–411.

Stiglitz, J.E., and A. Weiss (1983), "Incentive effects of terminations: Applications to credit and labor markets", American Economic Review 73:912–927.

Stover, R., R. Teas and R. Gardner (1985), "Agricultural lending decisions: A multiattribute analysis", American Journal of Agricultural Economics 67:513–520.

Strotz, R.H. (1956), "Myopia and inconsistency in dynamic utility maximization", Review of Economic Studies 23:165–180.

Tauer, L. (1985), "Use of life insurance to fund the farm purchase from heirs", American Journal of Agricultural Economics 67:60–69.

Thomas, K.. and M. Boehlje (1983), "Farm estate and transfer planning: A management perspective", North Central Regional Extension Publication No. 193 (University of Minnesota, USA).

Traill, B., D. Colman and T. Young (1978), "Estimating irreversible supply elasticities: Some new approaches", American Journal of Agricultural Economics 60:528–531.

Turvey, C.G. (1991), "Credit scoring for agricultural loans: A review with applications", Agricultural Finance Review 51:43–54.

Turvey, C.G., and R. Brown (1990), "Credit scoring for a federal lending institution: The case of Canada's farm credit corporation", Agricultural Finance Review 50:47–57.

Turvey, C.G., and A. Weersink (1997), "Credit risk and the demand for agricultural loans", Canadian Journal of Agricultural Economics 45:201–217.

Tweeten, L., and L. Quance (1969), "Positive measures of aggregate supply elasticities: Some new approaches", American Journal of Agricultural Economics 51:342–352.

Vandeputte, J.M., and C.B. Baker (1970), "Specifying the allocation of income between taxes, consumption, and savings in linear programming models", American Journal of Agricultural Economics 52:521–528.

Vasavada, U., and R.G. Chambers (1986), "Investment in U.S. agriculture", American Journal of Agricultural Economics 68:950–960.

Von Pischke, J.D. (1991), "Finance at the frontier: Debt capacity and the role of credit in the private economy" (The World Bank, Washington, D.C.).

Wachter, M.L., and B. Williamson (1978), "Obligational markets and the mechanics of inflation", Bell Journal of Economics 9:549–571.

Weersink, A.J., and L.W. Tauer (1989), "Comparative analysis of investment models for New York dairy farms", American Journal of Agricultural Economics 71:136–145.

Williamson, O.E. (1996), The Mechanisms of Governance (The Free Press, New York).

Wilson, P. and D. Barkley (1988), "Commercial banks market shares: Structural factors influencing their decline in the agricultural sector", Agricultural Finance Review 48:49–59.

Wood, J.H. (1975), Commercial Bank Loan and Investment Behavior (John Wiley & Sons, New York).

Yang, S.R., and W. Wilson (1996), "Credit allocation decisions of wheat exporting countries", Canadian Journal of Agricultural Economics 44:53–65.

Young, R.P., and P.J. Barry (1987), "Holding financial assets as a risk response: A portfolio analysis of Illinois cash grain farms", North Central Journal of Agricultural Economics 9(1).

Chapter 11

ECONOMIC IMPACTS OF AGRICULTURAL RESEARCH AND EXTENSION

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Contents

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Abstract

Agricultural research and extension programs have been built in most of the world's economies. A substantial number of economic impact studies evaluating the contributions of research and extension programs to increased farm productivity and farm incomes and to consumer welfare have been undertaken in recent years. This chapter reviews these studies using estimated rates of return on investment to index economic impacts. In almost all categories of studies, median (social) estimated rates of return are high, (often exceeding 40 percent) but the range of estimates was also high. The chapter concludes that most of the estimates were consistent with actual economic growth experiences.

JEL classification: Q16

1. Introductiou

Agricultural research is conducted both by private sector firms supplying inputs to farm producers and by public sector experiment stations, universities, and other research organizations. In the United States, agricultural research has been treated as a public sector responsibility for much of the nation's history. The U.S. Patent Office, one of the oldest government agencies in the U.S., recognizing that intellectual property right (patent) incentives were not available to stimulate the development of improved plants and animals in the nineteenth century, initiated programs to search for and import seeds and breeding animals from abroad.[1] After the establishment of the United States Department of Agriculture (USDA) and the Land Grant Colleges in 1862, the Hatch Act in 1878 provided for financial support for the State Agricultural Experiment Station system (SAES). Agricultural research in the public sector today is conducted in both USDA and SAES organizations and to a limited extent in general universities. Agricultural extension is also conducted by private sector firms and by public sector extension programs. Formal extension program development occurred somewhat later in the U.S. than was the case for research.[2]

The development of agricultural research and extension programs in the U.S. occurred at roughly the same time that similar programs were being developed in Europe. By the beginning of the twentieth century, most of today's developed countries had agricultural research systems in place. By the middle of the twentieth century many of today's developing countries had agricultural research and extension systems as well.[3] The perceived success of both research and extension programs in the first half of the twentieth century led to the judgment that these programs should be central components in the large-scale economic development programs ushered in after World War II.

Today, a complex system of international agricultural research centers (IARCs), national agricultural research programs (NARs), and sub-national or regional programs has been built covering most of the globe. Similarly, extension programs have been developed in most countries. These programs are under various forms of review and evaluation, as is appropriate given their perceived importance as public sector investments. Some of these evaluations are administrative or financial, others are informal "peer" reviews and ratings. Some reviews are economic impact evaluations, and these are the concern of this paper.

Economic impact evaluations differ from other evaluations in that they measure economic benefits produced by a program and associate these benefits with the economic

[1] Huffman and Evenson (1993) discuss the development of the U.S. research and extension system and the early role of the patent office.

[2] The Capper–Volstead Act of 1914 provided for formal extension services, but as with research programs, official government sanction and support for these programs came only after state and private experiments with precursor programs were deemed to be successful.

[3] See Boyce and Evenson (1975), Judd, Boyce, and Evenson (1986), and Pardey and Roseboom (1989) for international reviews of investment in research and extension.

costs of the program. This means computing a benefit/cost ratio and/or other associated economic calculation, such as the present value of benefits net of costs, or internal rates of return to investment.[4] Many evaluations, such as the "monitoring and evaluation" activities associated with World Bank research and extension projects, provide indicators of benefits (such as the number of beneficiaries) or of project outputs (farmers visited, experiments completed, etc.), but do not calculate actual value measures of benefits and costs. These evaluations are important and useful, but are not economic impact evaluations as defined here.

Economic impact evaluations are intended to measure whether a project or program actually had (or is expected to have) an economic impact and to associate impacts with project or program costs. They do not measure whether the project or program was designed optimally or managed and executed optimally. Many extension and research projects and programs have had significant economic impacts even though they were not as productive as they might have been.[5] Project/program design and execution issues are informed by economic impact studies, but also require other types of evaluation. Economic evaluations, however, address basic investment and resource allocation issues that other evaluations do not address.

Economic impact evaluations can be classified into *ex ante* evaluations (undertaken before the project or program is initiated) and *ex post* evaluations (undertaken after the project is initiated, sometimes after it is completed). In practice, *ex ante* project evaluations are used by international aid agencies and to some degree by national agencies to guide investments at the project level. These evaluations are seldom reported in published form. They are also seldom compared with subsequent *ex post* evaluations.[6]

The organization of this chapter is as follows: in Section 2 a brief review of institutional and analytic models of extension and research impacts is presented. Some of these models have implications for the empirical specifications surveyed in later sections. Section 3 reviews *ex post* studies of extension impacts. A number of these studies were based on farm-level observations, and methodological issues associated with these

[4] Many of these evaluations also undertake growth accounting. In addition to the literature reviewed here, a "gray" literature exists. Alston et al. (1998b) report a meta-analysis of rates of return that includes more of the gray literature than reviewed here. Unfortunately, a comparison of studies covered cannot be made as the authors treat their references as "data" and state that data from the International Food Policy Research Institute (IFPRI) studies will not be released until after publication of the report. This chapter has benefited greatly from an earlier review by Reuben Echeverría (1990).

[5] Economic impact studies are often downgraded as measures of investment effectiveness because they do not directly address project/program efficiency. The recent World Bank Operations Evaluation Department (OED) Review of Agricultural Extension and Research [Purcell and Anderson (1997)] reflects this perspective. It is critical of returns to research studies because they do not address project effectiveness. Given the World Bank's use of *ex ante* project evaluation methods (stressing economic impact indicators) the OED perspective on economic impact studies is puzzling.

[6] *Ex ante* economic calculations can be found in project reports of the World Bank and the regional development banks (the Asian Development Bank and the Inter-American Development Bank). As noted, however, few *ex ante–ex post* studies have been undertaken.

studies are addressed. Section 4 reviews *ex post* studies of applied agricultural research impacts. Section 5 reviews studies of R&D spillovers (to the agricultural sector from private sector research and development R&D) and "germplasmic" spillovers from pre-invention science. Section 6 reviews *ex ante* studies. The concluding section addresses the "credibility" of the estimates and consistency of estimated rates of return with actual growth experience.[7]

2. Iustitutioual, aualytic, aud methodology issues (for *ex post* studies)

Extension programs seek two general objectives. The first is to provide technical education services to farmers through demonstrations, lectures, contact farmers, and other media. The second is to function in an interactive fashion with the suppliers of new technology, by providing demand feedback to technology suppliers and technical information to farmers to enable them to better evaluate potentially useful new technology and ultimately to adopt (and adapt) new technology in their production systems.

Applied agricultural research programs in both the public and private sectors seek to invent new technology for specific client or market groups. The market for agricultural inventions is highly differentiated because the actual economic value of inventions is sensitive to soil, climate, price, infrastructure, and institutional settings. Models of invention typically specify a distribution of potential inventions whose parameters are determined by the stock of past inventions and invention methods or techniques (i.e., the technology of technology production). This feature of invention calls for specifying two types of spillovers: (1) invention-to-invention spillovers (which are often spatial), and (2) science (or pre-invention science)-to-invention spillovers.

The studies reviewed here are empirical and most entail direct statistical estimation of coefficients for variables that measure the economic impacts of extension, applied research, or pre-invention science "services". All require some form of production framework. In this section alternative production frameworks are first briefly reviewed. Then a simple characterization of technological infrastructure is presented and related to extension and research programs. A more formal model of research and extension interactions is then presented. Finally, methodological issues associated with the specification of research and extension variables are discussed.

[7] There appears to be considerable skepticism regarding estimated rates of return [Ruttan (1998)]. They are widely perceived to be overestimated. This is true even though the economic impacts for other projects such as rural credit programs, rural development programs, and rural infrastructure programs (roads, etc.) are typically less thoroughly documented or are apparently relatively low. A recent paper [Alston et al. (1998a)] reporting low rates of return proclaims that appropriate time lag estimation techniques result in low returns to research and extension. Serious flaws in this paper are noted later in this review (footnote 20), but the fact that it has attracted attention attests to skepticism. This issue of skepticism is revisited in the growth accounting section of the paper where it is shown that most high rates of return to research and extension are consistent with growth experience.

2.1. Production frameworks

The starting point of economic impact studies is a productivity-technology specification. Consider the general specification of a "meta-transformation function":

$$G(Y, X, F, C, E, T, I, S) = 0, \tag{1}$$

where

Y is a vector of outputs,
X is a vector of variable factors,
F is a vector of fixed factors,
C is a vector of climate factors,
E is a vector of edaphic or soil quality factors,
T is a vector of technology (inventions),
I is a vector of market infrastructure,
S is a vector of farmer skills.

There are several empirical options to identify economic impacts of a change in T (extension and research services) based on this expression. All entail meaningfully defining measures or proxies for T (as well as measuring Y, X, F, C, E, I, and S accurately).

The empirical options are:

(a) To convert (1) to an aggregate "meta-production function" (MPF) by aggregating commodities into a single output measure:

$$Y_A = F(X, F, C, E, T, I, S) \tag{2}$$

and estimating (2) with farm-level or aggregated cross-section and/or time series data.

(b) To derive the output supply-factor demand system from the maximized profits function (or minimized cost function) via the Shephard–Hotelling lemma and estimate the profit function and/or its derivative output supply and factor demand functions. (This is the cost (CF) or profits (PF) production structure.)

$$\begin{aligned} \pi^* &= \pi(P_y, P_x, C, E, T, I, S), \\ \partial\pi^*/\partial P_y &= Y^* = Y(P_y, P_x, C, E, T, I, S), \\ \partial\pi^*/\partial P_x &= X^* = X(P_y, P_x, C, E, T, I, S). \end{aligned} \tag{3}$$

(c) To derive "residual" total factor productivity (TFP) indexes from (1) and utilize a TFP decomposition specification (the PD production structure):

$$Y/X = \mathrm{TFP} = T(C, E, T, I, S). \tag{4}$$

(d) To derive partial factor productivity (PFP) indexes from (1) and utilize a PFP decomposition specification (the PD(Y) production structure):

$$\mathrm{PFP}(Y/Ha, Y/L \text{ etc.}) = P(C, E, T, I, S). \tag{5}$$

Each of these options has been pursued in the studies reviewed in this paper. Methods for estimation or measuring the relationship between T, the technology variables, and the economic variables, have included direct statistical estimation of (2), (3), (4), or (5), and non-statistical use of experimental and other evidence. The options themselves have different implications and interpretations as well as having functional form implications for estimation.

The aggregate production function structure is often estimated with farm data. It requires that variable inputs, X, be treated as exogenous to the decision maker. It is typically argued in these studies that observed X vectors are profit-maximizing vectors and that these are functions of exogenous prices and fixed factors (as in (3)). This is a strong assumption in many settings. (From (2) one can compute the partial effect of T on Y, i.e., $\partial Y/\partial T$, holding X constant, but one cannot compute the total effect of T on Y ($\partial X/\partial T$ cannot be computed).)

One of the problems with any statistical method is that one must have meaningful variation in the T variables to identify their effects. This often means resorting to data with broad geographic or time series dimensions. Such data are sometimes poorly suited to estimating production parameters. The TFP decomposition specification often has an advantage in these situations because production parameters are implicit in the TFP computations based on prices. With reasonable price data, TFP indexes can be computed over time and in some situations over cross-sections.[8] This may allow better estimates of T effects on productivity, $\partial(Y/X)/\partial T$.

The richest specification is the duality-based specification, (3). It has the advantage that independent variables are exogenous and it allows estimates of T impacts on all endogenous variables in the system.[9]

The partial productivity framework suffers from the obvious fact that these measures are affected by other factors not included in the denominator. Nonetheless, given widely available yield and area data, some useful studies can be undertaken in this framework.

[8] Approximations to a Divisia index (Tornqvist/Theil) are generally regarded to be the appropriate TFP calculation method. Some growth accounting adjustments to inputs can affect the estimates of T parameters in (4). For example, adjustments for capital stock quality may effectively remove some of the contributions of research from the TFP measure. Many studies adjust for labor quality using schooling data. This, of course, eliminates the possibility for estimating schooling effects in (4), but it may improve prospects for estimating T effects because schooling S can be dropped from (4).

[9] This specification is also the most demanding of data.

2.2. Technological infrastructure and institutions

Agricultural extension and research programs contribute to economic growth in an interactive way. The contribution of each depends on the developmental stage of the economy. Both are subject to diminishing returns. To aid in clarifying these points, consider Figure 1. Here, five different stages or levels of technology infrastructure are considered. For each, a set of yield levels is depicted for a typical crop. These yield levels should be considered to be standardized for fertilizer, water, labor, and other factor levels.

Four yield levels are depicted. The first is the actual yield (A) realized on the average farmer's fields. The second is the "best practice" yield (BP) which can be realized using the best available technology. It is possible that some farmers obtain best practice yields but the average farmer does not. The third yield level is the "research potential" (RP) yield, i.e., it is the hypothetical best practice yield that would be expected to be attained as a result of a successful applied research program directed toward this crop. The fourth

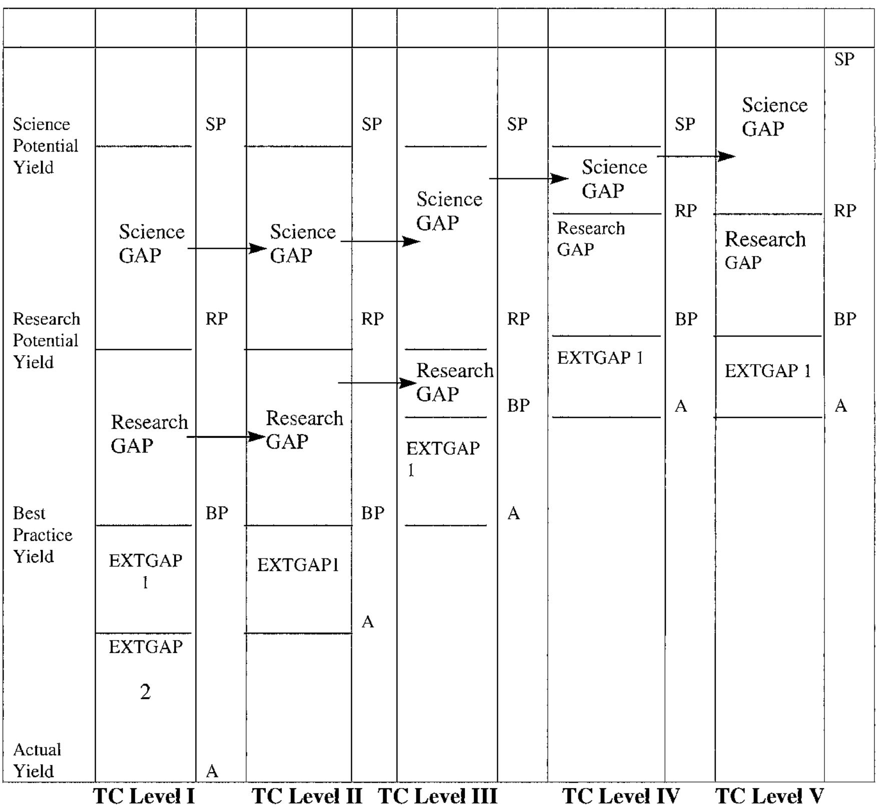

Figure 1. Schematic crop yields (and GAPs) by technological capacity level.

is the "science potential" (SP) yield. This is also a hypothetical yield. It is the research potential yield attainable if new scientific discoveries (e.g., in biotechnology) are made and utilized in an applied research program.

Associated with these yields we can define three "gaps". The "extension gap" is the difference between best practice (BP) and average (A) yields. Extension programs are designed to close this gap. The "research gap" is the difference between research potential (RP) yields and best practice (BP) yields. Applied research programs, if successful, will close this gap (and will thus open up the extension gap). Similarly, a "science gap" exists between science potential (SP) and research potential (RP) yields.

Consider technology infrastructure stage I. This is a stage where little extension, research or science is being undertaken. Farmer schooling levels are low, markets are poor and infrastructure lacking.[10] The extension gap is large in this stage and thus there is considerable scope for a high payoff to extension, even if there are few effective research programs that are raising best practice yields. After extension programs have achieved a transition to stage II, the extension gap will have been reduced to some fraction of its original size (EXTGAP 1). The gains from reducing the original gap (EXTGAP 2) may be quite large and they are "permanent" in the sense that they are long-term gains that could not have been produced by other programs (at least not in a short time period).

Once an economy achieves stage II, it has exploited EXTGAP 2. There is further scope for extension contributions but they are not what they were in stage I (EXTGAP 1). In fact, the economy now becomes dependent on the closing of the research gap to open up the extension gap. As the economy is transformed from stage II to stage III a direct link between research and extension is forged. Extension programs now become responsible for extending relatively newly developed technology to farmers.

When pre-invention science becomes more effective, the research potential yield (RP) is raised and with active research and extension programs the economy may move into stage IV. Further progress, i.e., to stage V and beyond, depends on effective pre-invention science, research and extension programming.

Consider the situation in Africa and Asia. It appears that much of Africa has not made the transition yet to stage II and there is limited evidence that it has achieved a transition to stage III where research systems are producing significant flows of new technology suited to farmers in most regions. This is in contrast to the situation in both South and Southeast Asia where by the mid-1960s many economies were already in stage II and where "green revolution" technology in rice, wheat, corn, and other crops has enabled them to make the transition to stage III. Today, in some Asian countries, there are prospects for moving to stage IV.

It is possible that spill-ins from abroad can raise best practice yields before economies have made the transition to stage II. Most research gains, however, have been realized in economies that have already achieved stage II market, infrastructure, and skill levels. In some cases this has been induced by the development (often in international centers) of

[10] Many countries in sub-Saharan Africa fit this description.

genetic resources and methods that increase the RP yield levels. In Africa these RP yield levels for some countries may be quite low because of limited genetic resources and difficult disease and insect problems, so that the research gap is actually quite small. If this is the case, "stimulus from above" in the form of improvements in science (closing of the science gap) may be required to achieve better research performance.

2.3. Formal models

The economics literature includes models of technology diffusion, of invention, and of growth. In practice, these literatures are not well integrated. Technology diffusion (adoption) models typically consider technology to have already been produced and address the mechanisms of diffusion – usually employing a logistic or sigmoid functional form. Models of invention do integrate research and extension activities and are probably most useful for providing structure for the activities discussed in an informal way in Figure 1. The "new endogenous growth" literature has some insights to offer as regards R&D and invention but does not effectively integrate the invention model perspective into formal growth models.[11]

As noted earlier, extension programs are designed to (a) provide general technical adult education services and (b) to facilitate the evaluation and adoption of recently developed technology. The technology diffusion literature specifies a logistic form for the adoption of technology:

$$T_i^* = 1/\big(1 - \exp(a + bt + c\mathrm{EXT})\big). \tag{6}$$

This functional form is relevant to adoption studies (the second function of extension) but not necessarily to studies where the first function of extension is important.[12]

Invention models can be combined with diffusion specifications, but typically are not. Consider an invention discovery model based on a simple random search model. For a given distribution of potential inventions the probability of making an invention for the n th draw from any distribution is $1/n$. A new invention must have a higher quality index (e.g., the yield of a plant variety) than previously discovered inventions. The expected cumulative number of inventions from n experiments (or draws) in a given distribution is:

$$\mathrm{E}(I)n = \sum_{\ell=1}^{n} \frac{1}{i} \approx G + \ln(n). \tag{7}$$

[11] The models of Romer (1986, 1990) provide a serious treatment of invention but do not effectively address spillovers.

[12] This is usually estimated by taking logarithms [Feder et al. (1985)].

This expression for research discoveries was first derived by Evenson and Kislev (1975) for an exponential distribution of potential inventions. Kortum (1994) generalized this expression for any search distribution.[13]

Expression (7) relates inventions (I) to research (n). Empirical work relating research to productivity requires the further step of relating inventions to productivity. Kortum (1994) derives the standard relationship between research and productivity used in industrial studies

$$\ln(\mathrm{TFP}) = \lambda \ln(\mathrm{RESS}), \tag{8}$$

where RESS is the cumulated research stock (net of depreciation).[14]

Since empirical studies are undertaken using data where extension services are not constant and where the underlying parameters of applied invention search are also not constant, the empirical specification should be extended to include extension variables and pre-invention research variables.

Extension has two effects on productivity. Most importantly, it speeds up the rate of adoption of inventions by farmers. This role is subject to diminishing returns in a manner similar to invention, calling for a ln(EXT) term. However, extension can influence inventions as well. It can facilitate inventions by conveying farmer evaluation signals to inventors more rapidly. It can also help inventors to identify unpromising search avenues, and this changes the parameters of the underlying invention search distribution. This argues for a $\ln(\mathrm{EXT}) \times \ln(\mathrm{RESS})$ term.

$$\ln(\mathrm{TFP}) = a + b\ln(\mathrm{RESS}) + c\ln(\mathrm{EXT}) + d\ln(\mathrm{RESS})\ln(\mathrm{EXT}). \tag{9}$$

Pre-invention science is designed to change the parameters of the underlying search distribution as well. These discoveries may shift the mean of the underlying search distribution leading to an added term for pre-invention science.

$$\ln(\mathrm{TFP}) = a + b\ln(\mathrm{RESS}) + c\ln(\mathrm{EXT}) + d\ln(\mathrm{RESS})\ln(\mathrm{EXT}) + e\ln(\mathrm{PRINV}). \tag{10}$$

Pre-invention science may also shift the variance of the underlying distribution as well, calling for an added interaction term in TFP decomposition specifications.

$$\begin{aligned}\ln(\mathrm{TFP}) = {} & a + b\ln(\mathrm{RESS}) + c\ln(\mathrm{EXT}) + d\ln(\mathrm{RESS})\ln(\mathrm{EXT}) \\ & + e\ln(\mathrm{PRINV}) + f\ln(\mathrm{PRINV})\ln(\mathrm{RESS}).\end{aligned} \tag{11}$$

[13] This semi-logarithmic approximation is accurate when n is large.

[14] Evenson and Kislev (1975) utilized an exponential distribution of potential inventions. They showed that the logarithmic approximation held for this distribution as well.

Few of the studies reviewed below were motivated by the model described here. It does, however, have some functional form implications, and while they were generally not imposed or even recognized in reported studies, the interpretative insights of the model will be useful in discussing the findings of the studies.[15]

2.4. *Specifying research and extension variables in empirical studies*

Most of the studies reviewed in subsequent sections utilized a statistical specification of one of the production frameworks discussed above. This requires the development of research and extension variables that are appropriate to the unit of observation. These variables are conceptually similar to capital stock variables that measure capital service flows to the unit of observation. The observation may be a farm or an aggregate of farms. Production or productivity may be measured in level form or in rate-of-change form. The observation is typically for a given location and period.

Research and extension service flow variables then need to consider time weight, spatial weight, and deflator issues.

2.4.1. *Time weights*

Research and extension programs have economic impacts that typically last for more than one period. Accordingly, the services provided by these programs to a given location in a given period may be based on research and extension activities undertaken in prior periods.

Figures 2a and 2b depict alternative extension and research "time shapes". Consider the extension weights (Figure 2a). Two cases for the effects of extension activity in time t_0 on technology adoption patterns are depicted. In case 1, applicable to advanced technology infrastructure levels (see Figure 1), good substitutes for extension activities exist. Accordingly, productive technology will eventually be fully adopted in the absence of the extension program. The technology will be adopted earlier, given the presence of an extension program.

In case 2, applicable to low levels of technological infrastructure (e.g., stage 1, Figure 1), good substitutes for extension programs do not exist. In this case, productive technology may not be fully adopted in the absence of extension programs. Extension then has both a speeding-up effect and a level effect.[16]

The "time-shape" weights associated with these two extension cases will depend on the production framework used. If the dependent variable is the level of production or of partial productivity, the time weights are as depicted in panels 1.1 and 2.1. For case 1,

[15] Note that this model is not a simple "linear model of science" where PRINV recharges the invention pool and inventions determine the productivity of extension. Extension and research have "upstream" effects. However, the idea of exhaustion of invention pools, or of attempting to invent when the pool has not really been created, is relevant to research policy making.

[16] The level effect can be seen as exploiting EXTGAP 2.

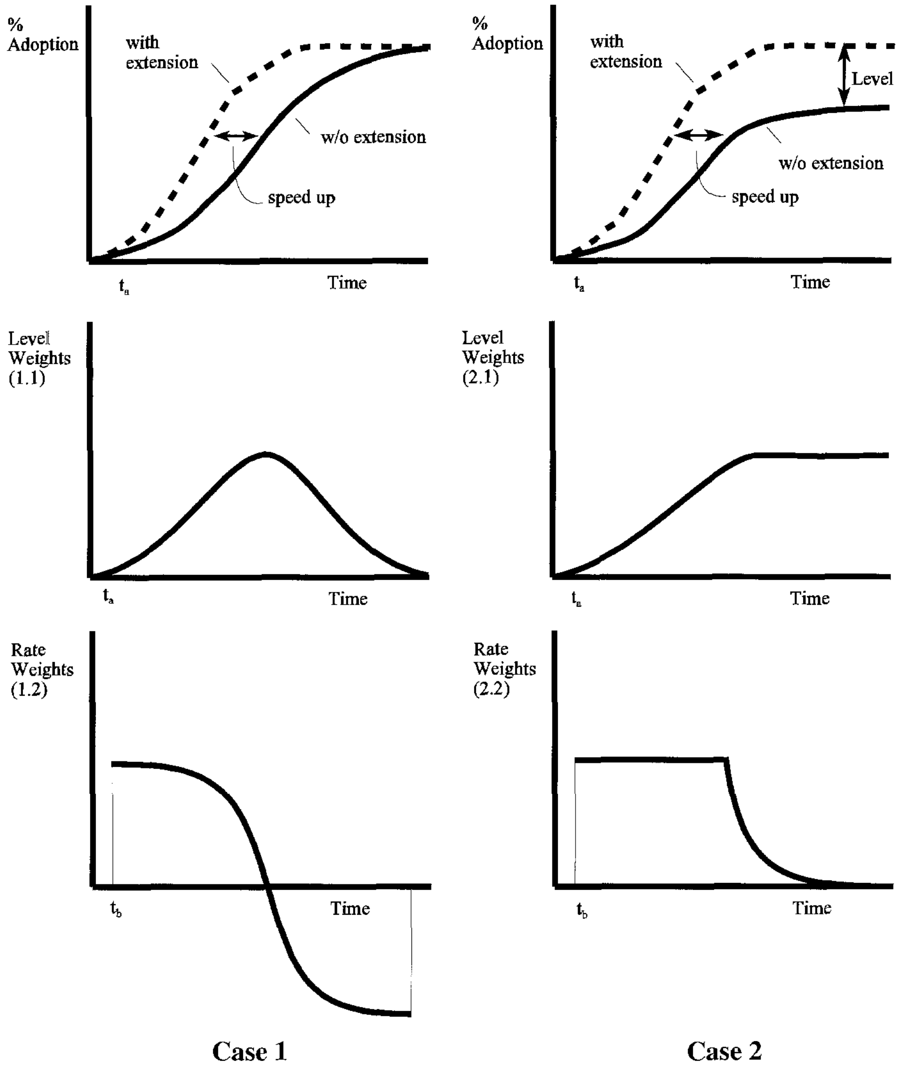

Figure 2a. Extension time shapes.

extension activity conducted prior to period $t - t_a$ is not relevant to the observation. For case 2 all prior extension may be relevant.

When the dependent variable is a rate of change as in a first difference or a change in a TFP index, the time weights are as depicted in panels 1.2 and 2.1. Note that in panel 1.2 there are negative weights for extension in some prior periods. This illustrates the fact that when extension has merely a speeding-up effect it does not actually have a net

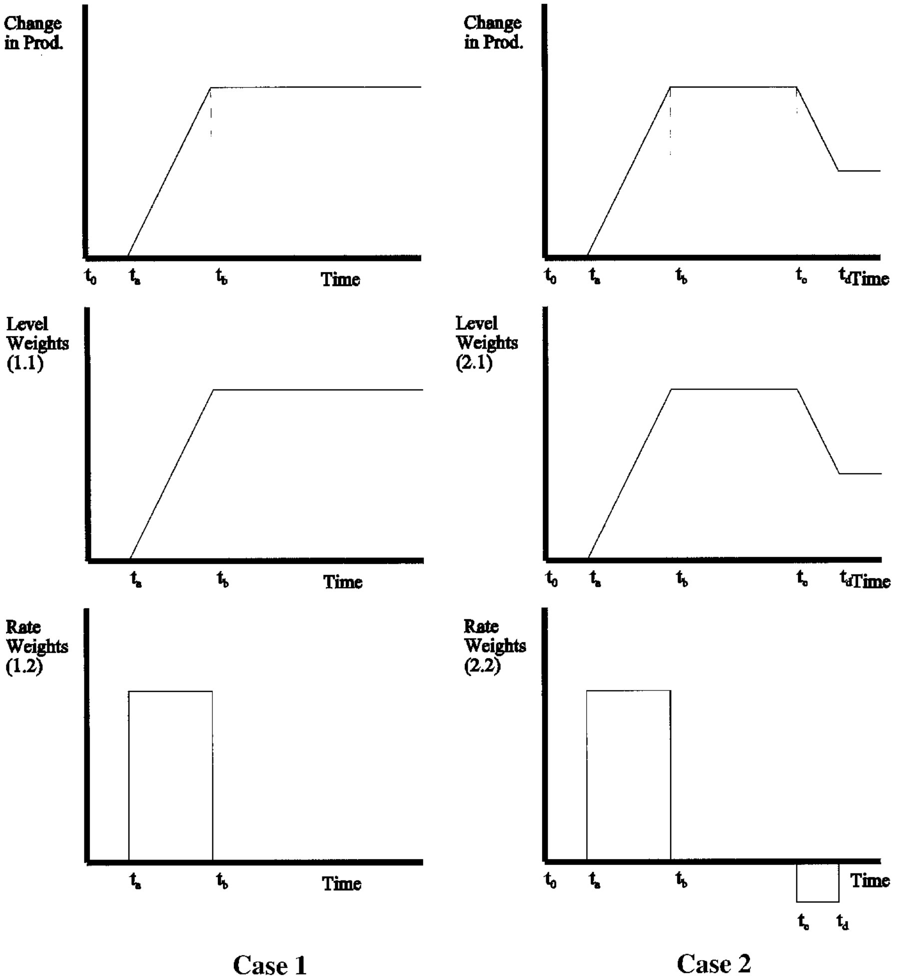

Figure 2b. Research time shapes.

effect on the growth in production or productivity. For case 2 it does have an effect on the level of production and on growth.

Many of the studies reviewed here utilized a total factor productivity (TFP) decomposition framework where production data were first used to compute a TFP index. Then in a second stage this TFP measure is regressed on research and extension variables. Often the TFP measure is set at some level (1 or 100) in the base period (t_b) and then annual changes are "cumulated" in future periods. For this case the time shape weights are as depicted in panels 1.2 and 2.2 for the period $t_{b+1} - t_b$ and cumulated for subsequent periods. This produces a time shape similar to the shape depicted in panels 1.1 and 1.2 except that there is a cut-off in past activities associated with the date t_b.[17]

Research service time shape weights are also depicted for two cases (Figure 2b). In case 1 research activity in t_0 has future impacts that are depicted in three segments:[18]

segment a from t_0 to t_a in which no impact is realized

segment b for t_a to t_b in which a rising impact is realized

segment c from t_0 to ∞ in which the effect is constant

In case 1, research service impacts (in the form of inventions adopted) do not "depreciate". They may become obsolete (i.e., replaced by improved inventions), but the improved inventions "build on" the inventions they displace. Thus the original inventions "live on" as part of the inventions that displace them.

In research case 2 real depreciation of inventions takes place as depicted in the segment d. This may be due to such factors as pest and pathogen responses to host plant resistance breeding improvements, or to incomplete "building on". After some point (segment e) research activity at t_0 will be "buried" in future productivity levels.[19] This is reflected in the time weight panels 1.1 and 2.2. As with extension, when the production structure is in rate of change form, the time shapes are quite different (panels 1.2 and 2.2). When cumulated TFP measures are used there is a cut-off on early research that is buried (segment c in case 1 or e in case 2) before t_b, the beginning date of the TFP series. It is not appropriate to include this research (or extension) in the estimation.

Strategies for estimating time weights include:

(a) "free form" estimates obtained by including a number of lagged research and/or extension variables;

(b) "segment length" estimates obtained by constructing alternative lengths of the segments depicted in Figures 2a and 2b and undertaking an iterative search over segment lengths to minimize mean square error (a form of non-linear least squares estimation [Evenson (1968)]);

(c) "distributed lag" estimates obtained by imposing a functional form on the time shape – such as a Nerlovian exponentially declining structure as a quadratic or other form.

[17] That is, activities that affected only the base period and prior periods are inappropriate in the specifications because they only affect the constant term.

[18] Note that these segments are not arbitrary. Research programs do not produce immediate impacts. Their contributions rise to a peak after several periods. Utilizing a distributed lag specification that does not recognize this logic can give very misleading estimates of the lag structure.

[19] The contribution is buried in the sense that its contribution is no longer affecting current inventions or improvements even though the original invention may have been quite important.

Free form lag estimates are generally not very satisfactory because with high multicollinearity between lagged research variables, coefficients tend to oscillate between positive and negative values and only make sense when smoothed.

Distributed lag estimates can impose very strong structure on time shapes, especially when improper or redundant (buried) lagged research is included in rate of change specifications.[20]

The segment length method, while crude, does allow flexibility in segment lengths while imposing reasonable shape weights for segments. (It is plausible that some form of non-parametric estimates would be an improvement.)[21]

2.4.2. Location spill-ins – spatial weights

Research and extension services have locational spill-overs. A geographic unit of observation is likely to receive services (spill-in) from activities located outside its geographic boundaries. These must be considered in developing research and extension variables.

Extension variables are perhaps easiest to deal with. Most extension services have a multi-level structure. Field staff are typically assigned to a region and to a set of client farms. Supervisory staff and subject matter specialists are typically assigned to cover more than one field staff unit. Field staff services from one region typically do not flow or "spill in" to other regions. However, subject matter specialist services probably do. This problem for extension is generally dealt with in the context of defining "extension services supplied" variables (see Section 3).[22]

For research variables the problem of spatial weights is more serious, especially as many research studies utilize repeated cross-section observations. These observations

[20] If buried research activities are included in a free form estimation specification they are essentially redundant variables. If they are included in a distributed lag specification with a polynomial or other form they can have a significant effect on time weight estimates. A recent paper by Alston et al. (1998a) claims that when "appropriate" estimation techniques are used, rates of return to research and extension are actually quite low. Their specification amalgamates research and extension time weights and includes buried activities in activities that do not contribute to TFP growth after 1950. Their free form estimates of lag weights show high rates of return. Imposing a polynomial specification with the buried activities down-weights more recent lags. This results in a substantial downward bias in rate of return estimates.

[21] The segment length method entails systematically searching for the segment length combination that minimizes means square error.

[22] Fixed effects estimations where spatial dummy variables are incorporated into the specification can have important effects on spill-in. For example, in two recent World Bank studies of Training and Visit (T&V) extension in Kenya, fixed effects in the form of district dummy variables altered the results. In the original study Evenson and Bindlish (1993) argued that using district dummy variables would essentially eliminate most of the relevant cross-section variations for the farms in the seven-district study. District dummies do not allow for "between district" variation. If there are substantial within-district spillovers from the subject-matter specialist and supervisory structure of the T&V system, within-district variation in staffing levels will capture little of the real differences in extension service. In later work Gautam and Anderson (1998) show that including district dummy variables does eliminate much of the correlation between extension services and farm productivity.

must be appropriately matched with the locations where applied research is conducted. Most large national research systems are organized by political region (e.g., the state system in the U.S.) and thus each research center can often be associated with a region. However, units of observation in one region (state) may benefit from research done in another region even when they are not the clients of the other region. They may benefit in two ways:

(1) Farmers may directly adopt inventions made in and for the other region, and
(2) Researchers in the region may experience enhanced research productivity because of inventions made in the other region. (See (11) and (12) where b could be changed by inventions made in the other regions.)

Spatial spill-in has been handled in three ways in the studies reviewed. Many studies have either ignored the issue or implicitly argued that spill-ins are roughly offset by spill-outs. A number of studies have utilized geo-climate region data to specify spillovers. A small number have defined spill-over barrier measures and used these to specify spillovers.

The geo-climate region methodology is similar to the segment length estimation for time weights. Evenson (1969), Welch and Evenson (1989), and Huffman and Evenson (1993) utilized geo-climate region and sub-region data to define the research stocks for a unit of observation i as:

$$R_i = \sum_j S_{ij} R_j, \tag{15}$$

where the spatial weights (S_{ij}) measured the relative importance of the neighboring research locations to region i. Searches over S_{ij} weights have also been combined with searches over time segment weights.[23]

The use of spillover barrier indexes in a few studies suggests that these are a convenient means for estimating spatial weights over a number of locations. The spillover barrier between two locations i and j is defined as:

$$\mathrm{SPB}_{ij} = 1 - C_{ij}/C_{ii}, \tag{16}$$

where C_{ii} is the minimum cost of producing the good in location i using the best (cost-minimizing) technology available to location i, and C_{ij} is the minimum cost of producing the good in region i when producers are constrained to use location j's minimum cost technology.

Crop yield trial data, where a common set of cultivars are planted in different locations, enable one to actually measure SPB_{ij} by comparing yields in location i of the

[23] This procedure is used in [Huffman and Evenson (1993)].

highest yielding cultivar in location i with the yield in location i of location j's highest yielding cultivar.[24] The actual spill-in variable can then be estimated as:

$$R_j = \sum_j (\mathrm{SPB}_{ij})^{\alpha} R_j, \tag{17}$$

where α can be estimated by non-linear techniques.[25]

2.4.3. Deflators

Deflators are needed for extension service variables for two purposes:

(1) To put financial data (expenditures) into constant currency units, and

(2) To account for farm contact heterogeneity.

The typical extension deflator is the number of farms or of areas served (see Section 3).

Deflators for research variables are also required to put financial data into constant currency units and to correct for diversity not captured by spillover measures (see Section 4).

3. Studies of agricultural extension impacts

Studies of agricultural extension impacts can be grouped into three categories:

A. Studies based on farm-level (cross-section) observations where extension services vary by observation but where it is presumed that research services do not vary by observation (Tables 1 and 2).

B. Studies based on aggregated farm production data (e.g., a district, country or state) usually in a cross-section framework, where both extension and applied research services are specified to vary by observation (and where research variables are included along with extension variables) (Table 3).

C. Studies based on aggregated farm data (usually repeated cross-section) where for reasons of data availability a variable measuring the combined services of research and extension is constructed (Table 4).

In this part, studies of the first two categories are reviewed. Discussion of the studies using a combined research-extension variable is deferred to Section 4 where research variables are discussed in more depth.

Cross-section studies based on farm-level observations where research services can be considered to be constant over observations and where extension services vary should

[24] Evenson (1992) developed SPB indexes using international yield trial data for rice and applied them to spillover estimates in India. Da Cruz and Evenson (1997) used similar procedures for Brazil.

[25] An alternative way to scale the SPB weights is $\mathrm{SPB}_{ij}^{\alpha-\gamma}$. This can also be estimated with non-linear techniques.

Table 1
Extension economic impact studies: Statistical methods: Farm as unit of observation; farm specific extension variables

Study	Country	Period of study	Production structure	Extension variable	IRR	Comments
Lever (1970)	Botswana	1969	MPF	Years extension available	nc	Low stat. significance
Harken (1973)	Japan	1972	MPF	Use of media by farms	nc	Path analysis
Moock (1973)	Kenya	1972	PD(Y)	Extension contact factor	nc	Factor analysis
Patrick and Kehrberg (1973)	Brazil	1972	MPF	Extension contacts	42–100+	
Hopcraft (1974)	Kenya	1973	MPF	Extension visits	nc	Demonstrations, visits (maize)
Hopcraft (1974)	Kenya	1973	MPF	Training courses, demonstration	nc	
Moock (1976)	Kenya	1974	PD(Y)	Index of contacts, visits, courses	nc	Significant for low schooling (maize)
Pachico and Ashby (1976)	Brazil	1974	MPF	Extension contacts	nc	n.s. (rice)
Cotlear (1986)	Peru	1975	MPF	Extension contact dummy	nc	Potatoes
Halim (1976)	Philippines	1975	MPF	Extension contacts prior years	nc	(rice)
Capule (1977)	Philippines	1975	MPF	Hours by farmer in extension contacts	nc	n.s. (rice)
Jamison and Lau (1982)	Malaysia	1980	MPF	Exposure to adult education courses	nc	n.s. (rice)
Pudasaini (1983)	Nepal	1982	MPF	Extension contacts	nc	n.s. (rice, maize)
Jamison and Moock (1984)	Nepal	1982	MPF	Dummy – recent contact	nc	n.s. (rice)
Perraton et al. (1985)	Malawi	1984	PD(Y)	Extension visits to farmers	nc	(maize)

Table 2
Extension economic impact studies: Statistical methods: Farm as unit of observation; extension supply variables

Study	Country	Period of study	Production structure	Extension variable	IRR	Comments
Hong (1975)	Korea	CS(895)	MPF	Extension spending in region	nc	(rice)
Jamison and Lau (1982)	Thailand	CS(184)	MPF	Extension available to village	nc	(non-chemical uses)
Jamison and Moock (1984)	Nepal	CS	MPF	Proportion of village farmers contacted	nc	(wheat)
Feder et al. (1985)	India	1984	PD(Y)	Dummy – extension type service	Low to high	(rice)
Feder et al. (1985)	India	1984	MPF	T&V management experiment	15+	T&V advantage
Cotlear (1986)	Peru	1985	MPF	Proportion hh's in village center	nc	S.S. in tradition region (potatoes)
Chou and Lau (1987)	Thailand	1985	MPF	Dummy: extension service to village	nc	n.s.
Deaton and Benjamin (1988)	Cote d'Ivoire	1986	PD(Y)	Dummy: extension agent available	nc	n.s.
Evenson (1988)	Paraguay	1988	PD(Y)	Hours Extension/Hectare	75–90	S.S. major crops
Evenson and Bravo-Ureta (1994)	Paraguay	1989	ED	Hours Extension/Hectare	nc	Coffee, casava, corn frontier methods
Evenson and Bindlish (1993)	Kenya	1990–91	MPF	Extension/Staff/Farm	100+	timing estimated
Evenson and Bindlish (1993)	Kenya	1982	MPF	Extension/Staff/Farm	88	Pre T&V
Evenson et al. (1995)	Burkina Faso	1991	MPF	Extension/Staff/Farm	91	T&V extension

Table 3
Extension economic impact studies: Statistical methods: Aggregate farms as unit of observation

Study	Country	Period of data	Production structure	Extension variable	IRR
Evenson and Jha (1973)	India	1953–57 CS	PD	Maturity rating district	14
Mohan and Evenson (1975)	India	1955–71 CS	PD	Presence of IADP	15
Huffman (1974)	USA	1959–74 CS	MPF	Extension staff/farm	16
Huffman (1976)	USA	1964 CS	MPF	Staff days/farm	110
Evenson (1979)	USA	1971 CSxTS	PD	Expenditures/region	100+
Huffman (1981)	USA	1979 CS	MPF	Extension days/county	110
Pray and Ahmed (1991)	Bangladesh	1951–61 CSxTS	MPF	Expenditure/district	nc
		1977–86 CSxTS	MPF		nc
Norton & Paczkowski (1993)	USA (Va)		MPF		52
Evenson (1992)	Indonesia	1971–89	PD	Expenditure/farm	92
Librero and Perez (1987)	Philippines	1956–83 CSxTS	MPF	Expenditure/province	nc
Setboonsarng and Evenson (1991)	Thailand	1953–71 CS-TS	PD(Y)	Expenditure/farm	nc
da Cruz et al. (1982)	Brazil	1970–75–80 CS-TS	PD	Expenditure/farm	nc
Evenson (1987)	Latin America	1960–82 CSxTS	PD(Y)	Ext.Ex/geo-climate region	0–80+
	Africa	1960–82 CSxTS	PD(Y)	Ext.Ex/geo-climate region	34–80+
	Asia	1960–82 CSxTS	PD(Y)	Ext.Ex/geo-climate region	80+
Evenson & McKinsey (1991)	India	1956–83 CSxTS	PD(Y)	Expenditure/farm	
	India	1956–83 CSxTS	PD(Y)	Wheat	82
	India	1956–83 CSxTS	PD(Y)	Rice	215
	India	1956–83 CSxTS	PD(Y)	Jowar	167
	India	1956–83 CSxTS	PD(Y)	Bajra	201
	India	1956–83 CSxTS	PD(Y)	Maize	56
	India	1956–83 CSxTS	PD(Y)	All	176
Evenson (1994)	USA	1950–72 CSxTS states	PD	Expenditure/state	Crops 101
	USA	1950–72 CSxTS states	PD	Expenditure/state	Livestock 89
	USA	1950–72 CSxTS states	PD	Expenditure/state	All 82
Evenson and Avila (1996)	Brazil	1970 1970–85 CSxTS	PD	Predicted extension contacts	Crops 33 Livestock 23 Aggregate 19
Evenson and Quizon (1991)	Philippines	1948–84	PD	Expenditure/farm	Positive (low)
Norton and Paczkowski (1993)	USA (Va)	1993	MPF		37

Table 4
Economic impact studies combining extension and public research

Study	Country	Period of analysis	Commodity	Production structure	IRR
Elias (1971)	Argentina	1943–63	Sugarcane	MPF	33–49
del Rey (1975)	Argentina	1943–63	Sugarcane	MPF	35–41
Pray (1978)	Punjab (India)	1906–56	Aggregate	MPF	34–44
	Punjab (Pakistan)	1948–63	Aggregate	MPF	23–37
Avila (1981)	Brazil	1959–78	Rice	MPF	83–119
White and Havlicek (1982)	USA	1943–77	Aggregate	MPF	7–36
Lu et al. (1979)	USA	1939–72	Aggregate	MPF	25
Zentner (1982)	Canada	1946–79	Wheat		30–39
Evenson (1979)	USA	1948–71	Aggregate	MPF	110
Nagy (1983)	Pakistan	1967–81	Maize	MPF	19
	Pakistan	1967–81	Wheat	MPF	58
Feijoo (1984)	Argentina	1950–80	Aggregate	MPF	41
da Silva (1984)	Brazil (Sao Paulo)	1970–80	Aggregate	MPF	60–102
Ayers (1985)	Brazil	1955–83	Soybeans	MPF	23–53
Nagy (1985)	Pakistan	1959–79	Aggregate	MPF	64
Khan and Akbari (1986)	Pakistan	1955–81	Aggregate	MPF	36
Norton et al. (1987)	Peru	1981–87	Aggregate		17–38
Scobie and Eveleens (1987)	New Zealand	1926–84	Aggregate	PD(Y)	30
Harvey (1988)	U.K.	1988	Aggregate		38–44
Setboonsarng and Evenson (1991)	Thailand	1991	Rice	MPF	40
Sterns and Bernsten (1994)	Cameroon	1979–91	Row pea	PD(Y)	3
	Cameroon	1979–91	Sorghum	PD(Y)	0
Howard et al. (1993)	Zambia	1978–91	Maize	PD(Y)	84–87
Kupfuma (1994)	Zimbabwe	1932–40	Maize	PD(Y)	43.5
Mudhara et al. (1995)	Zimbabwe	1970–95	Cotton	PD(Y)	47

offer a good "with/without" experimental design setting in which to measure economic impacts. In cases where panel data for the same farms over time can be utilized, a "before/after" design element is added. A before/after comparison might be made when extension programs were first introduced. However, the only panel farm-level data studies surveyed here of the before/after type attempted to measure the qualitative effect of a change in the design and management of extension from the traditional design to the Training and Visit (T&V) management implemented in World Bank funded extension projects in India [Feder et al. (1985)] in the early 1980s and in Kenya [Evenson and Bindlish (1993)] and Burkina Faso [Evenson et al. (1995)] in the late 1980s.[26]

[26] In one sense, the best opportunity to achieve a before/after statistical design is at the time when extension programs are first introduced. The effect of a change in design as in the case of T&V management is difficult to measure.

Tables 1 and 2 report summaries of the farm observation studies. All studies reported estimated coefficients for an extension variable. The production structure used most frequently was the aggregate meta production function although several used productivity (yield) decomposition. Most studies reported statistical significance. Only a few studies actually calculated an internal rate of return (IRR), the measure of impact used to compare studies in this review.

The studies summarized in Table 1 utilized a farm-level or farm-specific extension variable. This was typically an index of extension-staff–farm contact either in visits to the farm by extension staff or in farmer visits to extension meetings or demonstrations. Birkhaeuser et al. (1991), among others, have noted that this variable is subject to endogeneity bias. This is because at least some of the contacts are farmer-initiated. If one observes that more efficient farms have more extension contact, one cannot conclude that extension contact caused the efficiency difference. It may simply reflect the demand for information by the more efficient farmers.

A second form of endogeneity bias in farm-specific extension variables may be due to extension staff selectivity (i.e., the staff contact the best farmers more frequently). The remedy for this problem is to use a statistical procedure to deal with it (instrumental variables or 2SLS, 3SLS in a structural model). Only four of the studies covered in Table 1 utilized this remedy. These four studies did find statistically significant extension impacts, but taken as a group, Table 1 studies do not provide overwhelming evidence for large extension contributions. Many of these studies were early (pioneering) studies, however, that contributed insights to later studies.

The extension studies summarized in Table 2 addressed the endogeneity problem with the extension variable by creating variables measuring "extension services supplied". For some studies this variable took the form of a dummy variable indicating whether a community had extension services supplied to it. For others it was a measure of services supplied per farm or per unit of land area for a defined extension region. These variables were not farm-specific, but were assigned to each farm observation in the extension region.

The extension services variables, as noted, were typically deflated by the number of farms.[27] In addition time weights in some studies were estimated using the segment length method. The India, Burkina Faso, and Kenya studies all concluded that there were significant level segments (see Figure 2, case 2) and that the extension programs were probably mining EXTGAP 2 (see Figure 1). These three studies were of extension systems in countries with relatively low technology infrastructure levels.

[27] The "fixed effects" estimation issue is important here. Suppose there are district and sub-district extension programs. One can develop sub-district staff farm variables. District fixed effects will remove all between-district variation. Yet there may be important and real differences in the district programs because of spatial spillovers over sub-district programs. District fixed effects will remove them. [See Evenson and Bindlish (1993) and Gautam and Anderson (1998)].

Several of the studies in Table 2 (including the T&V extension studies) report relatively high rates of return to investment. These rates of return were based on the time weights, deflators, and estimated coefficients.[28]

Table 3 summarizes studies that were based on aggregated data. In some cases [Huffman (1974); Huffman (1981); da Cruz et al. (1982)] the data were district, municipal or state averages compiled from Census of Agriculture data. In other cases production and input data from different sources reported for the district and state level were utilized. One study was international. All of these studies included both research and extension variables and in some cases schooling variables as well (research variable estimates from these studies are summarized in Section 4).

Several of the studies summarized in Table 3 were for a single cross-section, but most were for pooled cross-section-time-series data (or repeated cross-sections). The option of a farm-specific extension variable was not available to these studies and most used a staff or expenditure per farm or area ratio. Several imposed time weights. Several estimated time weights using the segment technique noted above.

Most of the studies summarized in Table 3 reported rate of return calculations. These, of course, are marginal rates of return since they are based on coefficients estimated for the extension variable (sometimes interacted with other variables). The rate of return was typically calculated by simulating a one dollar increase in extension expenditure in time t, then calculating the change in the extension variable in subsequent periods from this investment utilizing the time weights. The estimated coefficient for the extension variable then enables one to construct the "benefits stream" associated with the investment (multiplying by the units affected), and the IRR is calculated from this.

When these estimated rates of return are considered along with the Table 1 and 2 estimates, the general picture suggests a broad range of economic impacts ranging from negligible impacts to very high impacts. Table 4 summarizes studies where the technology variable was based on combined extension and research data. These estimated rates of return range from modest to very high. They will be discussed further in the next section.

4. Studies of applied agricultural research (public sector)

The studies reviewed in this section can be categorized into two groups. The first group of studies adopted a "project evaluation" approach and these report "average" IRRs (see Table 5).[29] The second group adopted a statistical estimation approach utilizing one of the production structures described above. This entailed the construction of a

[28] The time weights are important in calculating rates of return to investment. The benefits stream from a given investment depend on these weights. The procedure for computing the benefits stream is to simulate the productivity gains from an expenditure increase in time t for future periods.

[29] Other reviewers describe these studies as using an "economic surplus" methodology. This is not very satisfactory since all studies calculate benefits in terms of economic surplus.

Table 5
Economic impact studies: Public sector. Agricultural research: Project evaluation methods

Study	Country	Commodity	Period	IRR%
Griliches (1958)	USA	Hybrid corn	1940–1955	35–40
Griliches (1958)	USA	Hybrid sorghum	1940–1957	20
Grossfield and Heath (1966)	U.K.	Potato harvester	1950–1967	High NPV computed
Peterson (1967)	USA	Poultry	1915–1960	21–25
Evenson (1969)	South Africa	Sugarcane	1945–1962	40
Barletta (1970)	Mexico	Wheat	1943–1963	90
Barletta (1970)	Mexico	Maize	1943–1963	35
Ayer (1970)	Brazil	Cotton	1924–1967	77+
Schmitz and Seckler (1970)	USA	Tomato harvester	1958–1969	37–46
Ayer and Schuh (1972)	Brazil	Cotton	1924–1967	77–110
Hines (1972)	Peru	Maize	1954–1967	35–40
Monteiro (1975)	Brazil	Cocoa	1923–1975	16–18
	Brazil	Cocoa	1958–1974	60–79
	Brazil	Cocoa	1958–1985	61–79
Fonseca (1976)	Brazil	Coffee	1933–1995	23–25
Hayami and Akino (1977)	Japan	Rice	1915–1950	25–27
Hayami and Akino (1977)	Japan	Rice	1930–1961	73–75
Hertford et al. (1977)	Colombia	Soybeans	1960–1971	79–96
	Colombia	Wheat	1953–1973	11–12
	Colombia	Cotton	1953–1972	None
Pee (1977)	Malaysia	Rubber	1932–1973	24
Peterson and Fitzharris (1977)	USA	Aggregate	1937–1942	50
	USA	Aggregate	1947–1952	51
	USA	Aggregate	1957–1962	49
	USA	Aggregate	1957–1972	34
Wennergren and Whitaker (1977)	Bolivia	Sheep	1966–1975	44
	Bolivia	Wheat	1966–1975	−48
Pray (1978)	Punjab (British India)	Research and extension	1906–1956	34–44
	Punjab (Pakistan)	Research and extension	1948–1963	23–37
Scobie and Posada (1978)	Bolivia	Rice	1957–1964	79–96
Kislev and Hoffman (1978)	Israel	Wheat	1954–1973	125–150
		Dry farming		94–113
		Field crops		13–16
Pray (1980)	Bangladesh	Wheat and rice	1961–1977	30–35
Moricochi (1980)	Brazil	Citrus	1933–1985	78–27
Avila (1981)	Brazil	Rice	1957–1964	79–96
Nagy (1983)	Pakistan	Wheat	1967–1981	58
	Pakistan	Maize	1967–1981	19
da Cruz et al. (1982)	Brazil	Aggregate	1974–1996	22–30
da Cruz and Avila (1983)	Brazil	Aggregate	1977–1982	20
Martinez and Sain (1983)	Panama	Maize	1979–1982	188
Bengston (1984)	USA	Forestry (Particleboard)	1975–2000	19–22

Table 5
Continued

Study	Country	Commodity	Period	IRR%
Feijòo (1984)	Argentina	Aggregate	1950–80	41
Monares (1984)	Rwanda	Potato seed	1978–85	40
Pinazza et al. (1984)	Brazil, Sao Paulo	Sugarcane	1972–82	35
Roessing (1984)	Brazil (CNPS)	Soybeans	1975–82	45–62
Norton and Paczkowski (1993)	USA (Va)	Aggregate	1949–79	58
Bare and Loveless (1985)	USA	Forestry	–	9–12
Bengston (1984)	USA	Forestry	–	35–40
Brinkman and Prentice (1985)	Canada – Ontario	Aggregate	1950	66
Herruzo (1985)	Spain	Rice	1941–80	15–18
Muchnik (1985)	Latin America	Rice	1968–90	17–44
Ulrich et al. (1985)	Canada	Malting barley	1951–88	31–75
Unnevehr (1986)	SE Asia	Rice quality	1983–84	29–61
Brunner and Strauss (1986)	USA	Forestry		73
Chang (1986)	USA	Forestry, pine		nc B/C = 16/1
Haygreen et al. (1986)	USA	Forestry	1972–81	14–36
Newman (1986)	USA	Forestry		0–7
Westgate (1986)	USA	Forestry	1969–2000	37–111
Haque et al. (1987)	Canada	Eggs	1968–84	106–123
Harvey (1988)	U.K.	Agricultural research and extension	Present	−37.5
Beck (1988)	U.K.	Horticultural crop protection	1979–2001	50
Ernstberger (1989)	Brazil	Rice		66–78
Hust et al. (1988)	Canada	Swine	1968–84	45
Luz Barbosa et al. (1988)	Brazil	Aggregate	1974–97	40
Zachariah et al. (1988)	Canada	Broilers	1968–84	8–4
Power and Russell (1988)	U.K.	Poultry feeding research	1980	Benefit cost rate of 10
World Bank (1988)	Burkina Faso Cote d'Ivoire and Togo	Cotton		11–41
Zachariah et al. (1988)	Uruguay	Rice	1965–85	52
Fox et al. (1989)	Canada	Dairy	1968–84	97
Schwartz et al. (1989)	Senegal	Cowpeas	1981–87	60–80
Bojanic and Echeverría (1990)	Bolivia (CIAT)	Soybeans	1974–89	63–80
Norton et al. (1992)	Tunisia	Seed potato	1976–85	81
Mazzueato (1992)	Kenya	Maize	1978	58
Norton and Paczkowski (1993)	USA (Va)	Aggregate	1949–89	58
Ewell (1992)	East Africa	Aggregate	1978–91	91
Schwartz et al. (1993)	Senegal	Cowpea	1980–85	31–92

Table 5
Continued

Study	Country	Commodity	Period	IRR%
Mazzueato and Ly (1994)	Niger	Cowpea, millot and sorghum	1975–91	0
Laker-Ojok (1994)	Uganda	Sunflower, cowpea, Soybean	1985–91	0
Boughton and Henry de Frahan (1994)	Mali	Maize	1969–91	135
Sanders (1994)	Ghana	Maize	1968–92	74
	Cameroon	Sorghum	1980–92	2
Smale and Heisey (1994)	Malawi	Maize	1957–92	4–64
Ahmed et al. (1995)	Sudan	Sorghum	1979–92	53–97
Seck et al. (1995)	Senegal	Cotton	1985–93	34–37
Ouédraego et al. (1995)	Burkina Faso	Aggregate	1988–94	7
Seidi (1996)	Guinea Bissau	Rice	1986–94	26

research services variable(s) and the direct estimation of a coefficient(s) for this variable. Economic impacts in the form of (marginal) IRRs were computed and reported in the studies of this group (see Table 6).

4.1. The project evaluation (economic surplus) studies

The term project evaluation is used here to refer to the use of methods relying on evidence from different sources to measure economic impact.

All methods should, in principle, address locational and timing dimensions. For project evaluation studies these dimensions are generally inherent in the project setup. One of the first and most important studies of this type was the hybrid corn study by Griliches (1958). Griliches did not treat the development of a single variety of hybrid corn or even the set of varieties released in Iowa as the project being evaluated. He recognized that the project encompassed the pre-invention science (PS) entailed in inventing a method of inventing (i.e., the hybridization methodology) and covered applied agricultural research (plant breeding) in both public and private R&D programs.

Griliches also recognized spillover barriers. The pattern of adoption of hybrid corn varieties varied by state because of high degrees of locational specificity of hybrid corn varieties. Alabama did not adopt hybrid corn varieties until applied hybrid corn breeding programs were developed in Alabama, targeting varieties to the soil and climate conditions in Alabama.

The Griliches study set forth the basics of the measurement of benefits. Hybrid corn varieties, when adopted, reduce marginal and average costs, and shift the supply curve to the right (which in competition is the summation of the marginal costs of farmers above the minimum point on the average variable cost curves). Economic benefits are the

Table 6
Economic impact studies: Public sector agricultural research: Statistical methods

Study	Country	Commodity	Period	Prod. structure	IRR
Tang (1963)	Japan	Aggregate	1880–58	MPF	35
Griliches (1964)	USA	Aggregate	1949–59	MPF	25–40
Latimer (1964)	USA	Aggregate	1949–59	MPF	n.s.
Peterson (1967)	USA	Poultry	1915–60	MPF	21–25
Evenson (1968)	USA	Aggregate	1949–59	MPF,T	47
Barletta (1970)	Mexico	All crops	1943–63	PD	45–93
Elias (1971)	Argentina	Sugarcane	1943–63		33–49
Duncan (1972)	Australia	Pastures	1948–69	MPF	58–68
Evenson and Jha (1973)	India	Aggregate	1953–71	PD	40
Cline (1975)	USA	Aggregate	1939–48	MPF	41–50
del Rey (1975)	Argentina	Sugarcane	1943–64	MPF	35–41
Bredahl and Peterson (1976)	USA	Aggregate	1937–42	MPF	56
	USA	Aggregate	1947–57	MPF	51
	USA	Aggregate	1957–62	MPF	49
	USA	Aggregate	1967–72	MPF	34
Kahlon et al. (1977)	India	Aggregate	1960–73	MPF	63
	India	Aggregate	1956–73	MPF	14–64
Lu et al. (1979)	USA	Aggregate	1938–72	MPF	24–31
Evenson and Flores (1978)	Asia (all)	Rice	1950–65	PP(Y)	32–39
	Asia (NARs)	Rice	1966–75	PP(Y)	73–78
	Asia (IRRI)	Rice	1966–75	PP(Y)	74–102
Flores et al. (1978)	Philippines	Rice	1966–75	PP(Y)	75
	Tropical Asia	Rice	1966–75	PP(Y)	46–71
Nagy and Furtan (1978)	Canada	Rapeseed	1960–75	MPF	90–110
Kislev and Hoffman (1978)	Israel	Wheat	1954–73	MPF	125–150
	Israel	Dry farming	1954–73	MPF	94–113
	Israel	Field Crop	1954–73	MPF	13–16
Evenson (1979)	USA	Aggregate	1868–1926	PD,T,G	65
	USA	Aggregate	1927–50	PP,T,G	95
	USA – South	Aggregate	1948–71	PD,T,G	130
	USA – North	Aggregate	1948–71	PD,T,G	93
	USA – West	Aggregate	1948–71	PD,T,G	95
Knutson and Tweeten (1979)	USA	Aggregate	1949–72	MPF (Alt)	28–47
Lu et al. (1979)	USA	Aggregate	1939–72	MPF	23–30
White et al. (1978)	USA	Aggregate	1929–77	MPF	28–37
Davis (1979)	USA	Aggregate	1949–59	MPF	66–100
Davis and Peterson (1981)	USA	Aggregate	1949	MPF	100
	USA	Aggregate	1954	MPF	79
	USA	Aggregate	1959	MPF	66
	USA	Aggregate	1964, 1969, 1974	MPF	37
Hasting (1981)	Australia	Aggregate	1946–68	MPF	nc (ss)
Norton (1981)	USA	Cash grains	1969–74	MPF	31–44
	USA	Poultry	1969–74	MPF	30–56
	USA	Dairy	1969–74	MPF	27–33
	USA	Livestock	1969–74	MPF	56–66

Table 6
Continued

Study	Country	Commodity	Period	Prod. structure	IRR
Otto and Havlicek (1981)	USA	Corn	1967–79	MPF	152–212
	USA	Wheat	1967–79	MPF	79–148
	USA	Soybeans	1967–79	MPF	188
Sundquist et al. (1981)	USA	Corn	1977	PP(Y)	115
	USA	Wheat	1977	PD(Y)	97
	USA	Soybeans	1977	PD(Y)	118
Welch and Evenson (1989)	USA	Aggregate	1969	MPF	55
Abidogun (1982)	Nigeria	Cocoa	1980		42
Evenson (1982)	Brazil	Aggregate	1966–74 (est)	MPF	69
White and Havlicek (1982)	USA	Aggregate	1943–77	MPF	7–36
Smith et al. (1983)	USA	Dairy	1978	MPF	25
	USA	Poultry	1978	MPF	61
	USA	Beef, swine, sheep	1978	MPF	22
Feijoo (1984)	Argentina	Aggregate	1950–80	MPF	41
Makau (1984)	Kenya	Wheat	1922–80	PD(Y)	33
Salmon (1984)	Indonesia	Rice	1965–77	PD(Y)	133
da Silva (1984)	Brazil (Sao Paulo)	Aggregate	1970–80	MPF	60–102
Doyle and Ridout (1985)	U.K.	Aggregate	1966–80	MPF	30
Nagy (1985)	Pakistan	Aggregate	1959–79	MPF	64
Ulrich et al. (1985)	Canada	Malting barley		PD(Y)	51
Boyle (1986)	Ireland	Aggregate	1963–83	MPF	26
Braha and Tweeten (1986)	USA	Aggregate	1959–82	MPF	47
Fox (1986)	USA	Livestock	1944–83	MPF	150
	USA	Crops	1944–83	MPF	180
Khan and Akbari (1986)	Pakistan	Aggregate	1955–81	MPF	36
Wise (1986)	U.K.	Aggregate	1986	MPF	8–15
Evenson (1987)	India	Aggregate	1959–75	PD,T,G	100
Librero and Perez (1987)	Philippines	Maize	1956–83	MPF	27–48
Librero and Perez (1987)	Philippines	Sugarcane	1956–83	MPF	51–71
Scobie and Eveleens (1987)	New Zealand	Aggregate	1976–84	MPF	30
Seldon (1987)	USA	Forestry (products)	1950–80	MPF	163+
Seldon and Newman (1987)	USA	Forestry (products)	1950–86	MPF	236+
Sumelius (1987)	Finland	Aggregate	1950–84	MPF	25–76
Tung and Strain [see Echeverría (1990)]	Canada	Aggregate	1961–80	MPF	high
Librero et al. (1988)	Philippines	Mango	1956–83	PD(Y)	85–107
Russel and Thirtle [see Echeverría (1990)]	U.K.	Rapeseed	1976–85	PD(Y)	BC = 327
Thirtle and Bottomley (1988)	U.K.	Aggregate	1950–81	MPF	70
Evenson (1989)	USA	Aggregate	1950–82	MPF,T,G	43
Evenson (1989)	USA	Crops	1950–82	MPF,T,G	45
Evenson (1989)	USA	Livestock	1950–82	MPF,T,G	11

Table 6
Continued

Study	Country	Commodity	Period	Prod. structure	IRR
Ribeiro (1982)	India	Pearl millet	1987		57
Evenson and McKinsey (1991)	India	Rice	1954–84	MPF,T,G	65
Librero and Emlano (1990)	Philippines	Poultry	1948–81	MPF	154
Pray and Ahmed (1991)	Pakistan	Aggregate	1948–81	MPF	100
Byerlee (1991)	Pakistan	Wheat	1965–88	PD	15–20
Karanjan (1990)	Kenya	Maize	1955–88	PD	40–60
Karanjan (1990)	Kenya	Wheat	1955–88	PD	68
Nagy (1991)	Pakistan	Maize	1967–81	PD	19
	Pakistan	Wheat	1967–81	PD	58
Azam et al. (1991)	Pakistan	Applied research	1956–85	PD,T	58
	Pakistan	Commodity research	1956–85	PD,T	88
	Pakistan	Wheat	1956–85	PD,T	76
	Pakistan	Rice	1956–85	PD,T	84–89
	Pakistan	Maize	1956–85	PD,T	46
	Pakistan	Bajra	1956–85	PD,T	44
	Pakistan	Jowar	1956–85	PD,T	52
	Pakistan	Cotton	1956–85	PD,T	102
Azam et al. (1991)	Pakistan	Sugarcane	1956–85	PD,T	ns
Evenson and McKinsey (1991)	India	Aggregate	1958–83	PD,T,G	65
	India	Wheat	1958–83	PD(Y),T,G	50
	India	Rice	1958–83	PD(Y),T,G	155
	India	Maize	1958–83	PD(Y),T,G	94
	India	Bajra	1958–83	PD(Y),T,G	107
	India	All cereals	1958–83	PD(Y),T,G	218
Dey and Evenson (1991)	Bangladesh	All crops	1973–89	PD	143
	Bangladesh	Rice	1973–89	PD(Y),T	165
	Bangladesh	Wheat	1973–89	PD(Y),T	85
	Bangladesh	Jute	1973–89	PD(Y),T	48
	Bangladesh	Potato	1973–89	PD(Y),T	129
	Bangladesh	Sugarcane	1973–89	PD(Y),T	94
	Bangladesh	Pulses	1973–89	PD(Y),T	25
	Bangladesh	Oilseeds	1973–89	PD(Y),T	57
Iqbal (1991)	Pakistan – Punjab	Rice	1971–88	MPF	42–72
	Pakistan – Sind	Rice	1971–88	MPF	50
	Pakistan – NWFD	Rice	1971–88	MPF	36–11
	Pakistan – Punjab	Cotton	1971–88	MPF	95–102
	Pakistan – Sind	Cotton	1971–88	MPF	49–51
Setboonsarng and Evenson (1991)	Thailand	Rice	1967–80	MPF	40
Evenson and Quizon (1991)	Philippines	Aggregate	1948–84	PF	70
	Philippines	National	1948–84	PF	50
	Philippines	Regional	1948–84	PF	100
Evenson (1992)	India	Aggregate	1959–75	MPF,T,G	72
Kumar and Mruthyunjaya (1992)	India	Cattle	1969–85	MPF	29

Table 6
Continued

Study	Country	Commodity	Period	Prod. structure	IRR
Evenson (1991)	USA	Applied – crop	1950–85	PD	45
	USA	Applied – livestock	1950–85	PD	11
Evenson (1992)	Indonesia	All crops	1971–89	PD,T	212
	Indonesia	Rice	1971–89	PD,T	285
	Indonesia	Maize	1971–89	PD,T	145
	Indonesia	Soybeans	1972–89	PD,T	184
	Indonesia	Mung beans	1971–89	PD,T	158
	Indonesia	Cassava	1971–89	PD,T	ns
	Indonesia	Groundnut	1971–89	PD,T	110
Fan and Pardey (1992)	China	All crops	1965–89	MFP	20
Rosegrant and Evenson (1993)	India	Public research	1956–87	PD,T,G	67
Evenson and Gollin (1996)	IRRI	Rice germplasm	1965–90	PD,T,G	100+
Huffman and Evenson (1993)	USA	Applied – crop	1950–85	PD,T,G	47
	USA	Applied – livestock	1950–85	PD,T,G	45
Evenson et al. (1994)	Indonesia	upland rice	1979–92	PD(Y),T,G	100+
	Indonesia	Irrigated rice	1979–82	PD(Y),T,G	100+
	Indonesia	Maize	1979–82	PD(Y),T,G	100+
	Indonesia	Soybeans	1979–82	PD(Y),T,G	10
	Indonesia	Cassava	1979–82	PD(Y),T,G	0
	Indonesia	Groundnut	1979–82	PD(Y),T,G	10
	Indonesia	Sweet potato	1979–82	PD(Y),T,G	100+
	Indonesia	Mung bean	1979–82	PD(Y),T,G	40
Evenson et al. (1994)	Indonesia	Cabbage	1979–82	PP(Y),T,G	100+
	Indonesia	Potato	1979–82	PP(Y),T,G	100
	Indonesia	Garlic	1979–82	PD(Y),T,G	100+
	Indonesia	Mustard	1979–82	PD(Y),T,G	100+
	Indonesia	Onion	1979–82	PD(Y),T,G	100+
	Indonesia	Shallot	1979–82	PD(Y),T,G	100+
	Indonesia	Rubber	1979–82	PD(Y),T,G	100+
	Indonesia	Oil palm	1979–82	PD(Y),T,G	100+
	Indonesia	Coffee	1979–82	PD(Y),T,G	20–100
	Indonesia	Tea	1979–82	PD(Y),T,G	60–100
	Indonesia	Sugar	1979–82	PD(Y),T,G	50–100
	Indonesia	Orange	1979–82	PD(Y),T,G	80
	Indonesia	Banana	1979–82	PD(Y),T,G	100+
	Indonesia	Papaya	1979–82	PD(Y),T,G	100+
	Indonesia	Mango	1979–82	PD(Y),T,G	0
	Indonesia	Pineapple	1979–82	PD(Y),T,G	100+
	Indonesia	Durian	1979–82	PD(Y),T,G	0
	Indonesia	Meat	1979–82	PD(Y),T,G	0
	Indonesia	Milk	1979–82	PD(Y),T,G	100+
	Indonesia	Eggs	1979–82	PD(Y),T,G	0

Table 6
Continued

Study	Country	Commodity	Period	Prod. structure	IRR
Evenson and Avila (1996)	Brazil	State research			
	Brazil	Soybeans	1979–92	PD(Y),T,G	40
	Brazil	Maize	1979–92	PD(Y),T,G	62
	Brazil	Beans	1979–92	PD(Y),T,G	54
	Brazil	Rice	1979–92	PD(Y),T,G	46
	Brazil	Wheat	1979–92	PD(Y),T,G	42
	Brazil	Federal research			
	Brazil	Soybean	1979–92	PD(Y),T,G	40
	Brazil	Maize	1979–92	PD(Y),T,G	58
	Brazil	Beans	1979–92	PD(Y),T,G	0
	Brazil	Rice	1979–92	PD(Y),T,G	37
	Brazil	Wheat	1979–92	PD(Y),T,G	40
Alston et al. (1998a)	USA	Aggregate		MPF,T	17–31
Chavas and Cox (1992)	USA	Aggregate		MPF	28
Townsend and van Zyl (1997)	South Africa	Wine grapes		MFP	40
Gopinath and Roe (1996)	USA	Aggregate		CF	37
Thirtle et al. (1997)	United Kingdom	Wheat			20+
Townsend et al. (1997)	South Africa	Maize			28–39
Traxler and Byerlee (1992)	Mexico	Crop mgmt			16–23
Makki et al. (1996)	USA	Aggregate	1930–1990		27
Makki and Tweeten (1993)	USA	Aggregate	1930–1990		93
Oehmke (1996)	USA	Aggregate	Pre–1930		neg
	USA	Aggregate	1930–1990		11.6
Morris et al. (1994)	Nepal	Wheat	1960–1990		84
Traxler and Pingali (1996)	India	Wheat			
Yee (1992)	USA	Aggregate	1931–85	MPF	49–58
Norton et al. (1992)	USA	Aggregate	1987	MPF	30
	USA	Cash grains	1987	MPF	31
	USA	Vegetables	1987	MPF	19
	USA	Fruits	1987	MPF	33
	USA	Other field crops	1987	MPF	34
	USA	Dairy	1987	MPF	95
	USA	Poultry	1987	MPF	46
	USA	Other livestock	1987	MPF	55
Khatri et al. (1995)	South Africa	Aggregate			44
Makana and Oehmke (1996)	Kenya	Wheat		PD(Y)	0–12
Akgunkov et al. (1996)	Kenya	Wheat	1921–90		14–30
Isinika (1995)	Tanzania	Aggregate	1972–92		33

change in consumer's and producer's surpluses and are measured by the area under the demand curve between the original supply curve and the shifted supply curve. Griliches noted that this area is well approximated by the change in average variable costs times the original quantity produced. (The elasticity of demand is crucial to the division of economic surplus between consumers and producers, but only affects the size of the small triangle for measurement of economic surplus.)[30]

Griliches (1958) used farm experimental data in a with-without design to measure the average variable cost shift associated with hybrid varieties.[31] With information on adoption rates and the size of the shift, a benefit stream from 1900 to 1957 was created. A cost stream (including both public sector and private firm costs) was also estimated. Griliches (1958) then performed the standard investment calculations to compute the present value of benefits and costs in 1957:

$$\mathrm{PVB}_{57} = \sum_{t=1900}^{1957} b_t (1.05)^{t-1900}, \tag{18}$$

$$\mathrm{PVC}_{57} = \sum_{t=1900}^{1957} c_t (1.05)^{t-1900}. \tag{19}$$

Griliches then computed the following ratio:

$$\frac{\mathrm{PVB}_{57} \times .05 + b_{57}}{\mathrm{PVC}_{57} \times .05 + c_{57}}. \tag{20}$$

This procedure converted the cumulated present values to flows, and under the assumption that 1957 benefits (b_{57}) and costs (c_{57}) would continue indefinitely, this ratio was interpreted as a "dollars benefit per dollar cost" ratio. The ratio (approximately 7) was sometimes interpreted as a 700 percent rate of return on investment. Griliches himself later noted that it should be interpreted as a modified benefit-cost ratio, not as a rate of return [Griliches (1998)]. He also computed the internal rate of return for the program (the rate of discount at which $\mathrm{PVB}_{57} = \mathrm{PVC}_{57}$) to be approximately 44 percent.

The Griliches study established the basic project evaluation methods for subsequent studies where project outcomes were measurable (e.g., adoption of hybrid corn varieties). These included:

(a) carefully defining the project's locational and timing dimensions;
(b) measuring project costs;
(c) measuring project outputs (adoption of hybrid corn varieties);

[30] There is little evidence that supply curve shifts have a convergence pattern. There is some evidence [see Evenson and Huffman (1993)] for technology-induced increases in farm size. This would be consistent with divergent supply curve shifts. Huffman and Evenson (1993) note that different magnitudes of shifts for farms of different sizes (e.g., large farms realize shifts, while small farms do not) do not produce non-parallel supply curve shifts.

[31] This shift was estimated to be 28 percent. Many non-economists contend that new technology must have a significant cost advantage (e.g., doubling) before it is adopted. Most careful studies show that this is not the case.

(d) estimating the economic impact of project outputs (i.e., on farm production, costs, and supply);
(e) converting economic impact estimates to project benefit estimates;
(f) performing economic calculations for PVB/PVC, PVB-PVC, and the internal rate of return where PVB = PVC.

Many of the studies summarized in Table 5 actually used statistical evidence. Some are based on time-series data only. Others used repeated cross-section data. The studies in Table 5 are distinguished from those in Table 6 in that they did not generally explicitly address the question of defining a research services variable. Most of the commodity studies summarized in Table 5, while based on partial factor productivity measures (yield changes), did attempt to correct for the "partial" bias by utilizing other input, quantity, and price data.

The 60-plus studies summarized in Table 5 covered a broad range of commodities in a broad range of countries. Almost all report high to very high internal rates of return. (Many studies reported a range of IRRs as noted in Table 5.)

4.2. Studies based on research variable coefficient estimates

In Table 6 a summary of roughly 120 studies utilizing research variable coefficient estimates is made. Some of these are also included in Table 3, where extension IRRs are reported. All of these studies are based on aggregate data. A few are based on cross-section data only. A larger number are based on time-series data. Most are based on repeated cross-section data. As with Table 5, a broad range of countries and commodities are studied, and as with Table 5, most IRRs are in the high to very high range.

The studies summarized in Table 4, where research and extension expenditure data are amalgamated into a single variable, are comparable to some of the studies summarized in Table 6. As noted in the discussion of time shapes and of spatial weights and deflators, the amalgamated variables present very difficult weighting problems. For the most part, the studies summarized in Table 4 were based on crude time lags and deflators as were many of the studies summarized in Table 6. They are probably best interpreted as research studies rather than extension studies.

Relatively few of the studies summarized in Table 6 actually estimated time weights (noted as T). Relatively few incorporated geographic spill-in specificators (noted by G). Most undertook some form of deflation (sometimes via dummy variables).

Several of the studies summarized in Table 6 also included pre-invention science and industrial R&D spill-in variables (these are summarized in Section 5).

Virtually all studies summarized in Tables 4 and 6 reported statistical significance for coefficient estimates of the research variable utilized. The rates of return calculated from these coefficients and the time weights cover a broad range.

As will be noted in the summary, there is a difference between evaluations of aggregate research programs and commodity research programs, with most of the very high IRRs being reported for the commodity programs. It will also be noted that the studies of applied agricultural research using project evaluation methods report fewer very high IRRs than do the studies using statistical methods.

Approximately half of the 200-plus IRRs reported in Table 6 utilized the meta production function structure. Approximately one-quarter used TFP decomposition and one-quarter used a yield decomposition structure. (Very few used the duality format in spite of its obvious richness.)

Many studies report a range of IRRs; only a few of these are average IRRs because most use statistical procedures to estimate impacts.

5. Studies of industrial R&D spill-in aud pre-Invention science spill-in

Surveys of research expenditure in recent years have identified considerable industrial R&D directed toward products sold to and used in the agricultural sector. Agricultural machinery and agricultural chemicals are obvious cases where industrial R&D is directed toward the improvement of agricultural inputs. Johnson and Evenson (1999) report estimates of patented inventions manufactured in a number of industries that are used in the agricultural sector.

Early studies argued that if the product improvements resulting from this R&D were priced to reflect the full value of the improvement, agricultural productivity would be unaffected by industrial R&D. Recent studies conclude, however, that when new industrial products first come on the market they are priced to only partially capture the real value of the improvement (most new models of equipment are better buys than the equipment that they replace). This produces a spill-in impact.

Table 7 summarizes several studies incorporating industrial R&D variables. As will be noted in the summary, the social (private plus spillover) rate of return to this industrial R&D is roughly equal to the social rate of return to public agricultural research.

Another type of spill-in that is recognized in few studies is the "recharge" spill-in from pre-invention science. Many of the studies summarized in Tables 4, 5, and 6

Table 7
Economic impact studies: Private sector R&D spill-in

Study	Country/region	Period of study	Productive structure	IRR
Rosegrant and Evenson (1993)	India	1956–87	PD	Dom 50+ For 50+
Huffman and Evenson (I993)	USA	1950–85	PD	Crops 4I
Ulrich et al. (I985)	Canada		PD	Malting barley 35
Gopinath and Roe (1996)	USA	I99I	CF	Food processing 7.2 Farm machinery 1.6 Total social 46.2
Evenson (1991)	USA	1950–85	PD	Crop 45–71 Livestock 81–89
Evenson and Avila (1996)	Brazil	1970–75–80–85	PD	nc

Table 8
Economic impact studies: Pre-invention science

Study	Country	Period of study	Production structure	EMIRR
Evenson (1979)	USA	1927–50	PD	110
		1946–71	PD	45
Huffman and Evenson (1993)	USA	1950–85	PD	Crop 57
				Livestock 83
				Aggregate 64
Evenson et al. (1999)	India	1954–87	PD	Domestic
				Foreign
Evenson and Flores (1978)	Int. (IRRI)	1966–75	PD	74–100
Evenson (1991)	USA	1950–85	PD	Crops 40–59
				Livestock 54–83
Azam et al. (1991)	Pakistan	1966–68	PD,T	39

actually covered a wide range of research program activities including many pre-invention science activities. The studies summarized in Table 8 specifically identified pre-invention expenditures and activities. It may be noted that these studies report relatively high rates of return.

6. *Ex ante* stndies

Research and extension programs in either public or private sector organizations require both design and resource allocation decisions. The project evaluation framework has been applied to many research and extension investment decisions. The World Bank and other lending or granting agencies require what is in effect *ex ante* impact evaluation studies as an integral part of the lending process. Yet it is probably fair to say that *ex ante* studies of research and extension lack credibility in these agencies.

Part of the problem with credibility is inherent in the high degree of uncertainty in extension and especially in research projects. As noted in an earlier section, research is subject to considerable uncertainty, including uncertainty as to the parameters of the search pool in which inventions are sought. Some of this uncertainty is associated with the fact that many of the important international and national agencies have not undertaken the *ex ante–ex post* evaluations required to establish credibility in *ex ante* (and in *ex post*) studies. It is of some interest to note that very few of the *ex post* studies reviewed have been completed by staff of the lending agencies or of national programs.[32]

[32] The World Bank's OED study of agricultural research and extension [Purcell and Anderson (1997)] did call for higher standards of *ex ante* evaluation of extension projects (and of research projects as well) but

The *ex ante* methodology as it has evolved since the early work of Fishel (1971) is based on the simple investment calculation:

$$\mathrm{PVB}_0 = \sum_{t=0}^{\infty} (b/u)_t U_t/(1+\pi)^t,$$
$$\mathrm{PVC}_0 = \sum_{t=0}^{\infty} C_t/(1+\pi)^t. \tag{21}$$

For a given research problem area (RPA) and a given research technique (RT) the *ex ante* analyst typically must specify the key design elements of the project and its magnitude. Thus PVC_0 is often specified initially (e.g., this could be a project seeking host plant drought tolerance through conventional breeding techniques, the project would specify the strategies, the pre-breeding activity, number of years, etc.).

Benefits can be separated into benefits per unit per year $(b/u)_t$ and units per year, U_t. At least one of these terms must be obtained by subjective probability estimation (SPE) by scientists with specialized knowledge (e.g., plant breeders with breeding experience and knowledge of genetic sources for drought tolerance). The "units" measure may also require estimation, but typically from different sources. One of the principles of *ex ante* analysis is that the best sources of information be consulted for each component.

Typically, the estimate $(b/u)_t$ has both a timing and a level effect. Since many projects are part of a sequence, it is often the case that the "achievement" estimate is stated in terms of potential achievement and achievement to date. This clarifies what is meant by remaining achievement. Then years-to-achievement estimates can be obtained associated with the potential achievement. In order to allow the source to express uncertainty about the estimate, the analyst can ask for a range of probabilities of achievement or, as in a recent rice research study, years to 25 percent achievement and years to 75 percent achievement [Evenson et al. (1996)].

Table 9 summarizes *ex ante* studies reported in various publications. Some of these studies are pure *ex ante* studies. Others are combined *ex ante–ex post* studies.

Interestingly, as noted in the next section, the rates of return computed for *ex ante* studies have less variability than those for *ex post* studies. They also have a lower mean and median.

did not attempt the *ex post–ex ante* comparisons required to give credibility to *ex ante* studies. It chose to stress informal *ex post* ratings of projects and was critical of existing *ex post* economic impact studies. The OED study was primarily concerned with the management and design issues associated with extension. It reached the conclusion that the Bank's T&V management focus was not the most effective management style for extension, although it is difficult to find the basis for this conclusion in the report. The *ex post* studies (see Tables 1 and 2) which concluded that T&V-managed extension programs did have an economic impact, but were less conclusive as to whether the T&V management style was more productive than alternatives, were criticized in the report.

Table 9
Ex ante economic impact studies of agricultural research programs

Study	Country/region	Period of study	Commodity	*Ex ante* IRR
Monteiro (1975)	Brazil	1923–1985	Cocoa	19–20
Fonseca (1976)	Brazil	1933–1995	Coffee	23–27
Easter and Norton (1977)	USA		Maize	
		1982–2000	Crop protection	B/C 137:1
		1985–2000	Production efficiency	B/C 118:1
	USA		Soybeans	
		1982–2000	Crop protection	45:1
		1985–2000	Production efficiency	40:1
Eddleman (1977)	USA	1978–1985	Aggregate	28
			Maize	32
			Soybeans	31
			Wheat	46
			Beef cattle and forage	16
			Swine	52
			Dairy	38
Moricochi (1980)	Brazil (Sao Paulo)	1933–1985	Citrus	18–28
Araji (1981)	USA	1978–2000	Integrated pest management	0–191
da Cruz et al. (1982)	Brazil	1974–1981	Physical capital	53
	Brazil	1974–1992	Total investment	22–43
Ribeiro (1982)	Brazil	1974–1994	Aggregate	69
	(M. Gerais)		Cotton	48
			Soybeans	36
da Cruz et al. (1982)	Brazil (EMBRAPA)	1974–1996	Human capital	22–30
da Cruz and Avila (1983)	Brazil (EMBRAPA)	1977–1991	Aggregate	38
Ambrosi and da Cruz (1984)	Brazil (EMBRAPA-CNPT)	1974–1990	Wheat	59–74
Avila et al. (1984)	Brazil (South Central)	1974–1996	Aggregate	38
Bengston (1984)	USA	1975–2000	Forestry (structural particleboard)	19–22
Ulrich et al. (1985)	Canada		Canola	51
Muchnik (1985)	Latin America	1968–1990	Rice	17–44
Martinez and Norton (1986)	USA		Broilers	100+
			Eggs	
Westgate (1986)	USA	1969–2000	Forestry (timber, containerized seedlings)	37–111
Norton et al. (1987)	Peru	1981–2000	Aggregate	17–38
	(INIPA)		Rice	17–44
			Maize	10–31
			Wheat	18–36

Table 9
Continued

Study	Country/ region	Period of study	Commodity	*Ex ante* IRR
			Potatoes	22–42
			Beans	14–24
Valdivia (1997)	Indonesia		Small ruminant research	19–25
Norgaard (1988)	Africa	1977–2003	Cassava	B/C 149:1
Henry de Frahan et al. (1989)	Mali	1990–2010	Aggregate	1–25
Karanja (1990)	Kenya	1955–1988	Maize	40–60
Schwartz and Oehmke (1990)	Senegal	1981–2005	cowpea	63
Seré and Jarvis (1998)	Latin America	1987–2037	Pastures	15–20
MacMillan et al. (1991)	Zimbabwe	1991–1996	Maize	B/C 1.35:1
Henry de Frahan et al. (1989)	Mali		Farming-systems research (FSR)	1
Sterns et al. (1993)	West Africa	1981–2017	Training	22–31
Laker-Ojok (1994)	Uganda	1985–2006	Maize	27–58
			Sunflower	10–66
			Soybean	0–20
Morris et al. (1994)	Nepal		Wheat varieties	49
Smale et al. (1998)	Mexico		Bread wheat disease resistance	40
Sterns and Bernsten (1994)	Cameroon	1979–1998	Cowpea	15
			Sorghum	1
Mazzueato and Ly (1994)	Niger	1975–2011	Millet, sorghum, and cowpea	2–10
Bertelsen and Ouédraego (N.d.)	Burkina Faso	1990–2003	Zaï	53
Fisher et al. (1995)	Senegal	1995–2004	Rice	66–83
Tre (1995)	Sierra Leone	1976–2010	Rice	18–21
Anandajayasekeram and	Zimbabwe	1980–1999	Sorghum	22
Martella (1995)	Namibia	1988–1999	Millet	11
Byerlee and Traxler (1995)	International	1970–1990	Wheat varieties	37–48
Mudhara et al. (1995)	Zimbabwe	1970–1995	Cotton	47
Kuyvenhoven et al. (1996)	Mali		Rock phosphate	43–271
Aghib and Lowenberg-DeBoer (N.d.)	10 countries	1985–2009	Sorghum	58
Chisi et al. (1997)	Zambia	1983–2005	Sorghum	12–19
Valdivia (1997)	Indonesia		Small ruminant research	19–25
Norgaard (1988)	Africa	1977–2003	Cassava	149:1
Schwartz and Oehmke (1990)	Senegal	1981–2005	Cowpea	63
MacMillan et al. (1991)	Zimbabwe	1991–1996	Maize	1.35:1
Henry de Frahan et al. (1989)	Mali		Farming-systems research	1
Sterns et al. (1993)	West Africa	1981–2017	Training	22–31
Laker-Ojok (1994)	Uganda	1985–2006	Maize	27–58
			Sunflower	10–66
			Soybean	0–20

Table 9
Continued

Study	Country/ region	Period of study	Commodity	*Ex ante* IRR
Sterns and Bernsten (1994)	Cameroon	1979–1996	Cowpea	15
			Sorghum	1
Mazzueato and Ly (1994)	Niger	1975–2011	Millet, sorghum, and cowpea	2–10
Bertelsen and Ouédraego (N.d.)	Burkina Faso	1990–2003	Zaï	53
Fisher et al. (1995)	Senegal	1995–2004	Rice	66–83
Tre (1995)	Sierra Leone	1976–2010	Rice	18–21
Anandajayasekeram and	Zimbabwe	1980–1999	Sorghum	22
Martella (1995)	Namibia	1988–1999	Millet	11
Kuyvenhoven et al. (1996)	Mali		Rock phosphate	43–27
Aghib and Lowenberg-DeBoer (N.d.)	10 countries	1985–2009	Sorghum	58
Chisi et al. (1997)	Zambia	1983–2005	Sorghum	12–19

7. Assessing the IRR evidence

The IRR evidence summarized in Tables 1–7 covers many studies, commodities, and regions. The studies, however, cannot be regarded as a truly representative sample of economic impact studies of research and extension programs because of "selectivity" bias. This bias takes two forms. First, highly successful programs are more likely to be evaluated. Second, "unsuccessful" evaluations, i.e., evaluations showing no impact, are less likely to be published than evaluations showing impact. There are, however, two factors that suggest that this bias may not be so serious as to render comparative assessments of this evidence to be of little value or relevance. The first is that one can compare the studies covering aggregate programs with studies of specific (successful) commodity programs. The aggregate programs include both successful and unsuccessful programs. The second is that the evidence is based on a substantial part of the world's agricultural research and extension programs.

With the appropriate caveats regarding selectivity, it will be useful to assess the IRR evidence by making comparisons between programs, regions, and periods. It will also be useful to assess the IRR evidence against the model discussed in Part II and against the arithmetic of growth. As noted earlier in this review, many reviewers of development experience suggest that most of the IRRs summarized here are overestimated.[33]

[33] This perception is often accompanied by a perception that significant economic growth can be obtained with few resources. TFP methods often create the impression that some growth is a residual "manna from heaven". In practice most TFP decomposition studies show that growth is not available "for nothing". But they also show that when technology infrastructure levels are adequate, small investments in growth production can have very high returns.

Table 10
Growth rate consistency comparisons. Annual growth rates in TFP required to support one percent of product investment

Time weights	IRR (percent)			
	20	40	60	100
1. Extension (1, 1, 1 0 –)	.39 (SR)	.45 (SR)	.50 (SR)	.57 (SR)
2. Extension (1, 1, .1 .5 –)	.39 (SR)	.45 (SR)	.50 (SR)	.57 (SR)
	.1 (LR)	.2 (LR)	.3 (LR)	.5 (LR)
3. Research (0, .2, .4, .6, .8, 1 –)	.31	.76	1.40	2.80
4. Research (0, .1, .2, .3, .4, .5, .6, .8, .9 1 –)	.42	.87	2.22	5.02

Turning first to the overestimation issue. Are the high IRRs reported inconsistent with actual growth experience? Table 10 reports the growth rate implications for two extension program time weight schemes and two research program time weight schemes for IRRs of 20, 40, 60, and 100 percent.

Consider the first extension time weight program where the effect of extension is simply to speed up adoption three years earlier than it would have occurred in the absence of the program. In the short run, i.e., in the first years after introducing the program, growth rates will be higher. But this will not produce a higher long-run rate of TFP growth.

Now consider the research programs where the contribution of the research program does not depreciate. The two weight sets represent the range of weights for most of the studies reviewed. Weight set 3 is a rapid research effect with the weights rising to the full effect in the sixth year after an investment of one percent of the value of production. A continuous program of investment of one percent of product each year must then produce TFP growth of .31 for an IRR of 20, .76 for an IRR of 40, 1.4 percent for an IRR of 60, and 2.8 percent for an IRR of 100. Weight set 4 is for a slower impact where the full effect of the program is realized in the eleventh year after investment. The growth rates required for these weights are higher. The second extension case is one where one-half of the extension contribution is permanent as in the cases where the technology infrastructure level is TI(1). The long-run growth implications of this are as noted.

IRRs for both extension and research studies are summarized in Table 11. Distributions of IRRs for a number of study categories are presented. Two features characterize virtually every category. The first is that mean and median IRRs are high. Seventy-four percent of the extension IRRs and 82 percent of the research IRRs exceed 20 percent. The second feature of the IRRs is that the range of estimates is broad. Every category (except for private sector R&D spillovers) includes studies reporting both low IRRs and high IRRs. Interestingly the category showing the narrowest range of IRRs is the *ex ante* study category.

Given the breadth of the range of IRRs in each category, it is difficult to draw strong conclusions regarding differences in means between categories. It can be noted, how-

Table 11
IRR estimates summary

	Number of IRRs reported	Percent distribution 0–20	21–40	41–60	61–0	81–100	100+	Approx. median IRR
Extension								
Farm observations	16	.56	0	.06	.06	.25	.06	18
Aggregate observations	29	.24	.14	.07	0	.27	.27	80
Combined research and extension	36	.14	.42	.28	.03	.08	.16	37
By region								
OECD	19	.11	.31	.16	0	.11	.16	50
Asia	21	.24	.19	.19	.14	.09	.14	47
Latin America	23	.13	.26	.34	.08	.08	.09	46
Africa	10	.40	.30	.20	.10	0	0	27
All extension	81	.26	.23	.16	.03	.19	.13	41
Applied research								
Project evaluation	121	.25	.31	.14	.18	.06	.07	40
Statistical	254	.14	.20	.23	.12	.10	.20	50
Aggregate programs	126	.16	.27	.29	.10	.09	.09	45
Commodity programs								
Wheat	30	.30	.13	.17	.10	.13	.17	51
Rice	48	.08	.23	.19	.27	.08	.14	60
Maize	25	.12	.28	.12	.16	.08	.24	56
Other cereals	27	.26	.15	.30	.11	.07	.11	47
Fruits and vegetables	34	.18	.18	.09	.15	.09	.32	67
All crops	207	.19	.19	.14	.16	.10	.21	58
Forest products	13	.23	.31	.68	.16	0	.23	37
Livestock	32	.21	.31	.25	.09	.03	.09	36
By region								
OECD	146	.15	.35	.21	.10	.07	.11	40
Asia	120	.08	.18	.21	.15	.11	.26	67
Latin America	80	.15	.29	.29	.15	.07	.06	47
Africa	44	.27	.27	.18	.11	.11	.05	37
All applied research	375	.18	.23	.20	.14	.08	.16	49
Pre-invention science	12	0	.17	.33	.17	.17	.17	60
Private sector R&D	11	.18	.09	.45	.09	.18	0	50
Ex ante research	87	.32	.34	.21	.06	.01	.06	42

ever, that the categories with the greatest proportions exceeding 40 percent are pre-invention science, private sector R&D, rice research, and fruits and vegetables research. Research studies have higher proportions exceeding 40 percent (59 percent) than is the case for extension studies (51 percent). Studies of commodity research programs have a higher proportion exceeding 40 percent (62 percent) than studies of aggregate research programs (57 percent).

Regional distributions vary with studies of both research and extension in Africa and have lower proportions exceeding 40 percent than in other regions. Asian research IRRs are especially high.

Actually, as noted above, some of the very high IRRs are "suspect" in that they could be inconsistent with actual economic growth experience. It is of interest to note that the proportion of very high (exceeding 80 percent) IRRs is highest for statistical commodity research studies where spending ratios are lowest (and where one may well be understating real research expenditure as well). Typically, for commodity programs even in developed countries, research/commodity value ratios are well below one percent. This is particularly true in Asia where the highest proportion of very high IRRs is reported.

The relatively high proportion of very high IRRs for extension may appear suspect, but as noted above, this is probably not inconsistent with growth experience. The high proportion of very high IRRs for pre-invention science is also consistent with growth experience because spending ratios are low.

Studies of industrial R&D indicate that the private IRRs captured by firms are generally similar to IRRs for other investments made by the firm [Mairesse and Mohnen (1995)]. These studies also show considerable spill-overs and indicate that the social rate of return is considerably higher than the private rate of return. The rate of return measured in the studies reviewed here is essentially the difference between the social and private IRR. Given that the public sector IRRs are actually social IRRs and reflect spillovers, the studies reviewed here suggest that the social IRRs for industrial R&D are also high and may well be of the same order of magnitude as public sector social IRRs.

It does not appear that there is a time trend in the IRRs reported. Studies for later periods show IRRs similar to studies of earlier periods.

While this review has not considered the few studies of determinants of investment in public sector agricultural research, it may be noted that the expansion of agricultural research and extension programs in the post World War II era of economic development has been heavily aid-driven. The training of agricultural scientists, especially in the 1950s, 1960s, and 1970s, was funded by international agencies and undertaken in leading agricultural universities in developed countries. Many NARs received grants and loans from international agencies. In recent years, international support has been declining. Some national programs have developed national support bases and these will continue to function. Others have not and are vulnerable to downsizing without international support.

The evidence for economic impacts of research and extension programs is probably more complete and comprehensive than the evidence for many other development programs (e.g., agricultural credit programs). While the range of IRR estimates is wide, the great majority of the IRR estimates indicate a high social rate of return to the investments made. Those high rates of return were realized in many NARs and IARCs and extension programs. These programs were not uniform in terms of design efficiency, scientist skills or management. Most, perhaps all, of these programs could have been improved. The broad scope of the evidence for high payoff suggests considerable international spillovers (and some studies measured this). Many research and extension programs are poorly managed and often resource-constrained. Many fail to produce proper statistical analyses of field trials. The evidence reviewed here is not inconsistent with this. But it does support the original vision of development economists. Research and extension programs have afforded high payoff investment opportunities.

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References

Abidogun, A. (1982), "Cocoa research in Nigeria: An ex-post investment analysis", Nigerian Journal of Economic and Social Studies 21–35.

Aghib, A., and J. Lowenberg-DeBoer (N.d.), "The regional impact of collaborative research and extension programs: The case of striga resistant sorghum varieties developed by INTSORMIL", Mimeo (Purdue University).

Ahmed, M.M., W.A. Masters and J.H. Sanders (1995), "Returns to research in economies with policy distortions: Hybrid sorghum in Sudan", Agricultural Economics 12:183–192.

Akgunkov, S., D. Makanda, J. Oehmke, R. Myers and Y. Choe (1996), "A dynamic analysis of Kenya wheat research and rate of return", in: Proceedings of the Conference on Global Agricultural Science Policy in the 21st Century, Melbourne.

Alston, J., B. Craig and P. Pardey (1998a), "Dynamics in the creation and depreciation of knowledge, and the returns to research", EPTD Discussion Paper No. 35 (International Food Policy Research Institute, Washington, D.C.).

Alston, J.M., M.C. Marra, P.G. Pardey, and T.J. Wyatt (1998b), "Research returns redux: A meta-analysis of the returns to agricultural R&D", EPTD Discussion Paper No. 38, Environment and Production Technology Division (International Food Policy Research Institute, Washington, D.C.).

Alston, J.M., and R.J. Venner (1998), "The effects of the U.S. plant variety protection act on wheat genetic improvement", paper presented at the symposium on "Intellectual Property Rights and Agricultural Research Impact", sponsored by NC208 and the CIMMYT Economics Program – El Batan, Mexico, March 5–7, 1998.

Ambrosi, I., and E.R. da Cruz (1984), "Taxas de retorno dos recursos aplicados em pesquisa no Centro Nacional de Pesquisa de Trigo", Passo Fundo (EMBRAPA, Brazil).

Anandajayasekeram, P., and D.R. Martella (1995), "Institutionalization of impact assessment: SACCAR's experience in Southern Africa", paper presented at USAID Collaborative Workshop on Agricultural Technology Development and Transfer in Sub-Saharan Africa, Harare, Zimbabwe, January 24–27, 1995.

Araji, A.A. (1981), "The economic impact of investment in integrated pest management", in: G.W. Norton, W.L. Fishel, A.A. Paulsen and W.B. Sundquist, eds., Evaluation of Agricultural Research, Miscellaneous Publication 8-1981 (Minnesota Agricultural Experiment Station, University of Minnesota).

Avila, A.F.D. (1981), "Evaluation de la recherché agronomique au Brésil: Le ces de la rechereche de l'IRGA ou Rio Grande do Sul", Ph.D. Dissertation (Fac. de Droitet des Sci. Econ., Montpellier).

Avila, A.F.D., J.E.A. Andrade, L.J.M. Irias and T.R. Quirino (1983), "Formacao do capital humano e retorno dos investimentos em telnamento na EMBRAPA", EMBRAPA-DDM Documentos 4, EMBRAPA-DRH Documentos 5 (EMBRAPA-DID, Brazil).

Avila, A.F.D., L.J. Irias and R.F.V. Veloso (1984), "Avaliação dos impactos socioeconómicos do Projeto PROCENSUL I-EMBRAPA/BID", Documentos 16 (EMBRAPA-DEP, Brasilia).

Aw-Hassan, A., E. Ghanem, A.A. Ali, M. Mansour and M.B. Solh (1995), "Economic returns from improved wheat technology in upper Egypt", ICARDA Social Science Papers – 1 (International Center for Agricultural Research in the Dry Areas).

Ayer, H.W. (1970), "The costs, returns and effects of agricultural research in Sao Paulo, Brazil", Ph.D. Dissertation (Purdue University).

Ayer, H.W., and G.E. Schuh (1972), "Social rates of return and other aspects of agricultural research: The case of cotton research in Sao Paulo, Brazil", American Journal of Agricultural Economics 54:557–569.

Ayers, C.H.S. (1985), "The contribution of agricultural research to soybean productivity in Brazil", Ph.D. Dissertation (University of Minnesota).

Azam, Q.T., E.A. Bloom and R.E. Evenson (1991), "Agricultural research productivity in Pakistan", Economic Growth Center Discussion Paper No. 644 (Economic Growth Center, Yale University, New Haven, CO).

Bare, B.B., and R. Loveless (1985), "A case history of the regional forest nutrition project: Investments, results, and applications", report submitted to the USDA Forest Service, North Central Forest Experiment Station (University of Washington).

Barletta, N.A. (1970), "Costs and social benefits of agricultural research in Mexico", Ph.D. Dissertation (University of Chicago).

Beck, H. (1988), "Costs and benefits of an agricultural research institute", Agricultural Economics Society Conference, Manchester.

Bengston, D.N. (1984), "Economic impacts of structural particleboard research", Forest Science 30(3):685–697.

Bertelsen, M., and S. Ouédraego (N.d.), "The value of research on indigenous knowledge: Preliminary evidence from the case of zai in Burkina Faso", Mimeo (Purdue University).

Birkhaeuser, D., R.E. Evenson and G. Feder (1991), "The economic impact of agricultural extension: A review", Economic Development and Cultural Change 39(3):607–650.

Bojanic, A., and G. Echeverría (1990), "Refornos a la inversiòn en investigaciòn agricola en Bolivia: El caso de la soja", Documento de frabajo (ISNAR, The Hague).

Boughton, D., and B. Henry de Frahan (1994), "Agricultural research impact assessment: The case of maize technology adoption in Southern Mali", International Development Working Paper No. 41 (Michigan State University, East Lansing, Michigan).

Boyce, J.K., and R.E. Evenson (1975), Agricultural Research Extension Programs (Agricultural Development Council, Inc., New York).

Boyle, G.E. (1986), "An exploratory assessment of the returns to agricultural research in Ireland, 1963–1983", Irish Journal of Agricultural Economics and Rural Sociology 11:57–71.

Braha, H., and L. Tweeten (1986), "Evaluating past and prospective future payoffs from public investments to increase agricultural productivity", Technical Bulletin T-165 (Agricultural Experiment Station, Oklahoma State University).

Bredahl, M., and W. Peterson (1976), "The productivity and allocation of research: U.S. agricultural experiment stations", American Journal of Agricultural Economics 58:684–692.

Brinkman, G.L., and B.E. Prentice (1985), "Returns to a provincial economy from investment in agricultural research: The case of Ontario in economics of agricultural research in Canada", K.K. Klein and W.H. Furtan, eds. (The University of Calgary Press, Calgary).

Brunner, A.D., and J.K. Strauss (1986), "The social returns to public R&D in the U.S. wood preserving industry (1950–1980)", Draft (Duke University).

Byerlee, D. (1991), "Adaptation and adoption of seed-fertilizer technology: Beyond the green revolution", paper presented at the Conference on Mechanisms of Socio-Economic Change in Rural Areas, Canberra, Australia.

Byerlee, D., and G. Traxler (1995), "National and international wheat improvement research in the post-green revolution period: Evolution and impacts", American Journal of Agricultural Economics 77:268–278.

Capule, C.A. (1977), "Education, extension and national status in Laguna Rice Household", M.A. Thesis (University of the Philippines).

Chang, S.U. (1986), "The economics of optimal stand growth and yield information gathering", report submitted to the USDA Forest Service (North Central Experiment Station, University of Kentucky).

Chavas, J.-P., and T.L. Cox (1992), "A nonparametric analysis of the influence of research on agricultural productivity", American Journal of Agricultural Economics 74:583–591.

Chisi, M., P. Anandajayasekeram, D. Martella, M. Ahmed and M. Mwape (1997), Impact Assessment of Sorghum Research in Zambia (SACCAR, Botswana).

Chou, E.C., and L.J. Lau (1987), "Farmer ability and farm productivity: A study of households in the Chiangmai Valley, Thailand 1972–1978", World Bank Discussion Paper, Education and Training Series, EDT Report 62 (World Bank, Washington, D.C.).

Cline, P.L. (1975), "Sources of productivity change in United States agriculture", Ph.D. Dissertation (Oklahoma State University).

Cotlear, D. (1986), "Farmer education and farm efficiency in Peru: The role of schooling, extension services and migration", World Bank Discussion Paper, Education and Training Series, Report No. EDT 49 (The World Bank).

da Cruz, E.R., and A.F.D. Avila (1983), "Reforno dos investimentos da EMBRAPA no area de abrangencia do BIRD 1", Brasilia, EMBRAPA-DDM (EMBRAPA-DEP Documentos, 19).

da Cruz, E.R., and R.E. Evenson (1997), "Technological spillovers in southern cone agriculture", Economia Aplicada 1(4):709–730.

da Cruz, E.R., V. Palma and A.F.D. Avila (1982), "Taxas de retorno dos investimentos da EMBRAPA: Investimentos totals e capital fisico", Brasilia, EMBRAPA-DID (EMBRAPA-DDM, Documentos, 1).

da Silva, G.L.S.P. (1984), "Contribucao s pesquisa e da extensao rural para a produtividade agricola: Observacoes no Caso de Sa Paulo", in: Congresso Brasileiro de Economia e Sociologia Rural, Anais 22, V.2. Brasilia, D.F. SOBER.

Davis, J.S. (1979), "Stability of the research production coefficient for U.S. agriculture", Ph.D. Dissertation (University of Minnesota).

Davis, J.S., and W. Peterson (1981), "The declining productivity of agricultural research", in: G.W. Norton, W.L. Fishel, A.A. Paulsen and W.B. Sundquist, eds., Evaluation of Agricultural Research, Miscellaneous Publication 8-1981 (Minnesota Agricultural Experiment Station, University of Minnesota).

Deaton, A., and D. Benjamin (1988), "The living standards survey and price policy reform: A study of cocoa and coffee production in Cote d'Ivoire", Living Standards Measurement Study, Working Paper No. 44 (The World Bank).

del Rey, E.C. (1975), "Rentabildad de la estaciòn experimental agricola de Tucumòn", 1943–64, Xa Reuniòn Anual de la Asociaciòn Argentina de Economia Politico, Tomo 1, Mar del Plata, Argentina.

Dey, M.M., and R.E. Evenson (1991), "The economic impact of rice research in Bangladesh" (Bangladesh Rice Research Institute, Gazipur, Bangladesh; International Rice Research Institute, Los Banos, Philippines; and Bangladesh Agricultural Research Council, Dhaka, Bangladesh).

Doyle, C.J., and M.S. Ridout (1985), "The impact of scientific research on UK agricultural productivity", Research Policy 14:109–116.

Duncan, R.C. (1972). "Evaluating returns to research in pasture improvement", Australian Journal of Agricultural Economics 16:153–168.

Easter, K.W., and G.W. Norton (1977), "Potential returns from increased research budgets for the Land-Grant universities", Agricultural Economics Research 29(4):127–133.

Echeverría, R.G. (1990), "Assessing the impact of agricultural research", in: Methods for Diagnosing Research System Constraints and Assessing the Impact of Agricultural Research, Vol. II: Assessing the Impact of Agricultural Research (ISNAR, The Hague).

Eddleman, B.R. (1977), "Impacts of reduced federal expenditures for agricultural research and education", IR-6 Information Report 60.

Elias, V.J. (1971), " Investigaciòn y desarroilo econòmico", Documento de trafajo de investigaciòn y desarrollo No. 7 (Universidad Nacional de Tucumò, Argentina).

Ernstberger, J. (1989), "Wohlfahrtseffekte der Entwicklung und Einfuhrung neuer Relssorten in Brasillen", Ph.D. Dissertation (Technische Universität München).

Evenson, R.E. (1968), "The contribution of agricultural research and extension to agricultural production", Ph.D. Dissertation (University of Chicago).

Evenson, R.E. (1969), "International Transmission of Technology in Sugarcane Production" (Economic Growth Center, Yale University, New Haven).

Evenson, R.E. (1979), "Agricultural research, extension and productivity change in U.S. agriculture: A historical decomposition analysis", Agricultural Research and Extension Evaluation Symposium, May 21–23, 1979, Moscow, Idaho.

Evenson, R.E. (1982), "Observations on Brazilian agricultural research and productivity", Revista de Economia Rural 20:368–401.

Evenson, R.E. (1987), "The international agricultural research centers: their impact on spending for national agricultural research and extension", CGIAR Study Paper No. 22 (The World Bank, Washington, D.C.).

Evenson, R.E. (1988), "Estimated economic consequences of PIDAP I and PIDAP II programs for crop production", unpublished (Yale University, Economic Growth Center).

Evenson, R.E. (1989), "Productivity decomposition in Brazilian agriculture", unpublished manuscript (Economic Growth Center, Yale University, New Haven, CT).

Evenson, R.E. (1991), "Research and extension in agricultural development", Forum Valuazione 2 (November).

Evenson, R.E. (1992), " Notes on the measurement of the economic consequences of agricultural research investments", in: D.R. Lee, S.K. and N. Uphoff, eds., Assessing the Impact of International Agricultural Research for Sustainable Development, Proceedings from a Symposium at Cornell University (CHFAD, Ithaca, New York).

Evenson, R.E. (1994), "Analyzing the transfer of agricultural technology", in: J.R. Anderson, ed., Agricultural Technology: Policy Issues for the International Community (CAB International, Wallingford, U.K.).

Evenson, R.E., E. Abdurachman, B. Hutabarat and A.C. Tubagus (1994), "Economic impacts of agricultural research in Indonesia", Study Report.

Evenson, R.E., and A.F. Avila (1996), "Productivity change and technology transfer in the Brazilian grain sector", Revista de Economia Rural.

Evenson, R.E., Q.T. Azam and E. Bloom (1991), Agricultural Research Productivity in Pakistan (Pakistan Agricultural Research Council, Islamabad).

Evenson, R.E., and V. Bindlish (1993), "Evaluation of the performance of T&V extension in Kenya", World Bank Agricultural and Rural Development Series #7 (World Bank).

Evenson, R.E., and V. Bindlish (1997), "The impact of T&V extension in Africa: The experience of Kenya and Burkina Faso" (World Bank Observer).

Evenson, R.E., V. Bindlish and M. Gbetibouo (1995), "Evaluation of T&V extension in Burkina Faso", World Bank Technical Paper Number 226 (African Technical Department Series).

Evenson, R.E., and B. Bravo-Ureta (1994), "Efficiency in agricultural production: The case of peasant farmers in eastern Paraguay", Agricultural Economics 10(1).

Evenson, R.E., and C. David (1993), Adjustment and Technology: The Case of Rice (OECD).

Evenson, R.E., and P. Flores (1978), Economic Consequences of New Rice Technology in Asia (International Rice Research Institute, Los Banos, Laguna, Philippines).

Evenson, R.E., and D. Gollin (1996), "Genetic resources, international organizations, and rice varietal improvement", Economic Development and Cultural Change 45(3):471–500.

Evenson, R.E., R. Herdt and M. Hossain (1996), Rice Research in Asia: Progress and Priorities (CAB International, Wallingford, U.K.).

Evenson, R.E., and W. Huffman (1993), "The effects of R&D on farm size, specialization and productivity", in: S.R. Johnson and S.A. Martin, eds., Industrial Policy for Agriculture in the Global Economy, Chapter 3 (Iowa State University Press, Ames, Iowa).

Evenson, R.E., and D. Jha (1973), "The contribution of agricultural research systems to agricultural production in India", Indian Journal of Agricultural Economics 28(4):212–230.

Evenson, R.E., and Y. Kislev (1975), Agricultural Research and Productivity (Yale University Press, New Haven, CT).

Evenson, R.E., and J. McKinsey (1991), "Research, extension, infrastructure and productivity change in Indian agriculture", in: R.E. Evenson and C.E. Pray, eds., Research and Productivity in Asian Agriculture (Cornell University Press, Ithaca, N.Y.).

Evenson, R.E., and C.E. Pray (1991), Research and Productivity in Asian Agriculture (Cornell University Press).

Evenson, R.E., C.E. Pray and M.W. Rosegrant (1999), Agricultural Research and Productivity Growth in India, Research Report 109 (International Food Policy Research Institute).

Evenson, R.E., and J. Quizon (1991), "Technology, infrastructure, output supply, and factor demand in Philippine agriculture", in: Research and Productivity in Asian Agriculture (Cornell University Press, Ithaca, NY).

Evenson, R.E., and M. Rosegrant (1993), "Agricultural productivity growth in Pakistan and India: A comparative analysis", The Pakistan Development Review 32(4).

Ewell, P. (1992), "The PRAPACE network: CIPNARS collaboration for sustainable agricultural production in Africa", papers presented at the Symposium on the Impact of Technology on Agricultural Transformation in Sub-Sahara Africa, Washington, D.C.

Fan, S., and P.G. Pardey (1992), Agricultural Research in China: Its Institutional Development and Impact (International Service for National Agricultural Research, The Hague, Netherlands).

Feder, G., R. Slade and L. Lau (1985), "The impact of agricultural extension: The training and visit system in Haryana", World Bank Staff Working Paper No. 756 (The World Bank).

Feijòo, V.M. (1984), "La rentabilldad de la inversiòn en investigaciòn agricola", XIX a Reuniòn Anual de la Asociacion Argentina de Economia Politica, Tomo I (Misiones, Argentina).

Fishel, W.L., ed. (1971), Resource Allocation in Agricultural Research (University of Minnesota Press, Minneapolis, MN).

Fisher, M.G., A. Fall and M. Sidibé (1995), "The impact of rice research in the Senegal river valley", Mimeo (ISRA/BAME, Dakar, Senegal).

Flores, P., R.E. Evenson and Y. Hayami (1978), "Social returns to rice research in the Philippines: Domestic benefits and foreign spillover", Economic Development and Cultural Change 26:591–607.

Fonseca, M.A.S. (1976), "Reforno social a los investimentos em pesquisa na cultiura do cafe", Master's Thesis (ESALCQ, Piracicaba, Brasil).

Fox, G. (1986), "Underinvestment, myopia and commodity bias: A test of three propositions of inefficiency in the U.S. agricultural research system" (University of Guelph, Department of Agricultural Economics and Business, Ontario).

Fox, G., R. Roberts and G.L. Brinkman (1989), "The return to Canadian federal dairy cattle research – 1968 to 1984", Working Paper 39/20 (University of Guelph, Department of Agriculture and Business).

Fuglie, K., N. Ballenger, K. Day, C. Klotz, M. Ollinger, J. Reilly, U. Vasavada and J. Yee (1996), "Agricultural research and development: Public and private investments under alternative markets and institutions", Agricultural Economic Report No. 735 (Natural Resources and Environment Division, Economic Research Service, U.S. Department of Agriculture).

Gautam, M., and J.R. Anderson (1998), "Reconsidering the evidence on the returns to T&V extension in Kenya" (Operations Evaluations Department, World Bank).

Gopinath, M., and T.L. Roe (1996), "R&D spillovers: Evidence from U.S. food processing, farm machinery and agriculture", Bulletin No. 96-2 (Economic Development Center, Department of Applied Economics, University of Minnesota, St. Paul, Minnesota).

Griliches, Z. (1958), "Research costs and social returns: Hybrid corn and related innovations", Journal of Political Economy 66:419–431.

Griliches, Z. (1964), "Research expenditures, education and the aggregate agricultural production function", American Economic Review 54:961–974.

Griliches, Z. (1998), Technology, Education and Productivity (Basil Blackwell, Oxford, UK) Chapter 14, 227–243.

Grossfield, K., and J.B. Heath (1966), "The benefit and cost of government support for research and development: A case study", Economic Journal 76:537–549.

Halim, A. (1976), "Schooling and extension and income producing Philippine households" (Bangladesh Agricultural University, Department of Agricultural Extension and Teachers Training).

Haque, A.K.E., G. Fox and G.L. Brinkman (1987), "The rate of return to egg research in Canada – 1968 to 1984", Working Paper 87/10 (Department of Agricultural Economics and Business, University of Guelph).

Harken, B.R. (1973), "The contribution of schooling to agricultural modernization: An empirical analysis", in: P. Foster and J.R. Sheffield, eds., Education and Rural Development (Evans Brothers Ltd.).

Harvey, A. (1988), "Research priorities in agriculture", Journal of Agricultural Economics 39:81–97.

Hasting, T. (1981), "The impact of scientific research on Australian rural productivity", Australian Journal of Agricultural Economics 25(1):48–59.

Hayami, Y., and N. Akino (1977), "Organization and productivity of agricultural research systems in Japan", in: T.M. Arndt, D.G. Dalrymple, and V.W. Ruttan, eds., Resource Allocation and Productivity in National and International Agricultural Research (University of Minnesota Press, Minneapolis).

Haygreen, J., H. Gregerson, I. Holland and R. Stone (1986), "The economic impact of timber utilization research", Forest Products Journal 36(2):12–20.

Henry de Frahan, B., D. Youssouf, S. Traore and M.B. Diarra (1989), "Feasibility study for the expansion of the farming systems research division in the fifth region of Mali" (Ministere de l'Agriculture and Michigan State University, Bamako).

Herruzo, A.C. (1985), "Returns to agricultural research: Rice breeding in Spain", European Review of Agricultural Economics 12:265–282.

Hertford, R., J. Ardila, A. Rocha and G. Trujillo (1977), "Productivity of agricultural research in Colombia", in: T.M. Arndt, D.G. Dalrymple and V.W. Ruttan, eds., Resource Allocation and Productivity in National and International Agricultural Research (University of Minnesota Press, Minneapolis).

Hines, J. (1972), "The utilization of research for development: Two case studies in rural modernization and agriculture in Peru", Ph.D. Dissertation (Princeton University).

Hong, K.Y. (1975), "An estimated economic contribution of schooling and extension in Korean agriculture", Ph.D. Dissertation (University of the Philippines, Los Banos).

Hopcraft, P.N. (1974), "Human resources and technical skills in agricultural development: An economic evaluation of education investments in Kenya's small farm sector", Ph.D. Dissertation (Stanford University).

Howard, J., G. Chitalu and S. Kalonge (1993), "The impact of investments in maize research and dissemination in Zambia. Part I: Main report", International Development Working Paper No. 39/1 (Michigan State University, East Lansing, Michigan).

Huffman, W.E. (1974), "Decision making: The role of education", American Journal of Agricultural Economics 56:672–683.

Huffman, W.E. (1976), "The productive value of human time in U.S. agriculture", American Journal of Agricultural Economics 58(4):672–683.

Huffman, W.E. (1981), "Black-white human capital differences: Impact on agricultural productivity in the U.S. south", American Economic Review 71(1):94–107.

Huffman, W., and R.E. Evenson (1989), "Supply and demand functions for multi-product U.S. cash grain farms", American Journal of Agricultural Economics 71(3):761–773.

Huffman, W.E., and R.E. Evenson (1993), "Science for agriculture: A longterm perspective" (Iowa State University Press, Ames).
Hust, M., G. Fox and G. Brinkman (1988), "The return to Canadian federal swine research – 1968 to 1984", Working Paper 88/4 (Department of Agricultural Economics and Business, University of Guelph).
Iqbal, M. (1991), "The rate of returns to investment in agricultural research: The case of rice and cotton in Pakistan", Dissertation (Ohio State University).
Isinika, A.C. (1995), "Assessing the effect of agricultural research expenditures on agricultural productivity in Tanzania", Ph.D. Dissertation (University of Kentucky, Lexington, Kentucky).
Jamison, D., and L.I. Lau (1982), Farmer Education and Farm Efficiency, World Bank Research Publication (Johns Hopkins University Press, Baltimore).
Jamison, D., and P.R. Moock (1984), "Farmer education and farm efficiency in Nepal: The role of schooling, extension services and cognitive skills", World Development 12(1):67–86.
Johnson, D.K., and R.E. Evenson (1999), "R&D spillovers to agriculture: Measurement and application", Contemporary Economic Policy 17(4):432-456.
Judd, M.A., J.K. Boyce and R.E. Evenson (1986), "Investing in agricultural supply: The determinants of agricultural research and extension", Economic Development and Cultural Change 35(1):77–113.
Kahlon, A.S., H.K. Bal, P.N. Saxena and D. Jha (1977), "Returns to investment in research in India", in: T.M. Arndt, D.G. Dalrymple and V.W. Ruttan, eds., Resource Allocation and Productivity in National and International Agricultural Research (University of Minnesota Press, Minneapolis).
Karanja, D.D. (1990), "The rate of return to maize research in Kenya: 1955–88", M.S. Thesis (Department of Agricultural Economics, Michigan State University, East Lansing, Michigan).
Khan, M.H., and A.H. Akbari (1986), "Impact on agricultural research and extension on crop productivity in Pakistan: A production function approach", World Development 14:757–762.
Khatri, Y.J. (1994), "Technical change and the returns to research in UK agriculture, 1953–1990", Ph.D. Dissertation (Department of Agricultural Economics and Management, University of Reading, England).
Khatri, Y., and C. Thirtle (1996), "Supply and demand functions for UK agriculture: Biases of technical change and the returns to public R&D", Journal of Agricultural Economics 47 (3):338–354.
Khatri, Y., C. Thirtle and J. van Zyl (1995), "South African agricultural competitiveness: A profit function approach to the effects of policy and technology", in: G.H. Peters and D. Hedley, eds., Agricultural Competitiveness: Market Forces and Policy Choice, Proceedings of the 22nd International Conference of Agricultural Economists, Harare, Zimbabwe.
Kim, J.I., and L.J. Lau (1994), "The sources of economic growth in the east Asian newly industrialized countries", Journal of Japanese and International Economics 235–271.
Kislev, Y., and M. Hoffman (1978), "Research and productivity in wheat in Israel", Journal of Development Studies 14(2):165–181.
Knutson, M., and L.G. Tweeten (1979), "Toward an optimal rate of growth in agricultural production research and extension", American Journal of Agricultural Economics 61:70–76.
Kortum, S. (1994), "A model of research, patenting, and productivity growth", Institute for Economic Development, Discussion Paper Series 37 (February) (Boston University).
Kumar, P., and Mruthyunjaya (1992), "Measurement and analysis of total factor productivity growth in wheat", Indian Journal of Agricultural Economics 47 (7):451–458.
Kupfuma, B. (1994), "The payoffs to hybrid maize research in Zimbabwe: An economic and institutional analysis", M.S. Thesis (Department of Agricultural Economics, Michigan State University, East Lansing, Michigan).
Kuyvenhoven, A., J.A. Becht and R. Ruben (1996), "Public investment for soil improvement in West Africa: Economic criteria for phosphate rock use to enhance soil fertility management", Mimeo, Public Goods and Services Project, Wageningen Agricultural University (Wageningen, The Netherlands).
Laker-Ojok, R. (1994), "The rate of return to agricultural research in Uganda: The case of oilseeds and maize", International Development Working Paper No. 42 (Michigan State University, East Lansing, Michigan).
Latimer, R. (1964), "Some economic aspects of agricultural research and extension in the U.S.", Ph.D. Dissertation (Purdue University).

Lever, B.G. (1970), Agricultural Extension in Botswana, Development Study No. 7 (University of Reading, Department of Agricultural Economics).

Librero, A.R., and N. Emlano (1990), Estimating Returns to Research Investment in Poultry in the Philippines (PCARRD, Los Banos, Laguna).

Librero, A.R., N.E. Emlano and M.B. Ocampo (1988), Estimating Returns to Research Investment in Mango in the Philippines (PCARRD, Los Banos, Laguna).

Librero, A., and M. Perez (1987), "Estimating returns to research investment in corn in the Philippines" (Socio-Economic Research Department, Philippine Council for Agriculture, Forestry, Natural Resources Research and Development, Los Banos).

Lu, Y.C., P. Cline and L. Quance (1979), "Prospects for productivity growth in U.S. agriculture", Agricultural Economics Report No. 435 (USDA-ESCS, Washington, D.C.).

Luz Barbosa, M.K.T., E. Rodrigues da Cruz and A.F.D. Avila (1988), "Beneficios sociates y econòmicos de la Investigaciòn de EMBRAPA: Una reevaluaciòn", paper presented at Seminario Latinoamericano y del Caribe Sobre Mecanismos de Evaluaciòn en Instituclones de Investigaciòn Agraria, Palpa, Colombia.

Macmillan, J., G. Mudimuk, J. MacRobert, L. Rugube, E. Guveya, L. Mutemeri and K. Chanakanyuka (1991), "Ex ante B/C analysis of small farm maize research demonstrations, Zimbabwe", Working Paper (Department of Agricultural Economics and Extension, University of Zimbabwe).

Mairesse, J., and P. Mohnen (1995), "Research and development and productivity – A survey of the econometric literature", Preliminary Version of paper (April).

Makana, D.W., and J.F. Oehmke (1996), "The history of and returns to Kenya wheat research" (Department of Agricultural Economics, Michigan State University, East Lansing, Michigan).

Makau, B.F. (1984), "Measurement of economic returns to wheat research in Kenya", unpublished M.A. Thesis (University of Nairobi, Kenya).

Makki, S.S., and L.G. Tweeten (1993), "Impact of research, extension, commodity programs, and prices on agricultural productivity", paper presented at the 1993 meetings of the American Agricultural Economics Association, Orlando, Florida.

Makki, S.S., L.G. Tweeten and C.S. Thraen (1996), "Returns to agricultural research: Are we assessing right?", contributed paper proceedings from the Conference on Global Agricultural Science Policy for the Twenty-First Century, August 26–28, Melbourne, Australia, pp. 89–114.

Marsden, J.S., G.E. Martin, D.J. Parham, T.J. Ridsdill Smith and B.G. Johnston (1980), Returns on Australian Agricultural Research, The joint Industries Assistance Commission – CSIRO benefit-cost study of the CSIRO Division of Entomology.

Martinez, J.C., and C. Sain (1983), "The economic return to institutional innovations in national agricultural research: On-farm research in IDIAP Panama", CIMMYT Economics Program Working Paper 04/83 (CIMMYT, Mexico D.F.).

Martinez, S., and G.W. Norton (1986), "Evaluating privately funded public research: An example with poultry and eggs", Southern Journal of Agricultural Economics (July) 129–140.

Masters, W.A., T. Bedingar and J.F. Oehmke (1996), "The impact of agricultural research in Africa: Aggregate and case study evidence", Mimeo (Department of Agricultural Economics, Purdue University, West Lafayette, Indiana).

Mazzueato, V. (1992), "Non-research policy effects on the rate of return to maize research in Kenya: 1955–88", M.S. Thesis (Department of Agricultural Economics, Michigan State University, East Lansing, Michigan).

Mazzueato, V., and S. Ly (1994), "An economic analysis of research and technology transfer of millet, sorghum and cowpeas in Niger" (ISNAR/East Lansing, The Hague, Netherlands; Michigan State University, Michigan).

Mohan, R., and R.E. Evenson (1975), "The intensive agricultural districts program in India: A new evaluation", Journal of Development Studies 11:135–154.

Monares, A. (1984), "Building an effective potato country program: The case of Rwanda", CIP Social Science Department Working Paper 1984-3 (Lima, Peru).

Monteiro, A. (1975), "Avaliacao economica da pesquisa agricola: O casu do cacau no Brasil", Master's Thesis (Vicosa, UFV).

Moock, P.R. (1973), "Managerial ability in small farm production: An analysis of maize yields in the vihiga division of Kenya", Ph.D. Dissertation (Columbia University).

Moock, P.R. (1976), "The efficiency of women as farm managers: Kenya", American Journal of Agricultural Economics 58(5):831–835.

Moricochi, F. (1980), Pesquisa e assistencia tecnica no cltricultura: Custos e refornos sociates, Master's Thesis (ESALQ, Piracicaba, Brasil).

Morris, M.L., H.J. Dubin and T. Pokhrel (1992), "Returns to wheat research in Nepal", Economics, Working Paper 92-04 (CIMMYT).

Morris, M.L., H.J. Dubin and T. Pokhrel (1994), "Returns to wheat breeding research in Nepal", Agricultural Economics 10:269–282.

Muchnik, E. (1985), As cited by Scobie and Eveleens (1987, p. 57).

Mudhara, M., P. Anandajayasekeeram, B. Kupfuma and E. Mazhangara (1995), Impact Assessment of Cotton Research and Enabling Environment in Zimbabwe, 1970–1995 (SACCAR, Botswana).

Nagy, J.G. (1983), "Estimating the yield advantage of high yielding wheat and maize: The use of Pakistani on-farm yield constraints data", The Pakistan Development Review 93.

Nagy, J.G. (1985), "The overall rate of return to agricultural research and extension investments in Pakistan", Pakistan Journal of Applied Economics 4(1):17–28.

Nagy, J.G. (1991), "Returns from agricultural research and extension in wheat and maize in Pakistan", in: R.E. Evenson and C.E. Pray, eds., Research and Productivity in Asian Agriculture (Cornell University Press, Ithaca, N.Y.).

Nagy, J.G., and W.H. Furtan (1978), "Economic costs and returns for crop development research: The case of rapeseed breeding in Canada", Canadian Journal of Agricultural Economics 26:1–14.

Newman, D.H. (1986), "An econometric analysis of aggregate gains from technical change in southern softwood forestry", Ph.D. Dissertation (Duke University).

Norgaard, R.B. (1988), "The biological control of cassava mealybug in Africa", American Journal of Agricultural Economics 70(2):366–371.

Norton, G.W. (1981), "The productivity and allocation of research: U.S. agricultural experiment stations, revisited", in: G.W. Norton, W.L. Fishel, A.A. Paulsen and W.B. Sundquist, eds., Evaluation of Agricultural Research, Miscellaneous Publication 8-1981 (Minnesota Agricultural Experiment Station, University of Minnesota).

Norton, G.W., J.D. Coffey and E. Berrier Frye (1984), "Estimating returns to agricultural research, extension, and teaching at the state level", Southern Journal of Agricultural Economics (July) 121–128.

Norton, G.W., V. Ganoza and C. Pomareda (1987), "Potential benefits to agricultural research and extension in Peru", American Journal of Agricultural Economics 69:274–257.

Norton, G.W., J. Ortiz and P.G. Pardey (1992), "The impact of foreign assistance on agricultural growth", Economic Development and Cultural Change 40(4):775–786.

Norton, G.W., and R. Paczkowski (1993), "Reaping the return on agricultural research and education in Virginia", Information Series 93-3 (College of Agriculture and Life Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia).

Oehmke, J.F. (1996), "The maturation of the U.S. agricultural research system and its impacts on productivity", Staff Paper #96-85 (Department of Agricultural Economics, Michigan State University, East Lansing, Michigan).

Oehmke, J.F., L. Daniels, J. Howard, M. Maredia and R. Bernsten (1991), "The impact of agricultural research: A review of the ex-post assessment literature with implications for Africa", Mimeo (Department of Agricultural Economics, Michigan State University, East Lansing, Michigan).

Oehmke, J.F., and W.A. Masters (1997), "The impacts of and returns to African agricultural research", Mimeo (Department of Agricultural Economics, Michigan State University, East Lansing, Michigan).

Otto and J. Havlicek, Jr. (1981), "As cited in Evenson, R.E. 1980. Human capital and agricultural productivity change", Draft (Yale University).

Ouedraego, S., and L. Illy (1996), "Evaluation de l'impact economique des cordons pierreux: Cas du plateau central au Burkina Faso", Mimeo (INERA, Ougadougou, Burkina Faso).

Ouedraego, S., L. Illy and F. Lompo (1995), "Evaluation de l'impact economique de la recherche et la vulgarisation agricole: Cas du maïs dans l'"ouest du Burkina Faso", Mimeo (INERA, Ougadougou, Burkina Faso).

Pachico, D.H., and J.A. Ashby (1976), "Investments in human capital and farm productivity: Some evidence from Brazil", Study prepared for Cornell University.

Pardey, P.G., and J. Roseboom (1989), ISNAR Agricultural Research Indicator Series: A Global Data Base on National Agricultural Research Systems (Cambridge University Press, New York).

Patrick, G.F., and E.W. Kehrberg (1973), "Costs and returns of education in five agricultural areas of Eastern Brazil", American Journal of Agricultural Economics 55:145–154.

Pee, T.Y. (1977), "Social returns from rubber research on peninsular Malaysia", Ph.D. Dissertation (Michigan State University).

Perraton, H.D., D. Jamison and F. Orivel (1985), "Mass media for agricultural extension in Malawi", Basis Education and Agricultural Extension, World Bank Staff Working Papers, No. 564 (Washington, D.C.).

Peterson, W.L. (1967), "Returns to poultry research in the United States", Journal of Farm Economics 49:656–669.

Peterson, W.L., and J.C. Fitzharris (1977), "The organization and productivity of the federal state research system in the United States", in: T.M. Arndt, D.G. Dalrymple and V.W. Ruttan, eds., Resource Allocation and Productivity in National and International Agricultural Research (University of Minnesota Press, Minneapolis).

Pinazza, A.H., A.C. Gemente and S. Matsuoka (1984), Reforno social dos recursos aplicados em pesquisa canavielra: O caso da varledade NA56-79, Congresso Braslieiro de Economia a Sociologic Rural, Salvador, BA, Anals, SOBER (21).

Power, A.P., and N.P. Russell (1988), "Economic evaluation of scientific research: A case study of the rate of return to poultry layer feeding system research", Government Economic Service Working Paper No. 101, London.

Pray, C.E. (1978), "The economics of agricultural research in British Punjab and Pakistani Punjab, 1905–75", Ph.D. Dissertation (University of Pennsylvania).

Pray, C.E. (1980), "The economics of agricultural research in Bangladesh", Bangladesh Journal of Agricultural Economics 2:1–36.

Pray, C.E., and Z. Ahmed (1991), "Research and agricultural productivity growth in Bangladesh", in: R.E. Evenson and C.E. Pray, eds., Research and Productivity in Asian Agriculture (Cornell University Press, Ithaca).

Pudasaini, S.P. (1983), "The effects of education in agriculture: Evidence from Nepal", American Journal of Agricultural Economics 65(3):509–515.

Purcell, D.L., and J.R. Anderson (1997), Agricultural Extension and Research (The World Bank, Washington, D.C.).

Ribeiro, J.L. (1982), "Retorno a Investimentos em Pesquisa Agropecnaria", Inf. Agropec. 8:39–44.

Roessing, A.C. (1984), "Taxa interna de retorno dos investimentos em pesquisa de soja", Documento 6 (EMBRAPA-CNPS, Brasilia, D.F.).

Romer, P. (1986), "Increasing returns and long-run growth", Journal of Political Economy 94:1002–1037.

Romer, P. (1990), "Endogenous technical change", Journal of Political Economy 98(5):S71–S102.

Rosegrant, M., and R.E. Evenson (1993), "Agricultural productivity growth in Pakistan and India: A comparative analysis", The Pakistan Development Review 32(4):433–438.

Ruttan, V.W. (1998), "International agricultural research: Four papers", Staff Paper Series P98-4 (Department of Applied Economics, University of Minnesota).

Salmon, D. (1984), "An evaluation of investment in agricultural research in Indonesia, 1965–1977", Ph.D. Dissertation (University of Minnesota).

Sanders, J.H. (1994), "Economic impact of the commodity research networks of SAFGRA", in: J.H. Sanders, T. Bezuneh and A.C. Schroeder, eds., Impact Assessment of the SAFGRAD Commodity Networks (US-AID/Africa Bureau, Washington, D.C.).

Schmitz, A., and D. Seckler (1970), "Mechanized agriculture and social welfare: The case of the tomato harvester", American Journal of Agricultural Economics 52:569–577.

Schwartz, L.A., and J.F. Oehmke (1990), "Applying a benefit/cost approach or rate of return analysis to specific CRSP projects", paper presented at the CRSP Conference, Michigan State University, East Lansing, Michigan, Mimeo (Department of Agricultural Economics, Michigan State University).

Schwartz, L., J.A. Sterns and J.F. Oehmke (1993), "Economic returns to cowpea research, extension and input distribution in Senegal", Agricultural Economics 8:161–171.

Schwartz, L.A., J.A. Sterns, J.F. Oehmke, and R.D. Freed (1989), "Impact study of the bean/cowpea collaborative research support program (CRSP) for Senegal", Draft (Department of Agricultural Economics, Michigan State University).

Scobie, G.M., and W.M. Eveleens (1987), "The return to investment in agricultural research in New Zealand: 1926–27 to 1983–84", MAF Economics Research Report 1/87 (Ruakura Agriculture Centre, Hamilton, New Zealand).

Scobie, G.M., and R.T. Posada (1978), "The impact of technical change on income distribution: The case of rice in Colombia", American Journal of Agricultural Economics 60:85–92.

Seck, P.A., M. Sidibé and A.M. Bèye (1995), "Impact social de la recherche et du transfer du technologies sur le coton au Senegal", Mimeo.

Seidi, S. (1996), "An economic analysis of rice research, extension, and seed production in Guinea-Bissau: Preliminary evidence from the case of swamp mangrove rice", preliminary report to Rice Economics Task Force of West African Rice Development Association, Bissau, Guinea-Bissau.

Seldon, B.J. (1987), "A nonresidual estimation of welfare gains from research: The case of public R&D in a forest product industry", Southern Economic Journal 54:64–80.

Seldon, B.J., and D.H. Newman (1987), "Marginal productivity of public research in the softwood plywood industry: A dual approach", Forest Science.

Sere, C., and L.S. Jarvis (1998), "The betting line of beef: Ex ante estimates of improved pasture research benefits for the Latin American tropics", paper presented at ISNAR/Rutgers Agricultural Technology Management Workshop, 6–8 July, New Jersey.

Setboonsarng, S., and R.E. Evenson (1991), "Technology, infrastructure, output supply and factor demand in Thailand's agriculture", in: R.E. Evenson and C. Pray, eds., Research Productivity and Income in Asian Agriculture (Cornell University Press, Ithaca).

Smale, M., and P. Heisey (1994), "Maize research in Malawi revisited: An emerging success story", Journal of International Development.

Smale, M., R.P. Singh, K. Sayre, P. Pingali, S. Rajaram and H.J. Dubin (1998), "Estimating the economic impact of breeding nonspecific resistance to leaf rust in modern bread wheat", Plant Disease.

Smith, B., G.W. Norton and J. Havlicek, Jr. (1983), "Impacts of public research expenditures on agricultural value-added in the U.S. and the northeast", Journal of the Northeastern Agricultural Economics Council 12:109–114.

Sterns, J.A., and R. Bernsten (1994), "Assessing the impact of cowpea and sorghum research and extension: Lessons learned in Northern Cameroon", International Development Working Paper No. 43 (Michigan State University, East Lansing, Michigan).

Sterns, J., J. Oehmke and L. Schwartz (1993), "Returns to education: The impacts of MSU training on West African scientists", Agricultural Economics Report No. 567 (Department of Agricultural Economics, Michigan State University, East Lansing, Michigan).

Sumelius, J. (1987), "The return to investment in agricultural research in Finland 1950–1984", Journal of Agricultural Science in Finland 59:257–353.

Sundquist, W.B., C. Cheng and G.W. Norton (1981), "Measuring returns to research expenditures for corn, wheat, and soybeans", in: G.W. Norton, W.L. Fishel, A.A. Paulsen and W.B. Sundquist, eds., Evaluation of Agricultural Research, Miscellaneous Publication 8-1981 (Minnesota Agricultural Experiment Station, University of Minnesota).

Tang, A. (1963), "Research and education in Japanese agricultural development", Economic Studies Quarterly 13:27–41.

Thirtle, C. (1996), "Producer funding of R&D: Productivity and returns to R&D in British sugar, 1954–93", 1996/1 (Department of Agricultural Economics and Management, University of Reading).

Thirtle, C., and P. Bottomley (1988), "Is publicly funded agricultural research excessive?" Journal of Agricultural Economics 31:27–41 and 91–99.

Thirtle, C., and P. Bottomley (1989), "The rate of return to public sector agricultural R&D in the UK, 1965–80", Applied Economics 21:381–400.

Thirtle, C., P. Bottomley, P. Palladino and D. Shimmelpfennig (1997), "The rise and fall of public sector plant breeding in the UK: A recursive model of basic and applied research, and diffusion", contributed paper for the IAAE Conference, Sacramento, August.

Thirtle, C., D. Hadley and R. Townsend (1995), "Policy-induced innovation in Sub-Saharan African agriculture", Development Policy Review 13(4):323–347.

Thirtle, C., J. Piesse and V. Smith (1997), "An economic approach to the structure, historical development and reform of agricultural R&D in the United Kingdom" (Centre for Agricultural Strategy, University of Reading).

Thirtle, C., R. Townsend, J. Amadi, A. Lusigi and J. van Zyl (1999), "The economic impact of agricultural research council expenditures", forthcoming in Agrekon.

Thirtle, C., and J. van Zyl (1994), "Returns to research and extension in South African commercial agriculture, 1947–91", South African Journal of Agricultural Extension 1–7.

Townsend, R., and J. van Zyl (1997), "The returns to research in wine grapes in South Africa", a report to the ARC.

Townsend, R., J. van Zyl and C. Thirtle (1997), "Assessing the benefits of research expenditures on maize production in South Africa", submitted to Agrekon (July).

Traxler, G., and D. Byerlee (1992), "Economic returns to crop management research in a post-green revolution setting", American Journal of Agricultural Economics 74(3):573–582.

Traxler, G., and P.L. Pingali (1996), "International coordination of research roles in plant genetic resource conservation and use", CIMMYT.

Tre, J.-P. (1995), "The rates of return to mangrove rice research in West Africa", unpublished M.S. Thesis (Purdue University, West Lafayette, Indiana).

Ulrich, A., W.H. Furtan and A. Schmitz (1985), "Public and private returns from joint venture research in agriculture: The case of malting barley", in: K. Klein and W. Furtan, eds., Economics of Agricultural Research in Canada (University of Calgary Press, Calgary).

Unnevehr, L.J. (1986), "Consumer demand for rice grain quality and returns to research for quality improvement in Southeast Asia", American Journal of Agricultural Economics 68:634–641.

Valdivia, C. (1997), "Returns to investments in small ruminant research in Indonesia: The small ruminant collaborative research support program (SR-CRSP) in West Java", Agricultural Economics Working Paper No. 1997-5 (Department of Agricultural Economics, University of Missouri-Columbia, Columbia, Missouri).

Welch, F., and R.E. Evenson (1989), "The impact and pervasiveness of crop and livestock improvement research in U.S. agriculture", Economic Growth Center (Yale University, New Haven, Connecticut).

Wennergren, E.B., and M.D. Whitaker (1977), "Social returns to U.S. technical assistance in Bolivian agriculture: The case of sheep and wheat", American Journal of Agricultural Economics 59:565–569.

Westgate, R.A. (1986), "Benefits and costs of containerized forest tree seedling research in the United States", in: D.P. Burns, ed., Evaluation and Planning of Forestry Research, General Technical Report NE-GTR-111 (USDA Forest Service, Northeastern Forest Experiment Station, Broomall, PA).

White, J.F., and J. Havlicek, Jr. (1982), "Optimal expenditures for agricultural research and extension: Implications on underfunding", American Journal of Agricultural Economics 64(1):47–54.

White, J.F., J. Havlicek, Jr. and D. Otto (1978), "Fifty years of technical change in American agriculture", International Conference of Agricultural Economists, Banff, Alberta, Canada, September 3–12, 1979.

Wise, W.S. (1986), "The calculation rates of return on agricultural research from production functions", Journal of Agricultural Economics 37(2):151–161.

Wise, W.S., and E. Fell (1980), "Supply shifts and the size of research benefits: Comment", American Journal of Agricultural Economics 62(4):838–840.

World Bank (1988), "Cotton development programs in Burkina Faso, Cote d'Ivoire, and Togo", A World Bank Operations Evaluation Study (Washington, D.C., The World Bank).

Yee, J. (1992), "Assessing rates of return to public and private agricultural research", Journal of Agricultural Economics Research 44(1):35–41.

Zachariah, O.E.R., G. Fox and G.L. Brinkman (1988), "The returns to broiler research in Canada – 1968 to 1984", Working Paper 88/3 (Department of Agriculture Economics and Business, University of Guelph).

Zentner, R.P. (1982), "An economic evaluation of public wheat research expenditures in Canada", Ph.D. Dissertation (University of Minnesota).

Chapter 12

THE AGRICULTURAL PRODUCER: THEORY AND STATISTICAL MEASUREMENT

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1. Introdnction

Agricultural production economics grew out of the study of farm management. Farm management grew out of the study of agronomy and horticulture. Early courses in farm management particularly at Cornell were largely empirically based and sought to develop the underlying economic principles through replication of experiments [Jensen (1977)]. "As marginal analysis reached a climax with Alfred Marshall, agricultural economics was just beginning to emerge as a discipline in land-grant colleges" [Johnson (1955), p. 206]. During the 1920s and 1930s, production economics began to emerge as an integrated field that analyzed farm management and production issues from farming to and including marketing of agricultural products. As in other fields of economics, the unifying paradigms for this emerging discipline were marginal economic analysis, comparative advantage, and competition [Jensen (1977)]. That agricultural production and farm management economics embraced these central economic paradigms of the time was indisputable and as such it could properly be viewed as a subdiscipline of economics. Because the issues and problems were agricultural, most agricultural economists to this day reside in colleges of agriculture throughout the world.

The marriage of economic paradigms to farm management and production economic issues is widely viewed as successful. Agricultural economists working with other agricultural scientists have enlightened many both as to normative and positive economic choices. However, many agricultural economists particularly of older vintages likely identify more with agricultural sciences and less with economics compared to younger vintages who tend to identify more with economics as the parent discipline [Pope and Hallam (1986)].

How and why does agricultural production economics differ from the application of economic principles to other production activities in the economy? Clearly, the goods and services studied are different and that alone may justify a separate field of study. However, in a deeper sense, is the current or proper methodology for studying agricultural production different than for studying, say, manufacturing? A basic question that must be addressed in a volume such as this is, "Why is the study of agricultural economics different than the study of the economics of any other sector?" and in particular, "What are the distinguishing features of agricultural production economics?"

In this chapter, we emphasize the production issues that differentiate agriculture from manufacturing. We begin in the following section by identifying a number of unique features of agricultural production – features not necessarily unique in their existence but unique by their combination and predominance in agriculture. While some mathematical characterizations in this section facilitate understanding, they are merely illustrative with formal analysis delayed to later sections. The purpose of Section 2 is to raise issues and questions related to the unique features of agriculture that are addressed in subsequent sections. The general conclusion is that agricultural production is heavily structured because of spatial, temporal, and stochastic issues. Section 3 develops a set of economic principles that are needed to address a sector dominated by such features. Some examples are used to illustrate the points with no attempt to achieve generality.

The general conclusion is that serious errors can be made if structural issues are ignored in analysis. Section 4 then develops some fundamental theoretical considerations needed to address the principles identified in Section 3 with generality at least in a short-run context. This backdrop is used to discuss the extent to which agricultural production economics, as depicted by the previous chapters in this Handbook, has addressed these needs. The implications of these results are that (i) reduced-form approaches that initiate empirical work from an arbitrary specification of the production possibilities frontier cannot determine many important characteristics of technology, (ii) approaches that under-represent structure are not useful for policy analysis because they embed policy assumptions, (iii) both early primal applications and standard current applications of duality have tended to focus on reduced-form representations, (iv) both dual and primal approaches should be expanded to consider a qualifying degree of structure, and (v) examination of structure is limited by data availability. In Section 5 we consider other needed generalizations that come into play in moving beyond the short run and the extent of related empirical progress thus far. This leads to a critical evaluation of the state of data for agricultural production analysis, a call for action to improve the scope of data, and a conclusion that the current state of agricultural production analysis is heavily limited by data availability.

2. Uniqneness of agricnltnral technology

Perhaps the most important reason for studying agricultural production separately is the uniqueness of agricultural technology associated with its biological nature and exposure to widely varying and unpredictable elements of nature. This section discusses some of the main features that differentiate agricultural production: (i) lags and intertemporal complexity with limited observability caused by biological processes, (ii) uncertainty in biological processes related to weather and pests, (iii) multiple outputs with cyclical flexibility in the output mix related to growing seasons, (iv) technological change with fragmented and mixed adoption associated with both physical and biological capital adjustment, and (v) atomistic heterogeneity in major characteristics such as soil productivity, climate, infrastructure, environmental sensitivity, farmer abilities, etc. While some limited parallels can be found with some of these features in other sectors, the combination and extent found in agriculture have critical implications for the ability to represent them empirically. They dramatically affect all other aspects of the agricultural sector including domestic markets, international trade, finance, environmental concerns, and policy issues. For example, unanticipated national crop failures cause dramatic swings in world markets and trade as in the commodity boom of the 1970s [Chambers and Just (1981)], and the spatial correlations of production practices with environmental characteristics dramatically influence environmental quality and response to policies [Just and Antle (1990)].

During the first half century of agricultural economics study, many agricultural production economists cooperated with the biological and soil science disciplines to integrate representations of biological and chemical processes and better represent the intricacies of relevant biological and physical relationships. As in engineering economics, there was a substantive interest in understanding and describing technology in cooperation with other disciplines. This interdisciplinary communication described technology in primal form. Some of the earliest production studies used agronomic data to estimate fertilizer response functions and optimal fertilization rates [Day (1965)]. Over time, a greater understanding of the science of input interactions has been accumulated to allow further economic insights into basic production problems [Berck and Helfand (1990); Paris (1992)]. As agricultural economics has evolved, dual methods have become prominent because of their simplicity, convenience, and power [Binswanger (1974)]. These methods have been widely applied but the applications typically lack the biological and dynamic detail that often accompanies other optimization or econometric models [Bryant et al. (1993); Woodward (1996); Burt (1993); Foster and Burt (1992)]. As a result, questions arise about whether agricultural production economists are now in a poorer position than earlier to assess plausibility of estimates and add cumulatively to a store of stylized facts regarded by the profession to describe agricultural technology. For example, Mundlak's review (2001) of the early production function literature emphasizes elasticity estimates and portrays the cumulative characterization of both production and supply-demand elasticities from that literature. Though no such similar review is available for recent literature, estimates of simple concepts such as elasticities are *remarkably* disparate even when similar methods (e.g., duality) and data are used [Shumway and Lim (1993), Table 3]. In this state of affairs, one must question whether agricultural production economists are approaching or losing track of the goal of better understanding and measuring behavior.

2.1. Sequential biological stages, temporal allocation, and limited observability

Agriculture in much of the world thrives with little division or specialization of labor [Allen and Lueck (1998)] because of (i) the sequential nature of production stages, (ii) non-overlapping annual growing seasons imposed by weather conditions, (iii) long time lags from application of variable inputs to harvest of finished outputs, (iv) relative unobservability of the state of production during this lag, and (v) moral hazard associated with using hired labor in certain stages of production where monitoring the effect on output is difficult.[1] Typically, a single person or family decides what to produce given the current capital stock and available services, and then applies variable inputs stage-by-stage through sequential production stages to produce the final product. A stage-wise delineation of the production process is possible in many cases because a relatively small number of sequential rather than concurrent operations are required. Such a production structure is typically imposed by the biological nature of agricultural

[1] For example, harvest labor for fruits and vegetables may be easy to monitor when wages are paid at a piece rate for the amount harvested. However, labor required to seed a crop may be harder to monitor because errors in application rates are largely unobserved until much later when crop stands are apparent or final production is realized.

production. By comparison, manufacturing with a small number of sequential rather than concurrent operations is hard to imagine and likely inefficient because assembly lines are precluded.

For some annual non-irrigated crops, few inputs are applied during the five to nine months between the time of planting and harvesting. For other annual crops, inputs such as pesticides may be applied for preventative reasons before or at planting as well as for prescriptive purposes after planting. A simplifying characteristic of crop production is that application of most inputs involves a costly trip over a field. Thus, most inputs cannot be economically applied continuously (irrigation and inputs applied through irrigation water are exceptions), but rather the timing of input applications is a crucial production decision because of weather.

Because input responses are weather-dependent and harvests are seasonal, production and revenue depend on the timing of input applications. Thus, an m-stage technically efficient input-output relationship might be described by the smooth function,

$$y = f\big(f_1(\boldsymbol{x}^1, t_1), \ldots, f_m(\boldsymbol{x}^m, t_m)\big), \tag{1}$$

where $\boldsymbol{x}^i$ is the variable input vector at time t_i and $\boldsymbol{x}^m$ is harvest inputs applied at harvest time t_m. Note that both the quantity of each $\boldsymbol{x}^i$ and the associated time of application t_i are decision variables. In other words, timing as well as quantities are input choices. The chosen harvest date may not correspond to maximum possible production not only due to time preferences and interest rate incentives but because of labor and machinery scheduling problems, weather, and uncertainty of crop maturity. Because of lags, each $\boldsymbol{x}^i$ is relevant to final output, $\partial f/\partial \boldsymbol{x}^i = (\partial f/\partial f_i)(\partial f_i/\partial x^i) \neq 0$.

In one of only a few studies that have treated timing of operations as decision variables, Just and Candler (1985) demonstrate that agricultural production functions tend to be concave in the timing of both planting and harvesting operations so a unique timing exists that is technically efficient. Antle, Capalbo, and Crissman (1994) similarly investigate optimal timing and suggest an efficiency dimension of input timing. Interestingly, optimal timing in the context of the whole farm operation may not be technically efficient when the availability of resources such as labor or machinery services is constrained. That is, available labor and machinery may not be sufficient to harvest all plots at the same time if they should all mature at the same time.[2]

Also unlike manufacturing where the quality of a continuous or intermediate-stage output is observable, the implications of the current state of a crop for final production are highly subjective at each stage of the growing cycle. In most manufacturing processes, the time it takes to create a finished product, $t_m - t_1$, is relatively short. Additionally, intermediate productivity is more observable compared to agriculture, e.g., how far an item has moved on an assembly line or how well an intermediate step of assembly has been accomplished. Thus, continuous monitoring of input productivity and

[2] One could define technical efficiency to include any non-price constraints but this seems at variance with typical technologically based definitions.

making related adjustments at each stage of the production process is more effective. In other words, technical efficiency is best achieved by examining carefully each stage's output as it occurs or by testing to reach conclusions about the technical efficiency of individual production stages.

In contrast, the long delay from input application to observed productivity tends to confound the observed effects of inputs applied in multiple stages of agricultural production processes. As a result, one cannot easily infer from output which stage is inefficient. Moreover, the effects of inputs observed on other farms may not apply because of differing soil and climatic features. The focus of management is thus more on following recommended guidelines, experimentation to adapt recommended guidelines to specific farm or plot circumstances, and monitoring exogenous and uncontrollable inputs such as weather and pests in order to formulate counter measures.

To better represent intraseasonal unobservability, suppose the representation of the production process assuming technical efficiency in the intermediate states of production follows[3]

$$y = f^*\big(f_1\big(\boldsymbol{x}^1, y_0\big), \ldots, f_m\big(\boldsymbol{x}^m, y_{m-1}\big)\big), \tag{2}$$

where the timings of input applications are implicit decision variables suppressed for simplicity. That is, efficient management at stage i involves maximizing the intermediate output, y_i, where the technology set at stage i is represented by $y_i \leqslant f_i(\boldsymbol{x}^i, y_{i-1})$ and y_0 represents initial conditions [Antle and Hatchett (1986)].[4] One way of conceptualizing the difference between agricultural and manufacturing production in this framework is that the intermediate outputs in agriculture, the y_i's, are largely unobservable. In many manufacturing contexts, the separate stage production functions are readily observed, estimated, and applied separately for management purposes. Thus, efficient farming is directed toward learning well the stage technology through acquiring information available from beyond the farm (such as guidelines from technology developers and universities), experimentation, monitoring uncontrollable inputs, and estimating optimal adjustments accordingly.

This recursively separable structure of production whereby inputs $\boldsymbol{x}_i$ in stage t_i are separable from inputs $\boldsymbol{x}^j$ in stage t_j $(j > i)$ has important implications for agricultural production analysis. For example, labor and capital services applied during pre-planting cultivation will be separable from labor and capital services applied to post-planting herbicide application. This property allows experiment station or extension scientists or scientists from input supply firms to make recommendations on specific input choices that are clear and relevant to farmers assuming that the state variable from the previous

[3] For convenience, we use the expression in (2) to represent a production process of the form

$$y = f_n(x_n, f_{n-1}(x_{n-1}, f_{n-2}(x_{n-2}, \ldots, f_1(x_1, y_0)\ldots))).$$

[4] This yields a variant of recursive separability [Blackorby et al. (1978)].

stage is typical (the case of experiment station guidelines) or monitored (the case of professional pesticide applicators).

Timing of operations has been largely ignored in agricultural production economics. Rather, public agricultural production data are recorded on an annual basis. Accordingly, the timing of input applications as well as the intermediate outputs are unobserved. To utilize such data, the firm is typically presumed to solve:

$$y = f^0(\boldsymbol{x}, y_0) = \max_{\{x^i\}} \left\{ f^*\left(f_1\left(\boldsymbol{x}^1, y_0\right), \ldots, f_m\left(\boldsymbol{x}^m, y_{m-1}\right)\right) \;\middle|\; \sum_i \boldsymbol{x}^i = \boldsymbol{x} \right\}. \tag{3}$$

Initial conditions are typically ignored because data are unavailable in which case the estimated technology corresponds to $y = f^0(\boldsymbol{x})$. In this approach, the aggregate input vector $\boldsymbol{x}$ is treated as the decision variable in the related profit maximization problem (possibly some elements of $\boldsymbol{x}$ are treated as fixed or quasi-fixed inputs).

Interestingly, the assumptions implicit in (3) for input aggregation tend to be inadequate as a representation of family farming, the predominant form of agricultural production. The reason is that some inputs such as family labor and fixed-capital service flows present recurring input constraints through the growing season rather than across the entire production season. As a result, the shadow price (or opportunity cost) of resources can vary considerably through the growing season. For example, farm machinery is typically idle or underutilized through much of the year but is used heavily during several weeks. A grain farmer's most expensive piece of equipment may be a combine that is used only 3 or 4 weeks of the year. Tractors may be used to capacity only at planting or cultivation time of the few dominant crops grown on a farm. In spite of low average use rates, farmers find ownership advantageous because all farmers in an area tend to need the same machinery services at the same time due to local climate and soil conditions that tend to dictate crop timing. Capital services may be hired to relax such constraints in some cases, but custom machinery service markets do not operate in many cases because demands are too seasonal. The implication is that available service flows from such equipment are constrained by fixed investments but the shadow prices caused by such constraints may vary widely through a crop season. For example, the shadow price of the service of a combine may be almost comparable to or even higher than custom hiring rates in the peak use season, but yet much lower in a secondary harvesting season where excess capacity is available. These possibilities explain why farmers choose to hold stocks of expensive machinery even though average use is light.

Likewise, family labor may have distinct advantages over hired labor for specific functions because of moral hazard. That is, additional labor may be hired for such needs as harvesting where productivity is easily monitored and rewarded by piece rates, but moral hazard problems may make hired labor a poor alternative for other types of labor needs such as seeding. Indeed, the superiority of using family labor for carrying out certain functions is an important explanation for survival and predominance of the family farm [Allen and Lueck (1998)]. As a result, family labor within the conventional production model (which typically does not consider moral hazard) can be reasonably treated as a recurring constraint through the growing season that is far more limiting at some times than at others. Thus, the shadow price of family labor may vary widely through the growing season. The widely varying nature of implicit prices of farmer-controlled resources across labor periods (stages of production) has been well-recognized in programming models used to represent agricultural technology [McCarl et al. (1977); Kutcher and Scandizzo (1981); Keplinger et al. (1998)].[5]

If the implicit shadow prices of recurring farmer-controlled inputs vary widely from stage to stage, then the implicit formulation in Equation (3) may be inadequate. Mundlak (2001) emphasizes the need for this generalization in his discussion regarding the representation of capital inputs as stocks versus flows. To emphasize this difference, let $\boldsymbol{x}^i$ represent a vector of purchased variable inputs in stage t_i, and let z^i represent a vector of uses of farmer-controlled inputs such as family labor and capital services in stage t_i. Also, let $\boldsymbol{k}$ be a vector of maximum uses or availability of services made possible by the fixed stock of farmer-controlled resources in each stage.[6] Then technology can be represented by

$$\begin{aligned} y &= f^0(\boldsymbol{x}, y_0 \mid \boldsymbol{k}) \\ &= \max_{\{\boldsymbol{x}^i, \boldsymbol{k}^i\}} \left\{ f^*\big(f_1\big(\boldsymbol{x}^1, y_0, z^1\big), \ldots, f_m\big(\boldsymbol{x}^m, y_{m-1}, z^m\big)\big) \,\middle|\, \sum_i \boldsymbol{x}^i = \boldsymbol{x}; z^i \leqslant \boldsymbol{k} \right\}. \end{aligned} \tag{4}$$

This formulation makes clear that varying implicit prices of fixed farmer-controlled inputs is likely. In some periods, the optimal choice may be $z^i = \boldsymbol{k}$ with a high implicit price while in others it is some $z^i < \boldsymbol{k}$ with a zero implicit price.

[5] Mathematical programming models of agricultural decisions have largely given way to econometric models of decisions as indicated by a review of the literature. Several reasons are as follows. First, there is a great desire for statistical inference whereas inference with inequality constraints is a daunting task [Amemiya (1985); Diewert and Wales (1987)]. Second, in traditional practice, programming approaches have typically used subjective and ad hoc approaches to calibrate models, which some regard as falling short of scientific standards. Third, a primary purpose of production economics has become development of aggregate models of behavior with which to undertake policy analysis. Aggregate programming models tend to generate supplies and demands with large and irregular steps that are regarded as implausible. To the extent firm-level heterogeneity can be handled by smooth econometric models, programming models are less useful. However, recent developments in data envelopment analysis and Bayesian applications have spawned greater interest in merging programming and econometric methods [Fried et al. (1993); Chavas and Cox (1988); Paris and Howitt (1998)]. We note also that modern computer technology is rapidly making possible the boot-strapping of statistical properties of programming models with realistic components such as intermittently binding inequality constraints [Vanker (1996)]. For the purposes of this chapter, we consider primarily the econometric approach to empirical work. However, the principles apply to programming models as well and may be ultimately implemented by some merger of programming and econometric methods.

[6] For simplicity, we assume that farmer-controlled resources and thus maximum uses are constant across production stages in the same growing season. If this is not the case, then time subscripts must be added to the limits of use.

These considerations raise questions about how explicitly models must depict the stage-wise production problem and what types of data are needed to do so. For example, if capital service input data are not available by stages, then Equation (4) suggests that capital input data must measure the state of the capital stock (which determines the maximum possible flow of capital services in each stage) rather than the aggregate flow of capital services over the entire growing season. Modeling the stage-wise choices of capital service flows given these stocks may greatly improve understanding of production decisions if data are available for analysis. But if data are unavailable, how can models represent these implicit production choices sufficiently?

2.2. Flexibility in the output mix and spatial allocation

In principle, all firms conceptually choose among producing and marketing multiple final outputs because, at least in principle at the capital investment stage, they decide what to produce. However, much of agriculture throughout the world involves actually producing multiple products simultaneously. While measures of diversification are beginning to decline in many areas, particularly in the post-war period in the United States and most notably for livestock firms [White and Irwin (1972)], crop farming remains highly diversified. An important factor in choosing an agricultural output mix is spatial allocation of inputs among plots. This aspect of agricultural production makes agriculture an interesting case for study of scope economies and the effect of scale on scope economies [Chavas (2001)].

Many multiple-product manufacturing settings involve products that are produced in fixed or limited proportions determined by fixed plant and equipment or physical properties of production processes such as chemical reactions. In others, multiple products result from abruptly switching an entire plant from the manufacturing of one product to another (where simultaneous production of several outputs is not feasible or economical). In agriculture, a few production processes lead to related joint products with limited flexibility such as meat in combination with hides or cotton in combination with cottonseed. However, farmers often have great flexibility in switching among annual crops from season to season and in allocating land, machinery services, and family labor among crops in the same season. Flexible capital leads to large elasticities of product transformation (and, hence, large supply elasticities) because farmers can readily change their relative output mix from one crop season to the next. Much of this flexibility occurs because allocated inputs have similar marginal revenue product schedules in the production of several crops.[7] For example, land and land preparation machinery have similar marginal values in production of corn and soybeans in the corn belt or in production of wheat and sorghum in the southern Great Plains. This is why other considerations are sufficient to cause farms to rotate plots of land and diversify production among such crops.

[7] Flexibility also implies that capital has relatively large marginal products in various states of nature as well.

Marshallian joint production is generally presumed to be a reasonable explanation for many economies of scope and the implied optimality of multi-product farms. Baumol, Panzar and Willig (1988) define inputs for such processes as public inputs because they can be costlessly redirected from one industry to another. Clearly some purchased capital such as buildings or tractors may have some of these characteristics when congestion effects are not present. Some aspects of management skill and information have these properties. Clearly weather is a classic public input [Pope (1976)]. However, the timing and nature of demands on private inputs (or public inputs with congestion effects) can also promote diversification.

For example, when several crops compete for the same farmer-controlled resources, constraints on allocation of these resources can play an important role in determining diversification of the product mix. Farmers must generally allocate farmer-controlled resources consisting of land, management ability, machinery services, and family labor among plots of land. Because these inputs must be allocated spatially among plots, and plots are generally planted to distinct crops (or distinct crop mixes in some developing agriculture), these allocations usually amount to allocations among crops as well. Producing multiple outputs, which have different peak input-use seasons according to their varied stages of production, thus provides a way of more fully utilizing farmer-controlled resources and allowing more off-farm labor possibilities. For example, by producing several crops with different growing seasons, or by producing both crops and livestock which have different seasonality requirements, a farmer may be able to use smaller-scale, less expensive machinery and more fully utilize available family labor and management ability than if the entire farm had to be covered with the same operation at one time. Such considerations can be so important that, when coupled with price incentives, they lead to diversification when specialization otherwise occurs [Pope (1976); Pope and Prescott (1980); Baker and McCarl (1982)].

Interestingly, most agricultural production scientists focus on the rate of application of inputs or input services to a particular plot on which a particular crop is grown. For example, extension specialists recommend different rates of fertilizer application for different crops and soil conditions. Pesticides are often regulated with specified application rates per acre under legal licensing requirements. In this context, the representations in (1)–(4) may apply where y is a vector of outputs and $\boldsymbol{x}^i$ is a vector which distinguishes not only type of input but location (plot and thus crop) of application. With non-jointness of all inputs, Equation (4) becomes

$$\begin{aligned} y^j &= f_j^*\big(f_{1j}\big(\boldsymbol{x}^{1j}, y_0^j, \boldsymbol{z}^{1j}\big), \ldots, f_{mj}\big(\boldsymbol{x}^{mj}, y_{m-1}^j, \boldsymbol{z}^{mj}\big)\big), \quad j = 1, \ldots, \\ &\text{subject to} \sum_j \boldsymbol{z}^{ij} \leqslant \boldsymbol{k}, \quad i = 1, \ldots, m, \end{aligned} \tag{5}$$

where $y^j = y_m^j$ is the quantity produced of output j, $\boldsymbol{x}^{ij}$ is a vector of purchased variable inputs allocated to output j in stage i, and $\boldsymbol{z}^{ij}$ is a vector of uses of farmer-controlled resources allocated to output j in stage i. That is, uses of farmer-controlled resources across all production activities must satisfy availability constraints jointly. Note for convenience and to represent availability constraints appropriately in (5), the first subscript of $\boldsymbol{x}$ is assumed to represent a common timing choice across all production activities so that $t_{ij} = t_i$ is the timing choice for operations in stage i of production for all outputs.[8] Also, note more generally that each y^j could represent a vector of outputs with j indexing additively separable production activities in which case (5) does not imply nonjointness of inputs.

The framework of (5) reflects the notion of allocated fixed inputs introduced by Shumway, Pope, and Nash (1984) and investigated by Just, Zilberman, and Hochman (1983), Leathers (1991), and Just et al. (1990). This literature recognizes that inputs such as land are typically measured and must generally be allocated to the production of specific crops (or crop mixes). While the nonjointness assumptions of these papers may be debatable, the need for farmers to allocate at least some purchased variable inputs and at least some farmer-controlled resources among plots is clear.

Public data typically report inputs and outputs for a region but generally do not give allocations of inputs to crops, plots, or production activities as does farm-level accounting and management data. As a result, problems of estimation of multi-output production relationships in agriculture typically have been simplified to eliminate the allocation problem. As in the case where temporal allocation of inputs is unobserved, elimination of spatial allocation variables presumably assumes implicitly that inputs are allocated among plots to achieve efficiency given that inputs have identical prices across plots. Thus, the firm is treated as solving an allocation problem of the form

$$\begin{aligned} y^1 &= f\left(\boldsymbol{x}, k, y^2, y^3, \ldots\right) \\ &= \max\left\{ y^1 \mid y^j = f_j^*\left(f_{1j}\left(\boldsymbol{x}^{1j}, z^{1j}\right), \ldots, f_{mj}\left(\boldsymbol{x}^{mj}, z^{mj}\right)\right),\ j = 1, \ldots; \right. \\ &\qquad \left. \sum_j z^{ij} \leqslant \boldsymbol{k},\ i = 1, \ldots, m;\ \sum_i \sum_j \boldsymbol{x}^{ij} \leqslant \boldsymbol{x} \right\} \end{aligned}$$

in the typical case where initial conditions are ignored. These practices raise questions regarding how explicitly allocation decisions must be represented in production models and how much understanding of the production problem can be gained by representing allocations explicitly. Can greater econometric efficiency be gained thereby? What data are required?

2.3. *Fragmented technology adoption and embodied technology*

Much has been written about technical change and technology adoption in agriculture [see the reviews by Sunding and Zilberman (2001) and by Evenson (2001)]. Such phenomena explain both the successes and failures of the "green revolution" and explain

[8] This represents no loss in generality because the input vector may be zero for some production activities in some production stages.

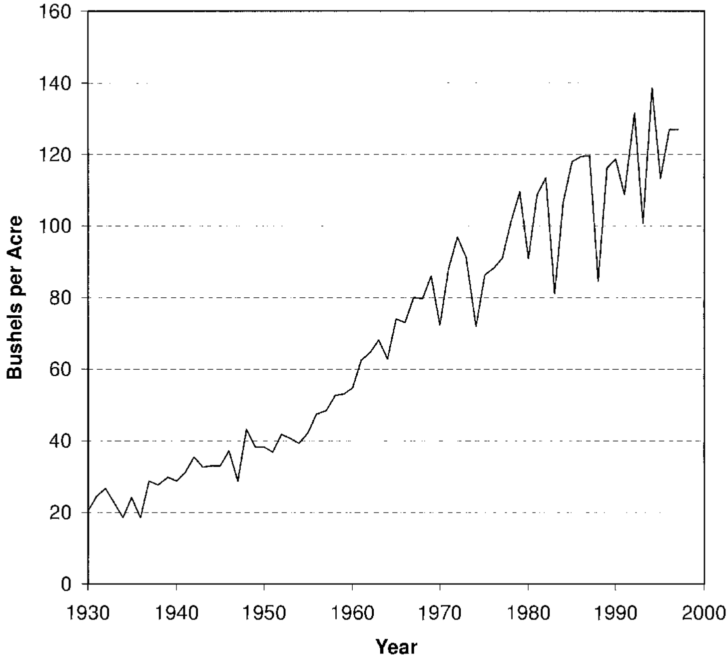

Figure 1. U.S. corn yield growth.

the dramatic growth in agricultural productivity in the twentieth century. More currently, they have much to say about potential agricultural responses to environmental problems, food safety, genetically modified organisms, and the induced innovation that is likely to occur as a result [Sunding and Zilberman (2001); Chavas (2001)]. The dramatic growth in productivity due to technology is illustrated in Figure 1 by the sixfold increase in average U.S. corn yields since 1930. Figure 2 illustrates how much higher the rate of growth in productivity per worker has been in agriculture compared to manufacturing and business.[9] Much of the growth in productivity in developing agriculture has come in the form of higher-yielding seeds, fertilizer use, tube wells for irrigation, and replacement of traditional crops by modern crops. A major explanation in developed agriculture lies in the development of larger-scale machinery, improved crop varieties and livestock breeds, and new inputs such as pesticides and growth hormones. In each case, the technology is embodied in either variable production inputs or in the capital stock.

[9] To construct Figure 2, U.S. Bureau of Labor Statistics indexes for productivity per hour in manufacturing and business are used. The productivity per worker index for agriculture is constructed from U.S. Economic Research Service data by dividing the index of total farm output by the index of farm labor input (see the 1999 Economic Report of the President). All indexes are then adjusted to 100 in 1949. Because the number of hours in the work week in manufacturing and business has been falling, a fair comparison would imply an even greater divergence in growth of output per worker.

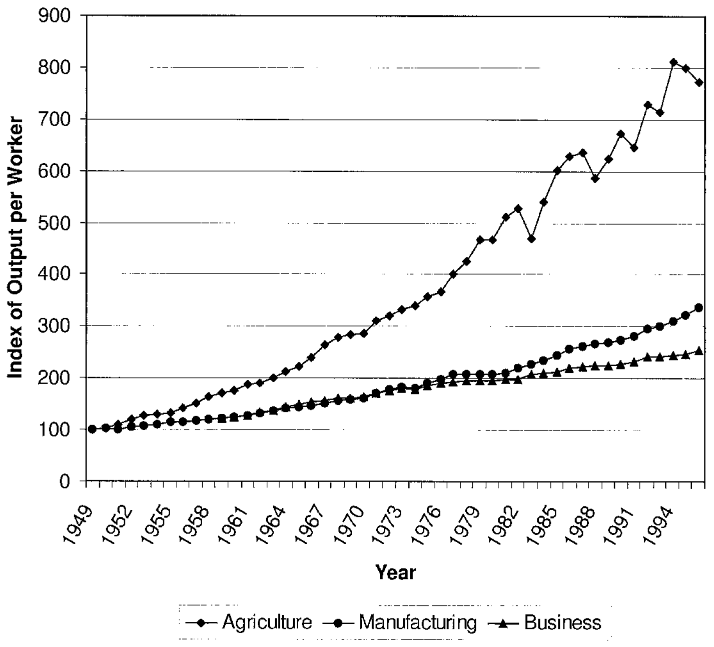

Figure 2. U.S. output per worker.

One of the core features of modern production processes is that production decisions often lag years behind capital decisions. For example, in automobile production, the cycle time from product design to production often takes at least two years. However, once the plant and equipment are in place, the application of inputs typically yields a finished output with very little lag. For example, the typical auto assembly plant produces a car every few minutes and the complete cycle time including pre-assembly of important components is measured in days. For mature industrial processes, this process evolves largely into "quality control".

Some aspects of agricultural production resemble the manufacturing paradigm. For example, producing tree crops and vineyards requires considerable time to put the capital stock in place (e.g., mature trees and vines). Similarly, livestock production involves considerable time to grow mature breeding animals (for gestation, birth, weaning, etc.). These biologically induced lags introduce some interesting and lengthy nonlinear dynamics into the production process [Chavas and Holt (1991, 1993)]. However, a unique aspect of agriculture (compared to manufacturing) is that once the physical capital (perennial crop stands and breeding herds in addition to machinery and buildings) are in place, the lag from the application of variable inputs to the finished output is relatively long.

Another largely unique feature of agricultural production – particularly annual crop production – is that the technology choice is described by a lengthy list of piecemeal decisions that must be made with each new growing season on each plot of land [Sunding and Zilberman (2001); Feder et al. (1985)]. For example, each time a crop is planted a producer can choose to grow a different crop, use a different seed variety, apply fertilizer, use herbicides, apply insecticides, or employ plant growth regulators. A typical grower may choose among 3 to 5 economical crops for the area, each crop may have from 3 to 5 prominent crop varieties with different levels of resistance to unforeseen weather and crop disease conditions, and the farmer may face from 3 to 5 attractive alternative choices each for fertilizers, herbicides, insecticides (if needed), etc. A farmer can choose to use low tillage methods or a variety of tilling operations to control weeds and conserve moisture. Some of these choices are influenced by the stock of equipment (variety and size). The stock of equipment is typically adjusted in piecemeal fashion because most tractors can accept a wide variety of equipment (although the size of equipment is constrained by the size of tractor). The variety of equipment on hand can constrain either the feasible or economical crop set. The size of equipment as well as family labor availability can constrain the amount of land that can be economically allocated to a particular crop/technology combination.

To complicate farmers' choices further, new technology is constantly being developed. New seed varieties and new pesticides are being developed every year and in some cases have dramatic effects on yields.[10] These effects explain the dramatic increase in crop yields as illustrated for corn in Figure 1. A typical problem, however, is that new technologies are unproven and are thus viewed as more risky. Farmers may delay adoption and observe responses obtained by neighbors or allocate small test plots to new technologies. For characterizations of technology to be consistent with such behavior, these uncertainties and options must be represented. Furthermore, technology embodied in machinery or perennial crops is largely fixed by vintage of the capital stock. Some farmers may adopt technologies on a small scale and then increasingly with learning by doing [Foster and Rosenzweig (1995)]. As a result of the complex nature of the technology choice and lags in adoption, a large number of technologies are employed concurrently by different farmers and on different plots by the same farmer [Feder et al. (1985)]. These phenomena complicate drawing inferences from agricultural production data that has been aggregated across heterogeneous farms as discussed further in the section on heterogeneity below. How explicitly does the distribution of technology need to be represented in production models? How much does the distribution of technology depend on the capital distribution? What data on technologies can improve production modeling and how?

2.4. Uncertainty: The role of weather and pests in biological processes

One way agricultural production differs from most manufacturing production is in the magnitude of the impact of uncontrollable factors – many of which are highly stochastic and unpredictable. The dominance of uncertainty in agricultural production is one

[10] The term 'pesticide' is a generic term that includes insecticides, herbicides, fungicides, rodenticides, and crop growth regulators.

reason the study of production under risk has flourished in agricultural economics [Moschini and Hennessy (2001)]. The highly unpredictable nature of agricultural production is illustrated by the yearly national-level corn yields depicted in Figure 1. Furthermore, the data in Figure 1 understate variability because averaging at the national level washes out variation among individual farms. Empirical evidence suggests that variability at the farm level is from 2 to 10 times greater than indicated by aggregate time series data [Just and Weninger (1999)]. The most important uncontrollable factors are weather, pests, and unpredictable biological processes, all of which vary from farm to farm. Weather and pests can cause either localized or widespread crop failures or shortfalls through hail storms, high winds, drought, crop disease, insects, and weed infestations.

Production variability translates also into relatively larger price variability in agriculture as well. The difference in price variability among sectors is highlighted by U.S. producer price indexes at the finished goods and consumer foods level. The variance of annual percentage changes in prices over 1989–1998 was 37.7 for crude consumer foods compared to 4.7 for finished consumer goods, 2.1 for finished capital equipment, 3.8 for processed consumer foods (which represents primarily non-food inputs of processing and packaging), and 5.7 for finished consumer goods excluding foods.

To illustrate the extent of uncontrollable random variation at the state level, the coefficients of variation (CVs) for corn and wheat yields in the United States in Table 1 suggest that farmers on average can have only about a 68 percent probability that production will be in an interval equal to 30 percent of expectations (as implied by normality when CVs average about .15). Furthermore, these coefficients of variation are considerably higher in some states (ranging from .04 to about .25 for both crops). The lower coefficients of variation occur mostly in states where expensive irrigation technology is used to compensate for low and irregular rainfall. Furthermore, it should be noted that much of the variation experienced by individual farmers is washed out by the statewide aggregate data summarized in Table 1 so that the statistics in Table 1 represent a significant underestimate of the effect of uncontrollable factors at the farm level.

Weather and pests are continuous inputs that affect crop growth throughout the entire growing season. Characterizing technically efficient decisions on the basis of ex post random draws of output is difficult because the impact of any vector of inputs $\boldsymbol{x}^i$ on output $(\partial y/\partial \boldsymbol{x}^i)$ is obscured by previous weather occurrences embodied in a largely unobserved state of the crop at time t_i and future weather occurrences embodied in the ultimate observed production, y. Drawing on the well-known literature under uncertainty, $(\boldsymbol{x}_i', G')$ is technically inefficient in an ex ante sense in stage t_i if $G(y_i \mid \boldsymbol{x}^i, y_{i-1}) < G'(y_i \mid \boldsymbol{x}^{i\prime}, y_{i-1})$ for all y_i where G and G' are cumulative distribution functions associated with y_i and $\boldsymbol{x}_i' \geqslant \boldsymbol{x}_i$. This relationship, however, merely represents first-degree stochastic dominance. First-degree stochastic dominance holds for a particular distribution (for a particular input vector) if it yields the largest output for every state of nature. A similar notion can be developed using conventional input distance measures [Färe (1996)]. If first-degree stochastic dominance fails, higher orders of dominance may provide potentially useful comparisons [Eeckhoudt and Gollier (1992)].

Table 1
Coefficients of variation and average yields for U.S. corn and wheat, 1988–97

State	Coefficient of variation		Mean yield	
	Corn	Wheat	Corn	Wheat
Alabama	0.23	0.19	75.2	38.1
Arizona	0.06	0.04	164.5	91.1
Arkansas	0.13	0.22	112.3	43.5
California	0.04	0.06	161.5	77.4
Colorado	0.11	0.10	143.0	33.0
Delaware	0.19	0.15	107.8	55.7
Florida	0.14	0.17	75.4	34.7
Georgia	0.19	0.16	89.6	40.8
Idaho	0.07	0.07	133.5	72.9
Illinois	0.19	0.19	124.3	49.5
Indiana	0.17	0.15	121.9	52.0
Iowa	0.20	0.18	122.3	38.4
Kansas	0.09	0.19	133.7	33.9
Kentucky	0.17	0.19	107.7	49.5
Louisiana	0.13	0.21	106.8	33.9
Maryland	0.22	0.14	104.2	54.6
Michigan	0.14	0.17	106.6	50.3
Minnesota	0.21	0.25	114.6	35.5
Mississippi	0.18	0.24	85.7	37.3
Missouri	0.18	0.16	107.0	43.0
Montana	0.16	0.21	114.7	30.4
Nebraska	0.10	0.12	126.4	34.5
Nevada		0.11		81.7
New Jersey	0.16	0.14	106.2	47.1
New Mexico	0.06	0.22	161.0	27.1
New York	0.10	0.10	101.5	50.7
North Carolina	0.14	0.13	87.7	44.6
North Dakota	0.23	0.25	78.0	29.1
Ohio	0.16	0.13	117.7	53.6
Oklahoma	0.13	0.18	120.1	28.0
Oregon	0.09	0.11	160.9	62.7
Pennsylvania	0.19	0.11	100.6	48.5
South Carolina	0.26	0.17	76.2	41.8
South Dakota	0.21	0.21	81.1	29.3
Tennessee	0.18	0.18	101.2	42.7
Texas	0.12	0.14	112.3	28.3
Utah	0.09	0.14	129.6	41.7
Virginia	0.20	0.13	97.7	54.5
Washington	0.04	0.13	182.0	57.2
West Virginia	0.17	0.09	93.1	47.8
Wisconsin	0.19	0.16	110.9	48.1
Wyoming	0.15	0.15	111.8	27.8
Average	0.15	0.16	111.2	45.8

One of the pressing issues in the measurement of efficiency across firms is that firms may have access to the same technology but may not have access to identical distributions of weather, i.e., identical distributions of outputs given inputs. To denote dependence on local random weather, the production response can be represented by

$$y = f\left(\boldsymbol{x}^1, \ldots, \boldsymbol{x}^m, \boldsymbol{k}, \boldsymbol{\varepsilon}\right), \tag{6}$$

where $\boldsymbol{k}$ represents all relevant capital inputs, $\boldsymbol{\varepsilon}$ is a vector of weather occurrences on a particular plot or farm, and the choice of timing of inputs is suppressed for convenience.

Adding intermediate temporal detail, a more informative representation is

$$y = \left\{f^*\left(f_1\left(\boldsymbol{x}^1, y_0, z^1, \boldsymbol{\varepsilon}^1\right), \ldots, f_m\left(\boldsymbol{x}^m, y_{m-1}, z^m, \boldsymbol{\varepsilon}^m\right)\right) \mid z^i \leqslant \boldsymbol{k}\right\}, \tag{7}$$

where $\boldsymbol{\varepsilon}^i$ represents local weather events occurring during stage t_i of the production process. The possibility for weather events to cause significant variation in final or stage output is large. Weather can cause certain operations (stages) to be largely ineffective or consume excessive resources unless choices of timing are altered. For example, trying to cultivate a field that is too wet can cause tillage to be ineffective or consume excessive labor. Or trying to plant a crop before adequate rain can result in an inadequate stand of seedlings. The associated consequences for output can be dramatic. For example, delaying planting of corn in Iowa beyond the average optimum of May 1 to May 20 implies more than a 10 percent decline in yields [Burger (1998)]. Weather can also reduce plant growth with excessive heat or inadequate rain or destroy crops at any stage through hail storms.

An important result following from the lags in (7) is that realized output may not be monotonically increasing in input variables. For example, bad weather (pest infestations) can reduce yields while motivating managers to use more labor (pesticides). Thus, a regression of output y_{t_n} on some total input vector $\boldsymbol{x} = \sum_i \boldsymbol{x}^i$ may suggest a negative association for some variables even though $\partial \mathrm{E}_i(y_{t_n})/\partial \boldsymbol{x}^i$ is positive, where E_i is the expectation of y_{t_n} taken at time t_i (using information available at time t_i). This has led some economists to model particular inputs as controlling the damage to normal growth [Feder (1979)].

Considerable early efforts were made to determine the relationship between yields and weather [Doll (1967); McQuigg and Doll (1961); de Janvry (1972)]. These studies try to use weather and ex post measurements of yields to model the conditional distributional of yields given controlled inputs. Voluminous data compiled by the U.S. National Weather Service include hourly temperature, wind, and precipitation data at a large number of weather stations in the United States. Because the data is so voluminous and detailed, suitable aggregator functions are needed but have not been developed. Alternatively, recent work has been content to consider a Taylor's series approximation of (6) at, say, $\mathrm{E}_n(\boldsymbol{\varepsilon}) = 0$ and estimate functions such as $y = \tilde{f}(\boldsymbol{x}, y_0, \boldsymbol{k}) + \tilde{g}(\boldsymbol{x}, y_0, \boldsymbol{k})\boldsymbol{\varepsilon}$ where y_0 is typically not measured. This leads to a function in terms of controllable inputs plus a heteroscedastic error [Just and Pope (1978, 1979); Antle (1983)]. More formally, a first-order Taylor series approximation of (7) is

$$\begin{aligned} y = \{ & f^*(f_1(\boldsymbol{x}^1, y_0, z^1, 0), \ldots, f_m(\boldsymbol{x}^m, y_{m-1}, z^m, 0)) \\ & + f^*_{\boldsymbol{\varepsilon}}(f_1(\boldsymbol{x}^1, y_0, z^1, 0), \ldots, f_m(\boldsymbol{x}^m, y_{m-1}, z^m, 0))\boldsymbol{\varepsilon} \mid z^i \leqslant \boldsymbol{k}\}, \end{aligned} \tag{8}$$

where subscripts of f^* represent differentiation, transposition is ignored for simplicity, and $\boldsymbol{\varepsilon}$ is a vector composed of $\boldsymbol{\varepsilon}^1, \ldots, \boldsymbol{\varepsilon}^m$. The key marginal effect of $\boldsymbol{x}^i$ on the variance (mean-preserving spread) of y is thus

$$\partial \operatorname{var}(y)/\partial \boldsymbol{x}^i = 2 f^*_{\boldsymbol{\varepsilon}}(\cdot) f^*_{\boldsymbol{\varepsilon x}^i}(\cdot) \mathrm{E}_m(\boldsymbol{\varepsilon}^2) \tag{9}$$

and has signs determined by elements of $f^*_{\boldsymbol{\varepsilon}}(\cdot) f^*_{\boldsymbol{\varepsilon x}^i}(\cdot)$.

While the structure of (8) appears quite complex for empirical purposes, considerable common structure between the first and second right-hand terms can be exploited for efficiency purposes. For example, the same separable structure is preserved in both the mean and the shock portion of production because it is generated by the same recursive structure of the production stages. Thus, if seeds are separable from labor and machinery in mean wheat production, the same should also be true for the variance. As suggested by Antle's (1983) work, the framework in (8) and (9) can also be expanded in a straightforward way to consider higher moments of the output distribution. The more recent work of Chambers and Quiggin (1998) can also be considered as a generalization of this characterization of production because it characterizes stochastic production by the production set in every state of nature [see Moschini and Hennessy (2001) in this Handbook for a brief explanation].[11]

More importantly, Equations (8) and (9) highlight a central issue in decision making when mean-variance decision models are appropriate; namely, that an input may contribute to the mean differently than it contributes to variance. Indeed, the contributions may be opposite in sign. An input in which (9) is negative (positive) is typically called risk reducing (increasing), following Just and Pope (1978, 1979). Another related possibility is to classify inputs based upon the marginal effect of risk aversion on use [Loehman and Nelson (92)]. A large body of research has developed on risk-reducing marketing, production, and financial strategies. Further examples of empirical research measuring the stochastic characteristics of inputs are found in Love and Buccola (1991); Regev et al. (1997); Horowitz and Lichtenberg (1993); and Nelson and Preckel (1989). However, for the most part, these studies have explored possibilities on a piecemeal basis and have not produced a coherent and widely used framework for agricultural production analysis. Many questions remain. How explicitly do stochastic elements of production have to be represented? Does the source of stochasticity make a difference? How can the micro-level stochastic production problem be represented adequately with available data?

[11] Assuming technical efficiency, characterizing all the moments of output is equivalent to characterizing efficient production in every state of nature because of the uniqueness of moment-generating functions.

2.5. Interseasonal complexity of biological and physical processes

A host of longer-run (inter-year) issues also complicate matters [Nerlove and Bessler (2001)]. Like manufacturing, these involve evolutions of the capital stock represented in k from one production period to the next and how these affect technology. The state of the capital stock is affected by how heavily it has been used in previous periods (which determines the likelihood of time-consuming breakdowns and costly repairs) as well as by net investment. However, an important consideration in agriculture is that initial crop-year soil conditions and pest infestations/resistances and perennial crop states in y_0 are dependent on previous cropping choices, fertilizer and pesticide applications, and soil tillage. The state of the machinery capital stock may be largely observable through inventory records and by inspecting wear, while the state of soil and pest conditions is largely unobservable except through extensive (and in some cases impractical) testing.[12]

In this context, both y_0 and $\boldsymbol{k}$ are affected by decisions in earlier growing seasons. Regarding t now as spanning growing seasons, output is Markovian through both y_0 and $\boldsymbol{k}$. This phenomenon is manifest by crop rotation practices where weed or insect cycles are broken by switching a given plot among crops on a regular basis. The need for such rotation is typically realized on the basis of previously observed infestations that occur otherwise, rather than direct indications of carry-over soil or pest conditions. Rotation actions are often undertaken on a preventative basis because once a serious problem occurs it affects an entire growing season before corrections can be made. Thus, a careful delineation of intertemporal production possibilities implies consideration of inter- and intra-year effects. Implied models contain non-linear dynamics with accompanying instability [Chavas and Holt (1991, 1993)].

The static or short-run generic description of technology in Sections 2.1–2.4 is consistent with this depiction of inter-cycle production because the choices made in a previous growing season are fixed in the current growing season. However, this simplification in theoretical modeling does not imply that initial conditions in y_0 can be ignored in empirical work as most production studies have done. Empirical work documenting the importance of inter-cycle production phenomena through carry-over conditions has been limited. See, e.g., Chambers and Lichtenberg (1995) for a rare study of interseasonal investment in soil capital.

The forward impacts of input choice are essential to many agricultural economic problems. For some inputs a positive future effect is clear, $\partial y_{i+j}/\partial \boldsymbol{x}^i > 0,\ j > 0$, while for others it is negative. For example, fertilizer has both initial and future positive effects (ignoring externalities) due to the carryover of nutrients in the soil [Woodward (1996)]. However, many pesticides have negative dynamic effects by inducing pest resistance [Hueth and Regev (1974); Clark and Carlson (1990)]. In addition, interpreting

[12] Often limited spot testing of soil is used as a basis for prescribing fertilizer needs but the results give only a crude estimate of the inventory of soil conditions. The extent of weed seed carry-over and gestating insect infestations are impractical to assess.

the y_i's as outputs in a given year, it is clear that nitrogen fixation of legumes and other crop rotational issues have positive marginal dynamic effects on future outputs. Seemingly, micro-studies of crop choice must consider these effects if they influence observed farmer choices. Finally, capital decisions have important interyear effects [Vasavada and Chambers (1986); Vasavada and Ball (1988); Morrison and Siegel (1998)].

While many advances have been made in conceptual representation of these interseasonal issues of production, many questions are not well understood. Data for investigating these issues empirically has been lacking, particularly for crop production, and accordingly few empirical studies have been undertaken. While livestock production has been examined with more dynamic detail, models have been conceptually less elegant and, thus, of less interest. Accordingly, little is known about interseasonal behavioral preferences, particularly where risk issues are important.

2.6. Atomistic heterogeneity and aggregation

While the concepts of production theory generally are developed at the individual firm level, much of the empirical work in agricultural production is done at the aggregate level of a state or nation. Use of aggregate data has occurred because few firm-level data sets have been developed and access to them is limited or conditional.[13] Thus, the discussion of agricultural production analysis cannot be complete without considering the problem of aggregation.

Agriculture is atomistic with respect to most products. That is, the number of firms is large and each is individually unimportant at aggregate levels. Nevertheless, farms differ in many ways. The wide distribution of technology employed simultaneously across farms suggests one dimension of this problem. Another dimension is the wide variation in climate and soil quality across farms. Differences in soil quality have been highlighted historically by U.S. Natural Resources Conservation Service (formerly U.S. Soil Conservation Service) classifications of soil and land characteristics but are increasingly highlighted by precision farming techniques, localized incentives for environmental preservation and conservation practices, and location-specific environmental policy. The implications of variation in climate and soil for crop production and variability are depicted by the variation of both average yields and coefficients of variation of major crops among states in the United States as illustrated in Table 1. These variations explain much of the dramatic difference in crop mixes chosen by farmers from one location to another.

[13] There are exceptions such as the Agricultural Resource Management Study (formerly the Farm Cost and Returns Survey) data compiled by the U.S. Economic Research Service and the Kansas State University Farm Management Survey data in developed agriculture, and the ICRISAT Household Survey data and various other World Bank surveys in developing agriculture. However, access to such farm-level surveys tends to be limited to those with in-house affiliations, willingness to analyze the data in-house, or willingness to collaborate, and thus such data has been explored only to a limited extent.

Another dimension of heterogeneity imposed by geographic differences in climate and soil quality is the heterogeneity in prices induced thereby. As a result, land rents, the opportunity cost of labor and the price of services do not follow the law of one price. A considerable amount of output price variation also occurs due to differences in climate-induced product quality and timing of production [Pope and Chambers (1989); Chambers and Pope (1991)].

Though many inputs have similar marginal products across farms as well as space and enterprises, others such as chemicals, purchased services, and some machinery are highly and increasingly specialized. Some pesticides have primarily pre-emergent uses and others have primarily post-emergent uses. Most pesticides are used primarily on only a few crops and thus differ across farms. Aerial spraying equipment is primarily used for post-emergent applications while ground operations are primarily used for pre-emergent application. Aggregating such pesticide uses or machinery services over farms as well as time and space can be problematic. As technology turns more toward genetically engineered seeds, such as Roundup-ready soybeans which introduce dependence on specific pesticides, the allocation of a given total input quantity to enterprises to achieve technical efficiency may be trivial on individual farms but underrepresented by aggregates.

To represent heterogeneity, let $G(\boldsymbol{\varepsilon}, \boldsymbol{k} \mid \theta)$ represent the distribution across all farms of characteristics such as weather and pests, capital and technology, management ability, and other policy and input constraints imposed on farms by external conditions. Then following the representation in (7), aggregate production response is described by

$$y = \int \bigl\{ f^*\bigl(f_1\bigl(\boldsymbol{x}^1, y_0, z^1, \boldsymbol{\varepsilon}^1\bigr), \ldots, f_m\bigl(\boldsymbol{x}^m, y_{m-1}, z^m, \boldsymbol{\varepsilon}^m\bigr)\bigr) \mid z^i \leqslant \boldsymbol{k} \bigr\} \, \mathrm{d}G(\boldsymbol{\varepsilon}, \boldsymbol{k} \mid \theta). \tag{10}$$

In this framework, standard regularity conditions fail at the aggregate level even under profit maximization but distribution-sensitive aggregation such as in (10) can preserve practical versions of regularity conditions [Just and Pope (1999)]. These results raise questions about how specifically and explicitly stochastic sources of variation must be represented in production models. Of course, related considerations of heterogeneity in prices, expectations, and risk preferences are necessary to derive supplies and demands from representations of the production technology.

2.7. *Implications of the unique features of agricultural production*

The discussion in Sections 2.1–2.6 emphasizes a number of unique features of agricultural production that require specific attention. Time lags and stages imposed on the production process by biological characteristics of production suggest that one should appropriately represent the allocation of inputs over time within a crop season. Flexibility of crop mixes and specificity of inputs by crop (or location) highlight the importance of representing allocations over these dimensions. The role of farmer-owned resources such as land and labor, and their allocation, may imply significant economic constraints that, in turn, complicate the aggregation of capital service flows and family labor over time. How appropriate is production modeling when based only on data aggregated across these dimensions? How limited are the sets of issues that can be investigated?

Though empirical economic practices must of necessity work with aggregates at some level, we believe that agricultural economists have often been cavalier about temporal and spatial (biological) structure and heterogeneity in agriculture. This has led to inappropriate grouping of inputs and outputs over space and time. Spatial dimensions of input groupings may be particularly important in agriculture because inputs must be tailored to the heterogeneity of farm resources, which differ substantially by climate and land quality (location). For example, ignoring these circumstances may lead economists to conclude that too much land is used by a large farm with heterogeneous land quality in comparison to a "best practice" when in reality economists are not using "best practice" methods of aggregation. Such practices have implications for measuring technical or other inefficiencies as well as for measuring behavior. Similarly, time dimensions of input groupings may be more important in agriculture because production lags tend to be longer and thus encounter more price heterogeneity.

At a minimum, the conclusions that are being drawn must be carefully and fully qualified given these possibilities. One purpose of this chapter is to identify the extent of needed qualifications. In some cases, existing data allows more careful consideration of aggregation issues. For example, inventories of land qualities and of land allocations can be used to enhance economic understanding. However, data are rarely collected on intraseasonal input choices nor is it generally reported on spatial allocations. Thus, for issues that require data on intraseasonal or spatial choice, limitations of current data imply that there is a clear tension between the description of agriculture in Sections 2.1–2.6 and available data. Perhaps more importantly, these issues raise concern about whether approaches that require the specification of technology, either explicitly or implicitly, can correctly reflect technology when temporal and spatial aggregates are used.

The next few sections of this paper investigate conceptual and theoretical implications of the issues raised thus far regarding temporal (Section 2.1) and spatial (Section 2.2) allocation of inputs, the potential differences among generic inputs represented by embodied technology (Section 2.3), and the stochastic nature of production (Section 2.4). The nature of constraints imposed on service flows by farmer-owned resources is considered explicitly. A set of principles is developed in Section 3 that address these issues in agricultural production analysis. Then fundamental theoretical results are developed to apply these principles in Section 4. In Sections 3 and 4, we provide a critique of current approaches to agricultural production analysis, identify the limitations imposed by data availability, and suggest appropriate qualifications that must be attached to agricultural production studies given data limitations. In some cases, these qualifications invalidate many empirical findings to date. We suggest this is one reason for the poor performance of duality models noted by Mundlak (2001) and that some of these problems arise from trying to apply the concepts of production economics without sufficient attention to the unique features of agriculture discussed in this section.

Following Sections 3 and 4, we address in Section 5 the extent of generalizations that have been achieved in agricultural production analysis regarding the other unique features of agriculture identified above (Sections 2.5–2.6) and related issues. Relatively less emphasis is placed on these issues in this chapter because they are emphasized heavily by Sunding and Zilberman (2001) and Nerlove and Bessler (2001). However, we suggest implications of the principles of this paper that are applicable and which call for more structural and detailed analysis, empirical investigation in the context of a broader maintained model, and more adequate representation of heterogeneity as data allows.

3. Principles of agricultural technology representation

Before proceeding to consider appropriate principles for agricultural production analysis, introduction of some conventional concepts and definitions is useful to facilitate discussion. Following the seminal work of Nobel laureate Gerard Debreu, we define an economic good not only physically but also temporally and spatially [Debreu (1959, pp. 28–32)]. In other words, date and location in addition to physical identification of a commodity are essential. Debreu emphasizes that this distinction "should always be kept in mind" in his comprehensive mathematical representation of economic phenomena (p. 32). Thus, fertilizer applied to a particular wheat field at planting time is considered distinct from post-emergent fertilizer applied to the same wheat field at a later date and from fertilizer applied in planting a barley field or another wheat field even if on the same date and farm. Debreu also emphasizes with a long list of examples that the physical identification of goods must be complete. As an example, he emphasizes that land must be described completely by the nature of the soil and subsoil characteristics, crop residues, etc. (p. 30). These considerations have important implications for the analysis of agricultural production because of the unique features of agricultural production involving long time lags in the production process, wide variation in prices and local weather conditions, and great heterogeneity both among and within farms.

In contrast to Debreu's clear conceptual definitions, we note that carrying the distinction of space and time and even many of the attributes of physical identification has been largely dropped from empirical agricultural production studies. For example, it is not unusual to represent output as a single aggregate commodity, a two-dimensional measure with crop and livestock aggregates, or a short vector consisting of the aggregate production of several crops. Inputs often consist of four to six aggregate annual input quantities such as land, fertilizer, pesticides, seeds, labor, and machinery services. The role of weather and pests is usually swept under the guise of an ad hoc homoscedastic error term. Examples of such studies include many widely referenced studies of U.S. agriculture over the past two decades and virtually all of the production studies referenced in the survey by Shumway (1995). Thus, the specifications in (1)–(10) are rarely employed empirically in agriculture.