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SECTION 3

CLIMATE CHANGE, GLOBAL TRADE AND INVASIVE SPECIES

BUFFALO FLIES (*Haematobia exigua*) EXPANDING THEIR RANGE IN AUSTRALIA FACILITATED BY CLIMATE CHANGE: THE OPPORTUNITY FOR AREA-WIDE CONTROLS

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SUMMARY

Buffalo flies *Haematobia exigua* de Meijere were introduced to Australia in 1838 and have become major cattle pests in Australia's northern cattle industries. They have been steadily expanding their range southward and their spread is likely to be further facilitated by climate change. Control programmes consisting of compulsory chemical treatments and regulated cattle movements have proven unsuccessful in preventing the spread of buffalo flies and, without area-wide intervention, they are likely to become major cattle pests in Australia's southern beef and dairy industries. Buffalo flies do not have a pupal overwintering strategy but survive winter in localised foci of slowly cycling low level populations of flies. Populations increase and spread to infest surrounding areas when weather becomes favourable in summer. This suggests the potential for an area-wide control approach, targeting overwintering foci of the flies. A project has been initiated to transinfect buffalo flies with *Wolbachia,* determine the effects of *Wolbachia* infection in the flies, and assess the feasibility of control by *Wolbachia*-based approaches directly targeting overwintering foci of the flies.

Key Words: Bos indicus, Bos taurus, Bubalus bubalis, Chrysomya bezziana, Haematobia irritans, Lucilia cuprina, Stephanofilaria, Wolbachia, Muscidae, biological control, cattle, horn flies, invasive species

1. BUFFALO FLIES AND HORN FLIES

Buffalo flies *Haematobia exigua* de Meijere and horn flies *Haematobia irritans* (L.) are obligate parasites, living most of their lives on cattle, and leaving only to oviposit when cattle defecate. Both the male and the female subsist completely on blood, using their sharp mouthparts to pierce the animal's skin. If uncontrolled, infestations may reach several thousand flies per animal, each feeding up to 40 times daily, irritating cattle and causing production loss and welfare impacts.

J. Hendrichs, R. Pereira and M. J. B. Vreysen (eds.), Area-Wide Integrated Pest Management: Development and Field Application, pp. 463–482. CRC Press, Boca Raton, Florida, USA.

Horn flies have been estimated to cost the North American and Brazilian cattle industries close to USD 1000 million (Cupp et al. 1998) and USD 2540 million (Grisi et al. 2014) per annum respectively, whereas buffalo flies are estimated to cost the Australian beef cattle industry AUSD 99 million annually with losses presently confined mainly to the northern part of the country (Lane et al. 2015).

Buffalo fly feeding can lead to the development of lesions that are of significant welfare concern (Jonsson and Matchoss 1998), reduce hide value and make cattle less acceptable for the market (Guglielmone et al. 1999; Lane et al. 2015). These lesions can range in nature from dry and alopecic or scab encrusted, to severe open areas of ulceration (Johnson 1989). They are found most commonly beneath the eyes of cattle, but can also be prevalent on the neck, dewlap, belly and flanks (Sutherst et al. 2006) and their development and persistence has been associated with a currently unnamed species of filarial nematode (*Stephanofilaria* sp.), transmitted by buffalo flies (Johnson 1989; Shaw and Sutherland 2006). Although similar lesions are found associated with horn fly feeding, they are mainly abdominal in distribution and generally not nearly as severe as those associated with buffalo flies (Hibler 1966; Silva et al. 2010).

Skin lesions are most widespread in northern areas of Australia, where buffalo flies are present throughout the year, with up to 95% of cattle affected (Johnson et al. 1986). It is expected that the prevalence of lesions will increase in more southern parts of the fly range as global warming extends the length of the buffalo fly season and the intensity of fly attack. In a survey of Queensland dairy producers, buffalo flies were considered to be a greater problem for production than cattle ticks, and when asked what aspect of infestation concerned them most, 42% of producers noted the welfare effects (Jonsson and Matchoss 1998). In addition, the lesions present a potential focus for strikes by Old World screwworm *Chrysomya bezziana* (Villeneuve) flies, which are endemic in a number of Australia's nearest northern neighbouring countries and which are considered a major biosecurity risk for northern Australia (AHA 2017).

2. TAXONOMIC STATUS

Buffalo flies and horn flies are very closely related and have variously been considered as sub-species (Zumpt 1973; Pont 1973) and separate species (Skidmore 1985). The larval stages of the two species are extremely similar and are probably morphologically indistinguishable (Pont 1973). Morphological differentiation of the adults is also difficult, and the main distinguishing feature in the flies is the presence of 4 to 6 long curled hairs on the hind tarsi of male *H. exigua*, which are not found in *H. irritans* (Mackerras 1933; Iwasa and Ishiguro 2010). Kano et al. (1972) suggested a number of other morphological distinguishing features, but Iwasa and Ishiguro (2010) indicated that these varied with latitudinal gradient within each species. Snyder (1965), who studied many specimens from Micronesia, stated that even the bristling on the hind tarsi of *H. exigua* is variable (Zumpt 1973).

Urech et al. (2005), who measured buffalo flies cultured on cattle in Australia and horn flies from a laboratory colony in Florida, indicated that there were distinct differences in the cuticular hydrocarbons of the two groups of flies and suggested that these differences may support their status as separate species.

Iwasa and Ishiguro (2010) examined the mtDNA in the COI to COII genes of horn flies collected from two sites in Japan and buffalo flies from sites in Taiwan and Viet Nam and found sequence divergence of 1.8% - 1.9% between the two species. They concluded that the relative genetic divergence observed between and within the two species may indicate an intermediate status in species development. From a more recent study of molecular differentiation of the two species, using the mtDNA COI, cytochrome B (Cytb), NADH dehydrogenase subunit 5 (ND5) genes, and the nuclear and 18S and 28S ribosomal RNA regions, Low et al. (2014, 2017) concluded that the two species are genetically distinct and that the COI and Cytb genes were the most informative for distinguishing the two species. Regardless of whether or not buffalo and horn flies can be considered separate species, all indications are that they are extremely closely related.

3. INVASION AND DISTRIBUTION

Both buffalo and horn flies have proven to be extremely invasive species. Either *H. irritans* or *H. exigua* is now present in most major cattle production areas of the world, with the exception of sub-Saharan Africa, where the species *Haematobia thirouxi potans* (Bezzi) and *Haematobia minuta* (Bezzi) occupy this niche (Zumpt 1973) (Fig. 1).

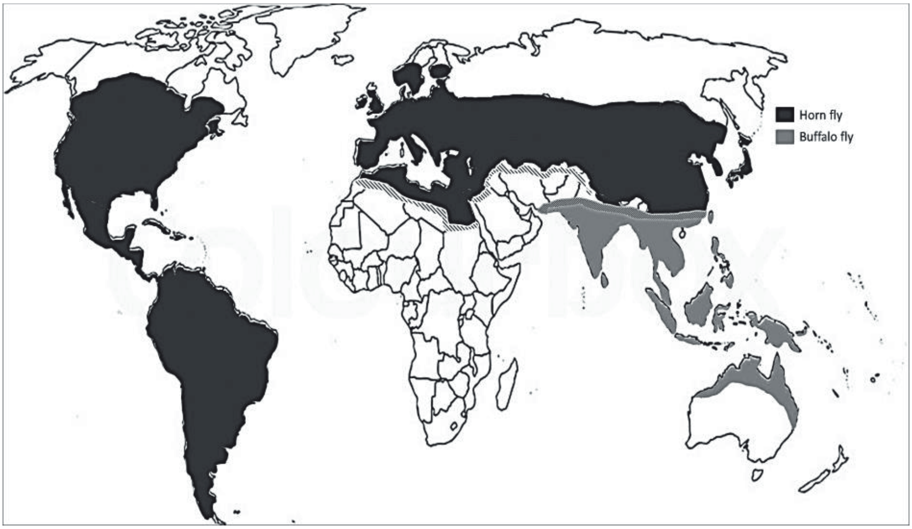

Figure 1. World distribution of horn fly H. irritans *and buffalo fly* H. exigua*.*

Horn flies were introduced to the east-coast of North America from Europe on imported cattle in 1885-86 (Butler and Okine 1999). They spread rapidly to reach California by 1893 and by 1900 had been reported from most of the USA, Canada and Puerto Rico. They were reported in South America from cattle in Colombia, Ecuador and Venezuela by 1937 (Mancebo et al. 2001), and were first reported in Brazil's northern-most State, Roraima in 1956.

By 1980, horn flies had spread south of the Amazon into Goiás state (Mancebo et al. 2001), by 1991 had reached the south of Brazil (Mancebo et al. 2001), and by 1993 had spread through Uruguay and all of the major cattle production areas in Argentina (22°S to 44°S) (Anziani et al. 1993; Guglielmone 1999).

On the western side of the continent horn flies were found in Bolivia before 1955 (Munro 1960), in Peru by at the latest 1973 (Zumpt 1973), and in Chile in 1967 (Gonzalez 1967), although it appears that they did not become a significant pest in Chile until 1993 (Campano and Avalos 1994). These records suggest that the southerly spread of horn flies in South America may have occurred independently on both the west and east sides of the continent.

3.1. Spread of Buffalo Flies in Australia

Buffalo flies have been similarly invasive in Australia, although their spread has occurred more slowly than for horn flies in the Americas, and has been limited at its southern extent by the inability of buffalo flies to undergo a winter pupal dormant phase, as occurs in horn flies (Ferrar 1969; Cook and Spain 1982). Buffalo flies entered mainland Australia near Darwin (12.5° S, 130.8° E) in 1838, probably on water buffalos (*Bubalus bubalis* L. 1758) introduced from Timor in 1825 (Tillyard 1931). Early spread occurred very slowly and coincided closely with the spread of buffalos (Hill 1917), which appear to be the preferred native host of the flies in Asia (Iwasa and Ishigura 2010) (Fig. 2).

It wasn't until 1928 that buffalo flies reached the Queensland border, approximately 1300 km southeast of their original point of introduction (Seddon 1967), subsequently spreading across the dry stretch of land south of the Gulf of Carpentaria to eastern Queensland during a series of wet years in 1939-41. From there, they spread rapidly to the east coast of Cape York in northern Australia and southwards along the eastern coast until they appeared to reach a southerly limit just north of Bundaberg (24.8°S latitude) by 1946. Here the spread paused, and no further southerly spread was observed for the next 30 years (Fig. 2).

Following a series of mild winters and wet years from 1973 onwards, changes to buffalo flies and tick regulatory programmes, possibly aided by changes in the chemicals used for cattle tick *Rhipicephalus australis* Fuller treatment, southerly range expansion recommenced and buffalo flies reached the Brisbane Valley and Nambour in 1977, the Tweed Valley in New South Wales in April 1978, and Bonville, south of Coffs harbour (30.4°S) in 1982 (Williams et al. 1985). Since then, the flies have continued their southerly spread with infestations seen as far south as Dubbo, Narromine and Maitland (32.7°S) in 2011 (Fig. 2). This represents an increase in their southerly range of approximately 1000 km in the last 40 years.

Following their first detection in New South Wales in 1978, the flies now survive the winter in many eastern parts of the state and have become a significant endemic cattle pest in these areas.

The impact of buffalo flies and the area affected in Australia varies significantly with season and weather conditions. During warm wet summers the distribution of the flies increases significantly in northern and north-eastern areas, and they may spread to affect cattle in an area potentially more than two times larger than the permanently infested range (Fig. 2).

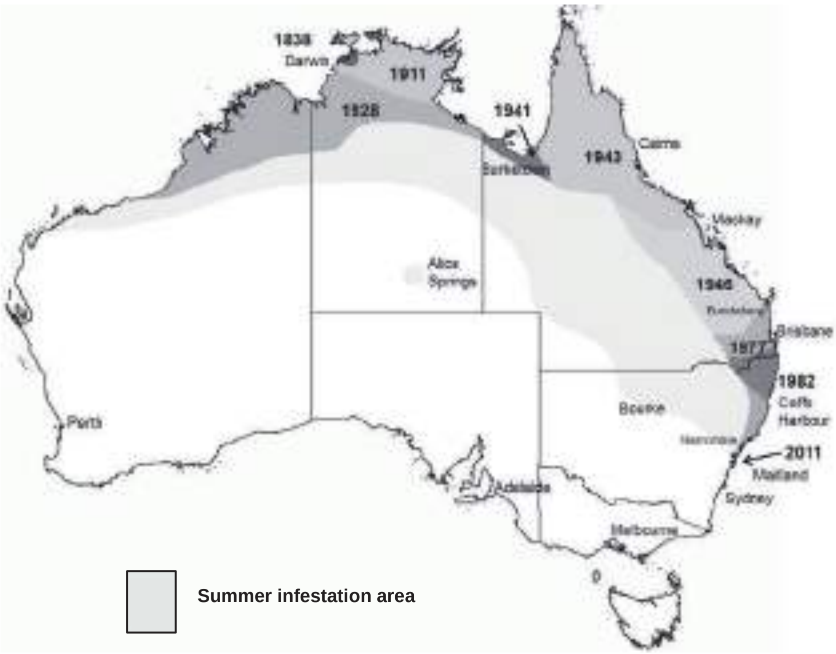

Figure 2: Spread over time of the buffalo fly H. exigua *in Australia.*

3.2. Effects of Climate Change

All indications to date suggest that climate change effects in Australia will facilitate the continued spread of buffalo flies into new areas and will increase the economic and welfare impacts in the southern parts of their current range (CSIRO/BOM 2016). Rising temperatures will enable more rapid *H. exigua* population growth, an increased number of generations each year, greater fly activity in many areas and longer seasons of cattle challenge. In addition, predicted rises in minimum temperatures and a reduction in the frequency of frosts will favour survival in marginal areas and further southerly extension of the flies' range. A possible increase in the summer incidence of rainfall in some areas of Australia may also favour the flies' breeding.

The results of CLIMEX modelling (R. Dobson personal communication 2015) suggest greater impacts from buffalo flies in the southern parts of their current range, including the potential for persisting fly populations to establish through most of the moist coastal belt of New South Wales and in foci as far south as South Australia and southern Western Australia (Fig. 3). In addition, increased weather variability and extreme rainfall events predicted under climate change may assist the spread of flies across inhospitable areas to new foci suitable for winter fly survival. Once established in these areas, new overwintering foci would provide a source for more extensive incursions during warm wet periods, similar to that seen in northern Australia.

The CLIMEX modelling does not account for factors such as a changing resource base, microclimate effects or changes in pest biology. In southern areas, the cattle industry is based largely on *Bos taurus* L. breeds that are more susceptible to buffalo flies than the *Bos indicus* L. cattle that predominate in northern areas (Frisch et al. 2000). In addition, northern cattle are normally treated to control cattle ticks, which can also impact on buffalo fly numbers, whereas few parasite treatments are applied to southern cattle. Thus, the southern beef and dairy industries provide a susceptible and largely untreated host resource extremely favourable for invasion by buffalo flies. Furthermore, adaption of insects at the edge of their range can be an important contributing factor in new pest invasions (Hill et al. 2011).

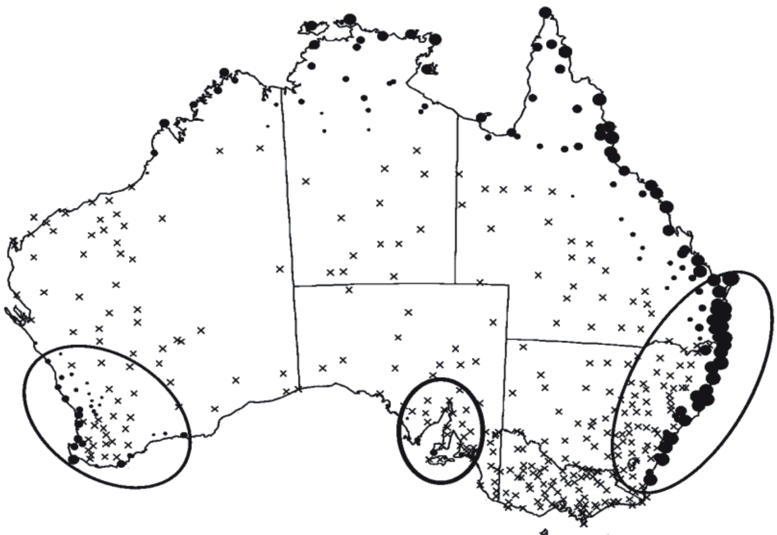

Figure 3. CLIMEX predictions of areas suitable for the establishment of persisting buffalo fly H. exigua *populations under predicted climate change. Size of solid circles indicates degree of favourability of areas for buffalo fly persistence; crosses indicate weather station sites not suitable for buffalo flies' persistence; the large open ellipses indicate areas of most significant range expansion (credit Rob Dobson).*

The degree to which genetic adaptation of buffalo flies to cooler temperatures has contributed to their southerly spread is uncertain. However, Iwasa and Ishigura (2010) note that the flies in their native range appear to prefer buffalo to cattle as hosts, and a period of adaptation to cattle and cooler Australian conditions may have contributed to their spread. Development of pupal overwintering capacity as they move south, a possibility given their close genetic relatedness with horn flies, is a concerning prospect and could see the species develop a temperate distribution in Australia, similar to the distribution seen for horn flies in the northern hemisphere and South America.

4. POTENTIAL FOR THE USE OF AREA-WIDE APPROACHES AGAINST BUFFALO FLIES IN AUSTRALIA

Currently, control of buffalo flies in Australia depends largely on chemical treatments, although techniques such as buffalo fly traps (Sutherst and Tozer 1995) and selection of more tolerant *Bos indicus* breeds (Frisch et al. 2000) are also used. In addition, dung beetles may assist the regulation of buffalo fly populations under some circumstances (Doube 1986). Treatments are applied almost exclusively on a herd-by-herd basis. However, modelling studies indicate the likely inefficiency of herd-by-herd approaches showing that the effects of invasion of pests from untreated areas can be devastating in compromising the effectiveness of control measures (Knipling 1972a). Application of control techniques on an area-wide basis, targeting the entire population rather than just individual properties or herds, can be much more efficient than more intensive programmes applied on a herd-by-herd basis. Area-wide approaches are expected to be particularly advantageous when pests are mobile and can readily auto-disseminate and therefore may not be easily controlled by property-based or herd-based programmes (Hendrichs et al. 2007), such as is the case with buffalo flies.

4.1. Chemical-based Programmes

Area-wide control programmes have historically been based mainly on the application of chemical insecticides by methods such as aerial spraying or intensive ground spraying, or in the case of diseases of livestock, by individual animal or herd treatments with quarantine controls and movement restrictions (Graham and Hourigan 1977).

At various stages in the spread of buffalo flies in Australia, regulatory programmes, supported by legislation, and which included movement controls and compulsory spraying of relocated cattle with insecticides, were used in an attempt to prevent their southerly incursion (Parliament of Queensland 1965). However, these programmes were not effective in stemming the southward spread of buffalo flies (Anonymous 1934; Roberts 1946; Eastaway 1974) and all were eventually abandoned in 1978 (Williams et al. 1985). However, buffalo flies remain a legislatively specified notifiable disease in some southern states of Australia, where the flies are not currently present (DAWR 2017).

4.2. Autocidal and Biologically-based Approaches

Programmes which require widespread application of insecticides are increasingly unacceptable on a community basis and can be compromised by the development of resistance or resurgence of pests from cattle that are not treated or where treatments are poorly applied. More biologically-based, species-specific and environment-friendly techniques which operate by disrupting biological processes of pests, generally find wider community acceptance and are often more effective than insecticide applications (Bourtzis et al. 2016). In addition, because of the ability of released insects to disperse into all areas occupied by the target field population and to actively search out and mate with target insects, biologically-based methods are often more effective against pests that can disperse autonomously, or which survive in cryptic habitats that are hard to reach with chemical sprays.

The most well-known of these approaches is the Sterile Insect Technique (SIT) in which insects of the target species are mass-reared and sterilised using low level ionizing radiation, followed by inundative releases of the sterilised insects (usually males) on an area-wide basis over the entire area of the target population (Vreysen and Robinson 2011; Dyck et al. 2021). The sterile males mate with field females, which consequently produce infertile eggs and through sequential releases the target population is suppressed, or under certain favourable conditions, eradicated.

Some of the most significant successes with the SIT have involved insect pests of livestock, including the eradication of New World screwworm *Cochliomyia hominivorax* (Coquerel) from North and Central America (Wyss 2000), eradication of an incursion of this pest in Libya (Lindquist et al. 1992), and removal of the tsetse fly *Glossina austeni* (Newstead) from the Island of Unguja in the Zanzibar archipelago (Vreysen et al. 2000, 2014). Localised eradication or suppression using the SIT has also been achieved on a number of occasions with other tsetse species in Africa (Vreysen et al. 2013). Successful eradication using this approach can be extremely cost efficient. For example, in the New World screwworm programme in the Americas it has been calculated that the direct benefits achieved each year from the programme are equal to or greater than the total cost of the sterile male release programme over the fifty years of its operation (Vreysen and Robinson 2011).

Horn flies are one of the species suggested by Knipling (1972b) as likely candidates for control by the SIT. Knipling considered that the close association of the flies with cattle and its consequent accessibility to control meant that fly populations could be readily reduced by insecticide treatment of cattle, then the remaining population eliminated using the SIT. In early trials with horn flies, cattle were sprayed with topical insecticides to reduce fly numbers. However, the subsequent sterile insect releases were compromised because the released flies were more susceptible to the insecticides used than were the field flies (Eschle et al. 1973, 1977). This was overcome by using methoprene, an insect growth regulator administered in drinking water, which targeted the larval stages of horn flies, and had no effect on the released adult flies. Trials on the isolated Kalaupapa peninsula of Molokai in Hawaii subsequently confirmed that a semi-isolated population could be effectively eradicated using this method, even in the very horn fly-favourable environment of Hawaii (Eschle et al. 1977). Unfortunately, the area was later reinfested by the introduction of infested cattle into the area.

Although the SIT is by far the most widely known and successful genetic technique used against livestock pests to date, SIT application is not always feasible and a range of other genetically-based techniques have also been tested, or are under contemplation. For example, in continental Australia the extensive areas of livestock production and the wide distribution of associated pest species, together with few natural geographic boundaries, made the use of the SIT impractical or at least of dubious cost-benefit for use against many livestock pests, as in the case of sheep blowfly *Lucilia cuprina* (Wiedemann). As a consequence, a range of other genetically-based techniques such as the use of compound chromosome and sex-linked translocation strains (field female killing systems), which were predicted to be more effective at lower release ratios, were developed and tested (Foster et al. 1985, 1988, 1991). Field testing showed promise for these other approaches, but for a number of reasons discussed by Scott (2014), they were never implemented for widespread use.

More recently, transgenic sexing strains of *L. cuprina* have been developed that carry a tetracycline-repressible female lethal genetic system that could form the basis for mass-production of only males of *L. cuprina,* and potentially other fly species, for use in genetic control programmes (Scott 2014). A range of other techniques such as the Release of Insects carrying Dominant Lethal (RIDL) genes, RNAi and homing endonuclease genes (HEG) are now also being considered for use with mosquitoes, tsetse flies and other species (reviewed by McGraw and O'Neill 2013; Bourtzis et al. 2016) and have proceeded to field testing in some instances (Harris et al. 2011). With increasing access to sequenced insect pest genomes (International *Glossina* Genome Initiative 2014; Anstead et al. 2015) and rapid advances in molecular technology, most notably the availability of new gene editing techniques such as CRISPR-Cas9, many new, purpose-designed approaches for control will likely emerge.

5. *Wolbachia* AND AREA-WIDE CONTROL OF BUFFALO FLIES

Other technologies of much current interest for use in area-wide control programmes are symbiont-based approaches (Bourtzis 2008; Bourtzis et al. 2016; McGraw and O'Neill 2013; Wilke and Marelli 2015), in particular the use of *Wolbachia*. *Wolbachia* are maternally transmitted intracellular bacteria in the family Alphabacteria, estimated to infect 40% of terrestrial arthropod species (Zug and Hammerstein 2012). *Wolbachia* are capable of spreading through insect populations by manipulating host reproductive processes and have many and varied other effects that present potential for use in buffalo fly control programmes (Hoffmann et al. 2015). These can be considered in three main groups:

1. Cytoplasmic incompatibility, which can be harnessed for population suppression, population replacement or potentially population elimination
2. Fitness effects induced by *Wolbachia* infection, and
3. Transmission blocking of secondary pathogens.

These strategies are considered below for their potential to reduce the impacts of buffalo flies or interrupt their spread into uninfected areas.

5.1. Cytoplasmic Incompatibility and Incompatible Insect Technique (IIT*)*

Wolbachia infection can interfere with insect reproduction in several ways, including through the induction of cytoplasmic incompatibility whereby matings between infected males and non-infected females or between males and females infected with incompatible *Wolbachia* strains (bidirectional incompatibility), produce infertile eggs. This approach when used as an insect suppression or eradication strategy has been termed the Incompatible Insect Technique (IIT) (Zabalou et al. 2009). The IIT method is similar in approach to SIT, with *Wolbachia*-infected males used as *de facto* sterile males. Since *Wolbachia* is not paternally transmitted, as long as similarly infected females are not also released, the *Wolbachia* strain present in the released males does not establish in the target population in the field. Thus, serial release of only the infected males can lead to population suppression or eradication.

The effectiveness of using *Wolbachia*-induced cytoplasmic incompatibility in this way was demonstrated as early as the 1960s when release of *Wolbachia*-infected male *Culex quinquefasciatus* Say mosquitoes, vectors of human filariasis, led to local eradication of this species from areas in Myanmar (Laven 1967). Since then, studies towards the use of IIT have been conducted with a range of mosquito species, including *Aedes polynesiensis* Marks (Brelsfoard et al. 2009; O'Connor et al. 2012), *Aedes albopictus* (Skuse) (Calvitti et al. 2010), *Anopheles stephensi* Liston (Bian et al. 2013) and *Culex pipiens pallens* (Coquillett) (Chen et al. 2013), as well as the veterinary pests *Glossina morsitans* Westwood (Alam et al. 2011; Bourtzis et al. 2016) and *Stomoxys calcitrans* (L.) (Kusmintarsih 2009).

Use of an IIT approach could be applicable for eradication of confined foci of overwintering populations of buffalo flies to prevent or retard southerly spread or to slow rates of re-colonisation of favourable northern areas in summer. The IIT method could also be used to eradicate buffalo flies that become established in relatively isolated areas as a result of climate change, such as those predicted in South Australia and south-western Western Australia (Fig. 2).

Ideally only male *Wolbachia*-infected buffalo flies would be released, but to date no method for accurate mass-sexing of horn or buffalo flies has been reported. In the case of the Hawaii SIT trials with horn flies, irradiated flies of both sexes were released (Eschle et al. 1977). Although this is usually undesirable, because it increases competition with field females for mates and can temporarily increase fly pressure on cattle, it did not compromise success in the case of the Hawaiian trial and may not be a consideration if used against low-level populations present in overwintering foci of buffalo flies.

Reduction of male mating competitiveness from the effects of irradiation is one of the difficulties sometimes experienced in SIT programmes (Zhang et al. 2015). As female flies are often sterilised at levels of radiation below that which causes reduction of competitiveness in males, this has led to the suggestion of the complementary simultaneous use of the SIT and the IIT, with *Wolbachia* used to induce functional sterility in the males and low-level irradiation used to sterilise the females thereby also assuring that the *Wolbachia* strain present in the released males does not establish in the target pest population (Brelsfoard et al. 2009; Zhang et al. 2015; Bourtzis et al. 2016). In the absence of a practical sexing method, a similar approach could be considered for buffalo flies.

Alternatively, the development of a self-sexing strain in stable flies *S. calcitrans* (Seawright et al. 1986), which are in the same subfamily as buffalo flies, the determination of a near infrared (NIR)-based method for sexing tsetse fly pupae (Dowell et al. 2005; Moran and Parker 2016), and the rapid advances with molecular techniques currently being made in other species (Scott 2014), suggest significant potential for the future development of a sexing method for buffalo flies.

Notwithstanding the potential added difficulties for artificial rearing, the use of a strain of *Wolbachia* that also confers a fitness disadvantage or inability to overwinter in infected flies, such as *w*MelPop (see below), is a further possibility to guard against the effects of inadvertent female release in a *Wolbachia*-based IIT programme.

5.2. *Using* Wolbachia-*Induced Fitness Effects to Collapse Overwintering Populations of Buffalo Flies*

Different strains of *Wolbachia* can induce a range of different effects on the fitness of infected hosts (Hoffmann et al. 2015). Some of these effects include reduced life span (McMeniman et al. 2009), mortality of eggs (McMeniman and O'Neill 2010), slowed larval development (Ross et al. 2014), and reduced overall fitness (Yeap et al. 2011, 2014; Ross et al. 2015). Infection with *Wolbachia* has also been shown to interfere with blood-feeding efficiency in mosquitoes (Moreira et al. 2009; Turley et al. 2009), and to affect locomotor activity in parasitoid wasps, *Drosophila* species, and some mosquitoes (Fleury et al. 2000; Peng et al. 2008; Evans et al. 2009). Similar effects in buffalo flies could also have deleterious effects on survival and mating efficiency, as well as the persistence of their populations, particularly during winter.

The most profound deleterious effects described have been from the 'popcorn' (*w*MelPop) strain of *Wolbachia*, initially isolated from laboratory populations of *Drosophila melanogaster* Meigen (Min and Benzer 1997). The *w*MelPop strain replicates in host cells, causing cellular damage, characteristic morphological changes in infected tissues, and a range of physiological effects. These effects reduce life span by approximately one-half in *D. melanogaster* and transinfected mosquitoes (Min and Benzer 1997; McMeniman et al. 2009). Reductions of life span of this magnitude, and other fitness characters, can have profound effects on the population dynamics of a species, particularly during unfavourable times of the year (Rasic et al. 2014). However, the effects of *Wolbachia* are highly strain-, host- and environment-dependent, and less profound effects on fitness have also been observed in other *Wolbachia*-host associations (Hoffmann et al. 2015).

Modelling conducted by Rasic et al. (2014) demonstrated potential for using fitness reductions induced by *Wolbachia* to suppress or eliminate *Aedes aegypti* L. populations, particularly in locally or seasonally variable environments. Their results suggested that the effects of *w*MelPop were not sufficient to reduce persistence of mosquito populations in the very favourable climates of north Queensland, but they were likely to cause local extinctions in the more mosquito-marginal environments of central Queensland. These predictions were supported by semi-field cage studies, which showed that reductions in the survival of desiccation-resistant eggs resulting from *w*MelPop infection, eliminated populations of *Ae. aegypti* during extended dry periods (Ritchie et al. 2015).

Wolbachia could also be used to drive co-inherited deleterious ‘payload genes’ in the genome of infected insects into the target pest population (Curtis and Sinkins 1998; Hoffmann and Turelli 2013; Champer et al. 2016). These genes could confer reduced fitness or conditionally lethal effects such as cold temperature sensitivity or insecticide susceptibility. Conversely the use of linked traits that confer a fitness advantage in certain circumstances might be used to facilitate the spread of *Wolbachia* strains into a population. For example, insecticide resistance that confers a competitive advantage under a spraying regime could be used to assist the spread of a *w*MelPop-infected strain that confers a pathogen blocking capability or seasonal lethality (Hoffmann and Turelli 2013).

As more pest insect genomes are characterised, along with the rapid advancement in molecular transformation technologies, it is expected that possibilities for this approach will grow rapidly. Using *Wolbachia* as the driving mechanism is expected to have greater public acceptance and less potential for unanticipated effects than transgenic gene drives (Champer et al. 2016). An attractive alternative approach is the direct transformation of *Wolbachia* genomes with genes to be driven into a pest population. Until recently, successful genetic transformation of *Wolbachia* had proved elusive, but the recent reporting of a phage-mediated system for the genetic modification of *Wolbachia* (Bordenstein and Bordenstein 2017) offers exciting possibilities in this area.

5.3. Stephanofilaria *Blocking*

Buffalo fly-associated lesions are of significant welfare and economic concern, with estimates of over 95% of cattle affected in northern areas of Australia (Johnson 1989). Although the exact etiology of buffalo fly-associated lesions is unclear, an unnamed species of filarial nematode (*Stephanofilaria* sp.*),* transmitted by buffalo flies and found in the lesions, is thought to play a role (Johnson et al. 1986; Johnson 1989). Surveys of buffalo flies collected from near Townsville in the 1980s found a 2.9% (range 0% - 9.3%) prevalence of *Stephanofilaria* in female flies (Johnson 1989), whereas a more recent study in 2004 measured infection rates between 29% and 57% in flies collected from four sites near Rockhampton (Shaw and Sutherland 2006).

Wolbachia infection has been demonstrated to reduce vectorial capacity of various species of mosquitoes for a range of pathogens, including filarial nematodes. Inhibition of development of filarial nematodes was seen with both *w*MelPop in *Ae. aegypti* (Kambris et al. 2009) and *w*AlbB in *Ae. polynesiensis* (Andrews et al. 2012) and resulted in a reduction in the prevalence of infective third stage nematodes in the mosquitoes. The mechanism of pathogen blocking is not completely understood but may be due to competition for host resources or modulation of host immune response, in particular reduction in levels of reactive oxygen species (Andrews et al. 2012). The *w*MelPop strain of *Wobachia* also reduces the efficiency of disease transmission by shortening the life span of vectors and reducing the likelihood that a pathogen will be able to complete its required extrinsic incubation period before host mortality.

The shortest incubation period seen for *Stephanofilaria* sp. in buffalo flies was 7 days (Johnson 1989), suggesting that the life-shortening effects of *w*MelPop

Wolbachia could also significantly affect the transmission dynamics of this filarial nematode species.

Lesions associated with horn fly-transmitted *Stephanofilaria stilesi* in North America appear to be less extensive and severe than buffalo fly-associated lesions in Australia (Hibler 1966). As horn flies are infected with *Wolbachia*, but buffalo flies are not, it is tempting to hypothesise that this difference may be associated with differences in the efficiency of *Stephanofilaria* transmission, although many other factors could also be involved. Disruption of the spread of *Stephanofilaria* or reduction in the severity of lesions by the introduction of a transmission-blocking *Wolbachia* strain into buffalo flies, would be a significant outcome for the Australian cattle industries from both economic and welfare perspectives.

6. BUFFALO FLY OVERWINTERING, A SUSCEPTIBLE STAGE FOR AREA-WIDE APPROACHES?

Horn flies have the ability to overwinter in the pupal phase, as pharate adults, whereas buffalo flies do not (Ferrar et al. 1969; Cook and Spain 1982), which is a major difference between the two species (Showler et al. 2014). In the northerly part of their range in North America, adult horn flies begin to disappear from cattle in autumn and do not reappear until the next spring. Overwintering dormancy allows horn flies to emerge and rapidly re-establish throughout the previous season's range when conditions become suitable in spring or summer. There is, however, significant plasticity in this response and at warmer latitudes horn fly populations continue cycling throughout the year (Showler et al. 2014).

In more marginal areas, horn flies may survive winter both as adults, with reduced activity, and in the pupal stage, with various levels of dormancy. Mendes and Linhares (1999) working in a warm winter climate in Brazil (21°30'S), verified diapause in 9.1% of winter pupae, even though horn flies were present on cattle year-round. These authors note that this dual overwintering mechanism could present difficulties for the design of cost-efficient eradication programmes for horn flies. The plasticity in overwintering response has most likely been a key factor allowing horn flies to disperse and become established in a wide range of environments.

In contrast to horn flies, buffalo flies die out through much of their summer range in winter (Fig. 2). Their range at the southern and continental edges in Australia is limited by cooler temperatures and low moisture levels in dung during winter (Cook and Spain 1982). Low temperatures either prevent development completely, or they slow the development of the larval stages to a degree that they can't be completed before moisture content in dung falls to lethal levels. The occurrence of frosts can also have a devastating effect on the survival of the soil stages, i.e. larvae and pupae (Cook and Spain 1982).

Williams et al. (1985) found that buffalo flies overwintered at the edge of their winter range as slowly cycling, low level fly populations in local areas of moderate microclimates. Most of these overwintering foci were in hilly, heavily timbered areas that were well-watered from either creeks, dams or swamps, and less exposed to low minimum temperatures or frosts than the low-lying surrounding areas. Nearly all of the overwintering sites identified were within 40 km of the coast, where temperatures were likely moderated by coastal influences. Re-colonisation of summer-suitable areas and southern range extension relied on overwintering of buffalo flies in these foci. When conditions became favourable each year, the flies built-up in numbers and either dispersed from these areas autonomously or were transported by cattle movements to reinfest their summer range (Fig. 2).

These localised overwintering foci provide a potential target for the application of *Wolbachia*-based approaches. The use of *Wolbachia* in either an IIT approach, to compromise *Stephanofilaria* transmission or to introduce a deleterious fitness factor, is likely to be most efficiently achieved at times of low fly populations, such as during overwintering, when suitable release ratios will be most readily achieved. Indeed, SIT and IIT approaches are often initiated when target populations are low, or involve population reduction by insecticide treatments prior to the release of infected flies.

Persistence of buffalo fly populations in overwintering foci is precarious and it is the soil stages that are most subject to adverse effects from low temperatures and dryness. Adult flies living with the warmth and blood provided by their cattle hosts are less affected by adverse winter conditions. Therefore, it is likely that released adult flies will be less exposed to the effects of winter conditions than the soil stages and able to persist for sufficient time to mate with overwintering adult flies and either interrupt reproduction or spread *Wolbachia* infection.

7. TOWARDS A *Wolbachia*-BASED APPROACH TO CONTROLLING BUFFALO FLIES

The effects of *Wolbachia* are most profound in new host associations (McGraw et al. 2002) and *Wolbachia*-based approaches to control require either the transinfection of *Wolbachia* into uninfected host populations, or transinfection of already infected populations with different strains of *Wolbachia* (O'Connor et al. 2012). Transinfection has most often been achieved by embryonic microinjection, but adult microinjection has also been successful in some instances (Hughes and Rasgon 2014). The success rate of microinjection is generally low, with subsequent loss of infection in newly injected hosts common, particularly in more distantly related host species. This is thought to be due to inability of the injected *Wolbachia* to adapt quickly enough to the new host environment. However, the probability of success can be increased by prior adaptation of *Wolbachia* in target host cell lines (McMeniman et al. 2008, 2009)

Although *Wolbachia* has not been found in buffalo flies, it is found widely in horn flies (Jeyaprakash and Hoy 2000; Floate et al. 2006; Zhang et al. 2009). The very close relatedness of buffalo and horn flies suggests it likely that the former will be a competent host for *Wolbachia* and that the likelihood of successful transinfection with suitable strains of *Wolbachia* is high.

We have successfully established cell lines for both horn and buffalo flies and have achieved persisting infections of *w*AlbB, *w*Mel, and *w*MelPop in cell lines for both species, also suggesting good potential for the successful transinfection of buffalo flies with *Wolbachia.*

We are undertaking a programme of microinjection towards the stable transinfection of buffalo flies with these three *Wolbachia* strains. We have also recently developed laboratory rearing methods for buffalo flies and have established a stable persisting laboratory colony (James et al. 2013). These methods will facilitate maintenance of transinfected strains and studies to determine the effects induced in these flies by infection with *w*AbB, *w*Mel and *w*MelPop, with a view to develop *Wolbachia*-based strategies for reducing buffalo fly spread and impacts.

8. CONCLUSION

Without intervention, buffalo flies are likely to become major cattle pests in Australia's southern beef and dairy industries, and also increase their impacts in northern herds. Their further southerly invasion is likely to be facilitated by the effects of climate change, together with the availability of a large, susceptible and mostly unprotected *Bos taurus* cattle population in the southern areas of Australia.

Previous regulatory procedures, based on spraying and cattle movement controls, have failed to prevent the southward spread of buffalo flies. Using an integrated area-wide approach incorporating use of a biological agent, such as *Wolbachia*, and focusing on the pest population rather than cattle, avoids potential disadvantages associated to widespread chemical use. In addition, *Wolbachia* are vertically transmitted from female flies to their eggs and restricted to living exclusively within host cells, thus minimising the potential for non-target effects. The use of *Wolbachia* has had good community acceptance in Australia to date (Kolopack et al. 2015) and importantly, a legislative framework for the release of *Wolbachia*-transinfected strains already exists in Australia (De Barro et al. 2011).

The design of optimal strategies will rely on a knowledge of the biological effects of candidate strains of *Wolbachia* in buffalo flies. A number of critical steps towards this end have been completed, including the establishment of an *in vitro* colony of buffalo flies as well as *Haematobia* cell lines transinfected with the *w*Alb, *w*Mel and *w*MelPop strains of *Wolbachia*.

We are currently undertaking embryonic and adult microinjection with these strains towards the establishment of transinfected buffalo fly lines. Successful completion of this step will allow characterisation of the effects of *Wolbachia* in buffalo flies towards the design of potential *Wolbachia*-based control strategies and an initial assessment of the likely feasibility of using a *Wolbachia*-based area-wide approach to reduce buffalo fly impacts in endemic areas and interrupt the southerly encroachment of buffalo flies.

9. ACKNOWLEDGEMENTS

We thank the Eliminate Dengue Programme for provision of *Wolbachia* strains; also Professors Elizabeth McGraw and Sassan Asgari for ongoing interest and advice, Professors Tim Kurrtii and Uli Munderloh for help in the establishment of the *Haematobia* cell lines, and Dr. Rob Dobson for permission to use the results of the buffalo fly CLIMEX modelling. We also gratefully acknowledge Meat and Livestock Australia for the provision of funding towards the research programme reported here.

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GIS-BASED MODELLING OF MEDITERRANEAN FRUIT FLY POPULATIONS IN GUATEMALA AS A SUPPORT FOR DECISION-MAKING ON PEST MANAGEMENT: EFFECTS OF ENSO, CLIMATE CHANGE, AND ECOLOGICAL FACTORS

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SUMMARY

The regional Mediterranean Fruit Fly Programme (Moscamed) in Belize, Guatemala and southern Mexico has applied geographic information systems (GIS) in the analysis of Mediterranean fruit fly populations since 2004. GIS allow integration of trapping data, control activities and environmental information; when combined with expert knowledge/interpretation (entomologist, ecologist and technical managers), they allow spatio-temporal analysis to determine geographic and temporal patterns, and their relationships with ecological factors and control activities. Ecological factors impacting the distribution of Mediterranean fruit fly (or medfly) populations also allow projecting pest demographics under climate change. Most of the prediction models of climate change indicate that the temperature will increase in the coming years. Temperature is a key ecological factor for insects in general, and medfly is no exception. Auclair et al. (2008) used the climate-host-insect interaction to develop predictive tools related with El Niño Southern Oscillation (ENSO) conditions, under the hypothesis that increasing temperatures will also increase medfly populations. A combination of GIS, statistical analysis, and climate change predictions indicate that hot El Niño years increase the reproductive rate of the pest, whereas cold La Niña years will have the opposite effect. With the medfly prediction model, early warnings can be provided to high-level decision makers and programme managers to act in an effective and timely-manner, including shifting in programme strategies and assigning larger budgetary resources to the programme when expecting difficult years.

Key Words: Geographic information systems, spatial-temporal analyses, temperature, El Niño Southern Oscillation (ENSO), La Niña years, Tephritidae, *Ceratitis capitata,* Belize, Guatemala, Mexico, population behaviour, population distribution, prediction models

J. Hendrichs, R. Pereira and M. J. B. Vreysen (eds.), Area-Wide Integrated Pest Management: Development and Field Application, pp. 483–504. CRC Press, Boca Raton, Florida, USA.

1. INTRODUCTION

The Mediterranean Fruit Fly Programme (Moscamed), managed jointly by the governments of Guatemala, Mexico and the USA, has been operating since 1977 to contain the Mediterranean fruit fly (*Ceratitis capitata* Wied.) (or medfly) in Guatemala and to protect the areas free of this pest in Guatemala, Mexico, Belize and the USA (Gutiérrez Samperio 1976; Enkerlin et al. 2015, 2017). Moscamed conducts two main activities:

1. Surveillance, through pest monitoring in infested areas, as well as detection and delimitation of the pest in areas of low pest prevalence and pest free areas using a geo-referenced trapping system located in Guatemala, Mexico and Belize; and
2. Control, through area-wide integrated pest management (AW-IPM) for population suppression and eradication, using a combination of environment-friendly techniques including the Sterile Insect Technique (SIT), aerial and ground sprays of an organically-approved insecticidal bait (spinosad), bait stations, and quarantine checkpoints to monitor and reduce movement of infested fruit into medfly free areas.

In 2004, Moscamed implemented a geographic information system (GIS) to manage the information related with detection of the pest, sterile fly releases, and the other activities involved in the AW-IPM activities. Since that time, information about ecological factors, such as hosts, temperature and rainfall, has been incorporated into the GIS. The GIS dataset has enabled new perspectives of the ecology and behaviour of the medfly populations but understanding the population ecology of medfly in Guatemala remains a key programme challenge. The relationship between coffee, *Coffea arabica* L. (as the main host) and fly captures was explained by Midgarden and Lira (2008). In addition, Auclair et al. (2008) found relationships between El Niño and medfly outbreak years by combining trapping and weather information.

One of the main factors that regulate the medfly populations is temperature. As with most insects, the medfly generational time is determined by degree-day accumulation. About 328ûC degree-days are needed to complete one life cycle from egg to adult (Grout and Stoltz 2007). The amount of time needed for this accumulation varies with temperature, and therefore also with altitude. Degree-days are the accumulation of heat units above a “base temperature” (the minimum needed for development) and below a thermal maximum (above which development is also halted) over a 24-hour period (Pedigo 1996). Below a minimum temperature threshold, no development takes place, but above it, heat units drive development. In the case of the medfly, USDA (2003) indicated that its lower threshold is ~12ûC and its upper threshold is ~28°C.

Temperature is not only important for medfly, but the increase of temperature is also one of the indicators of climate change (IPCC 2018). Climate can be defined as the long-term statistics of the meteorological elements in one particular area (WMO 1992), thus climate change is a difference in the long-term statistics of a given area between two different periods. Rahmstorf et al. (2012) observed that global mean temperature has been increasing due the climate change at 0.16 °C per decade. In areas below the upper threshold above which the medfly development is limited, these increases will have an impact on medfly population growth by shortening the time required for its life cycle, allowing the fly to complete more generations in the same time period, resulting in a higher rate of population increase.

Auclair et al. (2008) used an analysis of the climate-host-insect interaction to develop predictive tools related with El Niño conditions, under the hypothesis that an increase in temperatures will also cause increases in medfly population growth. These models have been used in Moscamed as an early warning system of pest population's growth. More recently we integrated other ecological factors, including soil types, to generate maps of the potential distribution of medfly, and how this distribution will be affected if temperatures continue to increase.

This chapter describes how Moscamed uses GIS to integrate the medfly ecology with observed patterns of populations, and how this information can be incorporated into prediction models that consider climate-host-medfly interaction in support of the pest management decision-making process.

2. MEDITERRANEAN FRUIT FLY PROGRAMME

Medfly was reported first time in Guatemala in 1975. In 1977, the governments of Guatemala, Mexico and the USA established Moscamed, a joint programme with the objective of protecting and promoting the fruit production in all three countries by containing the medfly in Guatemala (Enkerlin et al. 2015, 2017). Currently Moscamed operates in the state of Chiapas in Mexico, Guatemala and Belize to protect the medfly free areas in these countries and in the USA. The geographic area where Moscamed operates is shown in Fig. 1.

Figure 1. Area where the regional Moscamed programme operates in Belize, Guatemala and the state of Chiapas in Mexico to contain the invasive medfly, which is already established in Central and South America (credit Moscamed).

In order to detect the pest, Moscamed currently maintains a trapping network of 23 256 traps and conducts fruit sampling in strategic places. Coffee is the main and most abundant medfly host in this area. Moscamed, based on the reports of the coffee national institutions in Guatemala and Mexico, estimates that coffee covers an area of 5194 km^2. Therefore, a majority of the traps are installed in coffee production areas. The trap locations and the coffee areas are presented in Fig. 2. In 2017, Moscamed covered an area of 171 102 km^2, as can be seen in Fig. 3. Of that area, 87% (149 110 km^2) is considered as *Pest Free Area*, and most of the efforts and resources are oriented to maintain the pest free area status. A further 6% (9454 km^2) is considered as *Low Prevalence Area* and 7% (12 538 km^2) as *Suppression Area*.

The main control activity of the programme is the SIT, which is applied on an area-wide basis for prevention, eradication, and containment, depending on the presence of the pest (Hendrichs et al. 2021). The sterile fly densities (males/hectare) are determined for areas called "release blocks" based on the Rendón Method (Rendón 2008), with the aim of releasing higher densities in areas with higher pest population levels. Blocks are visited once or twice per week and evaluated on a weekly based to make adjustments in density, shape or location when needed. Weekly, Moscamed produces 1.4 billion sterile pupae and releases them in an area of around 5000 km^2 in Mexico and Guatemala. The SIT is combined with other control methods such as ground bait sprays, bait stations, and aerial bait sprays where populations are too high for only SIT releases. The distribution of sterile male release blocks and densities during one particular week in 2017 is presented in Fig. 4.

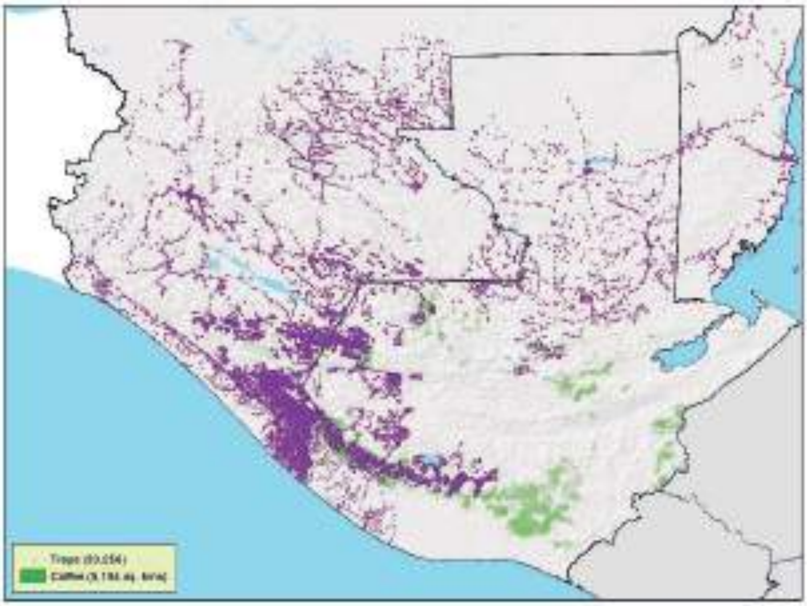

Figure 2. Moscamed trapping network in 2017, overlapping the main medfly host in Belize, Guatemala and the state of Chiapas in Mexico (credit Moscamed).

Figure 3. Moscamed working areas in 2017 in Belize, Guatemala and the state of Chiapas in Mexico (credit Moscamed).

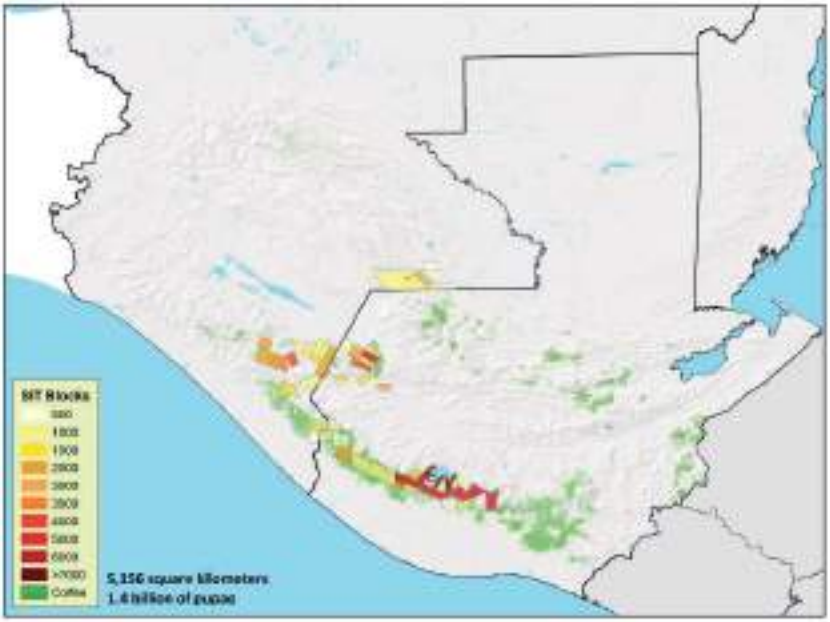

Figure 4. Sterile medfly release blocks in Guatemala and the state of Chiapas in Mexico. Numbers indicate fly release densities per hectare and per week (credit Moscamed).

3. CLIMATE CHANGE AND ITS IMPACT ON MEDFLY

The World Meteorological Organization (WMO) defines climate as the "synthesis of weather conditions in a given area, characterized by long-term statistics (mean values, variances, and probabilities of extreme values) of the meteorological elements in that area" (WMO 1992). The Intergovernmental Panel on Climate Change (IPCC) refers to climate change as a change in those long-term statistics of weather conditions for an extended period, typically decades or longer (IPCC 2018). Even though climate change may be due to natural processes, the main concern for IPCC is that since 1950´s the climate change has been accelerating and evidence is accumulating that it is caused by anthropogenic factors, with the increase of temperature being one of the indicators of climate change. Houghton (2015) indicates that the climate change can be observed as an increase in the mean, in the variance or in both. Considering temperature as the variable of interest, if the "new" climate has an increased mean temperature, this suggests less cold weather, more hot weather, and/or that the extreme hot weather will be higher. If there is an increase in the variance, it can be expected that there will be colder weather and hotter weather in the new climate. If there is an increase in both, the mean and the variance, then it is expected that there will be more hot weather, and the probability of occurrence of extreme hot weather will also be higher.

The IPCC considers that the three main lines of evidence of the climate change are: a) land and ocean surface temperature anomaly, b) sea level change, and c) greenhouse gas concentrations in the atmosphere (IPCC 2018). These three lines have shown an increase, which has become more evident after 1950. According to the IPCC, the changes in these three variables are related to the increase of emissions of the anthropogenic gases, which have accelerated global warming and in consequence catalysed changes in the climate. The IPCC forecast is that the temperature will continue increasing in the next decades (IPCC 2007). The IPCC observations regarding temperature indicate that the total temperature increase from 1850-1899 to 2001-2005 is 0.76°C [0.57°C to 0.95°C]. Hansen et al. (2013) observed that the global surface temperature in 2012 was +0.56°C (1°F) above the 1951-1980 base period average.

In this chapter, the increases of temperature are the main concern for medfly, since temperature is a key factor in its development and population dynamics. As will be discussed in Section 6, changes in temperature may trigger increases in medfly population levels.

4. GEOGRAPHIC INFORMATION SYSTEMS (GIS)

In a geographic information system (GIS), the physical world is represented as thematic layers, so that it can be described and analysed. A GIS is considered a computerized system used to acquire, store, analyse and display geographic information, which can be used to support the decision-making process. The main advantage of using a GIS is that spatial-temporal analyses can be conducted, and the results presented in an "easy-to-read" format such as maps, which are graphic and simplified representations of the reality.

With Moscamed in Guatemala establishing its GIS in 2004 (Lira 2010), the trapping network information generated by its operations is converted into geographic data and stored with other geographic layers such as land use, temperature, rainfall, altitude, and soil types in a digital format. Using different GIS operations, modelling and analyses of the medfly populations are conducted and different scenarios are generated. With the adequate cartographic techniques, i.e. generalization and symbolization, maps are provided to decision-makers to support their pest management decisions. According to Huisman and de By (2009) symbolization is the process to choose the visual design employed to communicate information on a map in an efficient manner by combining the visual variables of colour, intensity, size, orientation, transparency, and fill. The same authors indicate that generalization is the process of producing a graphic representation of a smaller scale from a larger original scale.

Midgarden et al. (2014) described that, for tephritid fruit fly programmes, GIS serve as a bridge between the trap samples and the spatial analysis methods. These methods enable: 1) improvement in the way to report and summarize the collected information in a more meaningful way; 2) identification of unrecognized patterns of population growth and spread, and 3) development of improved integrated pest management strategies. In the case of Moscamed, the use of GIS and improved understanding of medfly ecology allowed to change the containment and eradication strategies of the medfly in Guatemala. Starting in December of 2007, the Gradual Advance Plan (GAP) was implemented (McGovern et al. 2008). The GAP consists of pushing back the leading edge of the infestation by 10 to 20 km per year, with the subsequent movement of the low suppression and suppression areas into the adjacent infested areas in a strategy known as the "rolling carpet" approach (Hendrichs et al. 2021). The GAP allowed expanding the medfly-free area 150 km into Guatemala in less than four years, despite severe budget reductions (Enkerlin et al. 2017).

5. POPULATION BEHAVIOUR OF MEDITERRANEAN FRUIT FLY IN GUATEMALA

Over the year, in south-western Guatemala, the growth of medfly populations in infested areas has a logistic trend, with an S-shaped curve. Fig. 5 describes this behaviour in four phases. The population growth begins in November of each year, reaching maximum growth rate in January, and reaching the maximum population size in February. After that the growth rate decreases, and then the fly population gradually declines, and finally reaches a minimum in October/November. Because of the detection system used (mainly based on adult traps), this behaviour is measured as captures of adult flies, and it seems to occur independent of the availability of maturing coffee berries (Fig. 6). However, as explained by Midgarden and Lira (2008), the reason for this time-displacement is that the populations seen as adults were laid as eggs before, when coffee berries were available.

Depending on the altitude and the host availability, these 4 phases can occur earlier or later in the year, especially phases 2 and 3. But the general pattern is repeated every year. It can be said that the "medfly-year" runs from November to October.

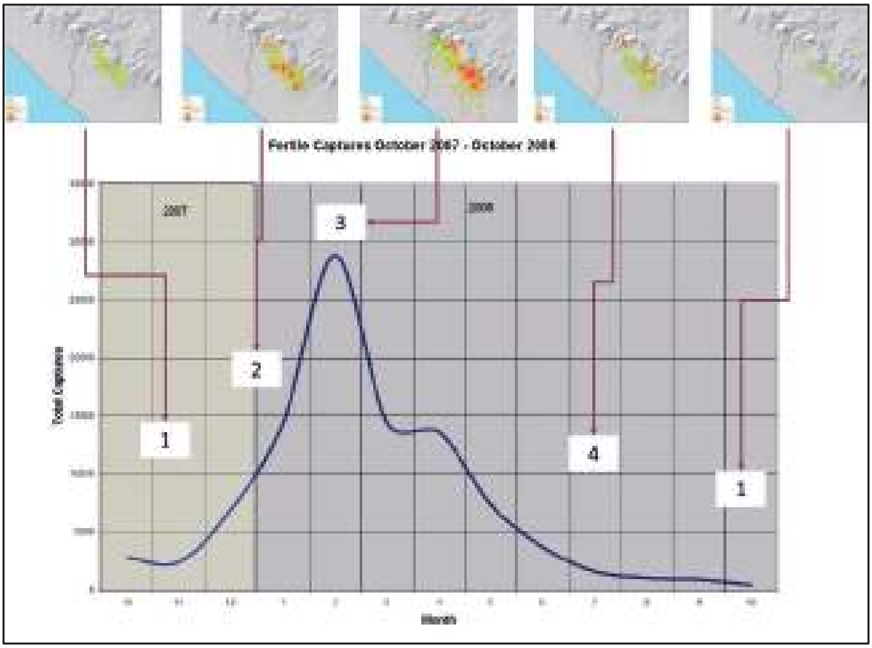

Figure 5: Four phases of medfly population behaviour in south-western Guatemala. 1. Beginning of population growth; 2. Maximum growth rate; 3. Maximum population size; 4. Decreasing rates and population declines, reaching a minimum size (credit Moscamed).

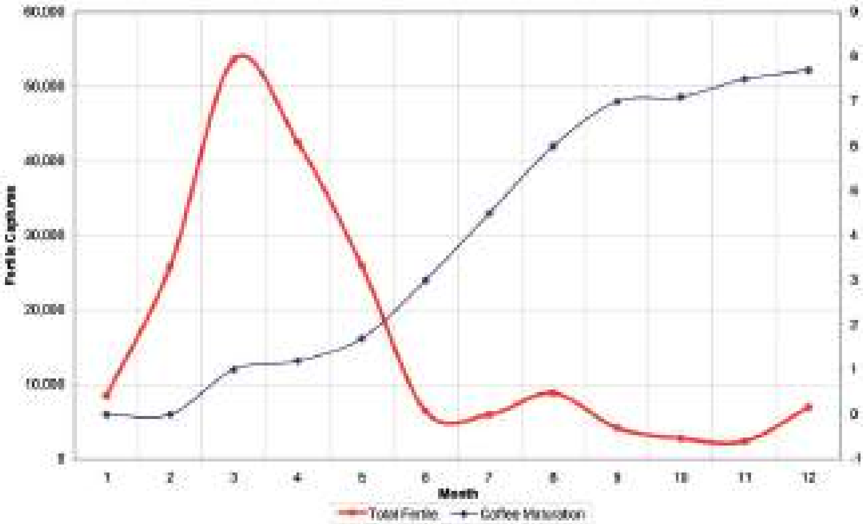

Figure 6. Relationship between captures of fertile medflies and coffee maturation throughout the year 2007 in the south-western region of Guatemala between 600 and 1500 m above sea level (the authors, based on Moscamed and ANACAFE 2008 data).

6. MEDITERRANEAN FRUIT FLY ECOLOGY: EFFECTS OF HOST, TEMPERATURE AND SOILS ON MEDFLY POPULATIONS

The population behaviour of medfly in Guatemala, described in the previous Section, can be explained by different ecological factors. We analysed three factors affecting medfly: host, temperature, and soils. The contribution of each of these ecological factors to medfly populations is discussed in this Section.

6.1. Main Host

Coffee is the main host of medfly in southern Mexico and Guatemala (Gutiérrez Samperio 1976). Midgarden and Lira (2008) explained how the coffee phenology (including events such as flowering and fructification) interacts with medfly biology. According to these authors, the adult fly population outbreaks may appear in one location after the coffee harvest, while the growing larval population was actually present at another location and at an earlier time (during the coffee berry fructification period).

This “shift” of the pest in time and space is related with the altitude gradient in which the main coffee production areas in Guatemala are located, with elevations varying from ~400 to ~2100 meters above the sea level. This altitudinal gradient drives a gradient in the time of maturation and harvesting of coffee; in consequence adult flies can infest the coffee berries at lower elevations in July, and gradually move up to higher elevations following the maturing phenology of coffee final harvest in December or later.

Midgarden and Lira (2008) observed that, due to the pupation time after coffee harvest, the emergence of the highest population of adult flies will occur in March-April of the next year. At that moment, coffee berries are scarce, likely resulting in extensive dispersal of mature adults to search for other available hosts including mandarin (*Citrus reticulata* L.), orange (*C. sinensis* L.), peach, (*Prunus persica* L.) and pear (*Pyrus communis* L.) at middle to high altitudes and guavas (*Psidium guajava* L.), caimito (*Chrysophilum caimito* L.) and tropical almond (*Terminalia catappa* L.) at lower altitudes (Enkerlin et al. 2016). In summary, Midgarden and Lira (2008) concluded that

> *“flies are captured in detection traps in March through April and can be seen as part of an ecological “shell game”: the fly population outbreaks appear in one location in April (non-infested or host-poor areas west of the leading edge of the pest population), while the growing population was actually present at another location months earlier (e.g. December in untreated coffee areas to the East)”.*

Fig. 6 summarizes the coffee-medfly relationship explained by Midgarden and Lira (2008) in relation to the months of the year. In the left Y axis, the number of fertile or wild fly captures per month is presented, and in the right Y axis the coffee maturation level is shown, in a scale of 0 to 8, being 0 no berries at all, and 8 total maturation. After December it is expected that most of the harvest occurs, “cleaning-up” mature coffee berries from the field.

6.2. Temperature

Regarding temperature, Ricalde et al. (2012) indicated that an insects' development depends on thermal requirements, with each insect species having an optimal temperature range for development, limited by lower and upper thresholds (base temperature (*Tb*) and upper limit (*Ts*)) plus a required thermal accumulation for developmental transition to complete a life cycle. The thermal accumulation between *Ts* and *Tb* in one day (24 hours) is measured in "degree-days". These are calculated as follows (example): if *Tb* of an insect is 10 °C, and temperature remains constant at 15 °C for 24 hours, 5 degree-days will be accumulated.

Ricalde et al. (2012) found that the base temperatures for medfly were between 8.47°C and 9.60°C and the degree-days required to complete the life cycle varies from 328 to 350, depending on the location. This is in accordance with Grout and Stoltz (2007), who found that for *C. capitata* be able to complete an egg-to-egg cycle (hatching from the egg, larvae growth, transformation into a pupae, emergence as an adult, reaching sexual maturity, copulation and laying of viable eggs), the thermal constants are: 337.8 degree-days, minimum development threshold of 9.6°C, maximum development threshold of 33.0°C, and optimum development threshold of 28.5°C. According to USDA (2003), the parameters for medfly are: a) ~ 328 degree-days for completing a life cycle, b) ~ 12°C as minimum threshold, and c) ~ 28°C as maximum. These estimates vary among them, but they can be used as reference to estimate the length of medfly life cycle.

Using the Grout and Stoltz (2007) thermal constants as reference, it is possible to estimate the length of the life cycle. If it is assumed that the daily temperature is constant at 28.5 °C, 17.87 days will be required to complete a life cycle, since each day 18.90 degree-days will be accumulated (28.5 °C minus 9.6 °C) to reach the needed 337.8 degree-days. If the temperature is constant at 20 °C, the number of days to complete a life cycle will be 32.48, since every day 10.40 degreed days will be accumulated (20 °C minus 9.6 °C). This dependency of insect development on temperature drives the population's behaviour: temperature speeds up or slows down the life cycles, and in consequence the resulting number of flies in a fixed period. If it is considered that the "medfly-year" runs from November to October (as indicated in Section 5) and the parameters proposed by USDA (2003) are applied to the average daily temperature of one weather station in one site of Moscamed's suppression area, it can be estimated that the number of life cycles for the "medfly-year" starting November 1st of 2012 to October 30th of 2013 is 7.74 (Fig. 7).

Based on these life cycles, and considering the other ecological factors as constant (host availability and soils) and an estimated population increase rate of 6x (Rendon 2008), from one wild female fly on day one of the medfly-year, after 365 days a medfly population of 1 021 780 flies can be expected (Fig. 8). It is important to stress that the quantitative estimate of the number of flies from one female does not relate directly to real population patterns (Fig. 5) because it considers only potential maximum, and not limitations from factors like host availability or predation.

To measure the impact of increasing temperatures on medfly populations, and assuming an increase of 1°C of temperature, the same estimation was made. That estimation indicates that with such a temperature increase, the number of life cycles in 365 days will be 8.86 (Fig. 9). Even though that it is only 1.11 more life cycles, under the same assumptions (host availability, soils, and population increase rate), with that increase of temperature, a population of 7 463 038 flies (more than 7 times higher) is to be expected after 365 days (Fig. 10). These estimations reflect the drastic effect of temperature on medfly populations.

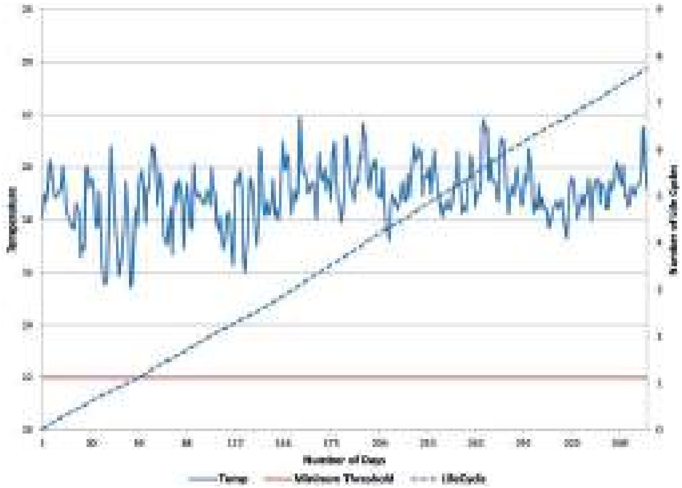

Figure 7. Average daily temperature and number of medfly life cycles expected from November 1st of 2012 to October 30th of 2013 in a coffee farm in the suppression area in Guatemala at 1600 meters above sea level (the authors, based on weather information of ANACAFE 2014).

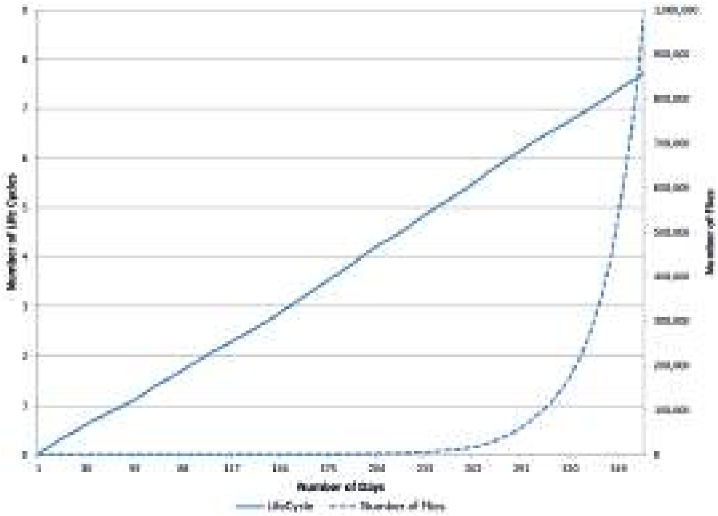

Figure 8. Number of life cycles and number of medflies (offspring from one wild female fly on day one) expected from November 1st of 2012 to October 31th of 2013 in a coffee farm in the suppression area in Guatemala at 1600 meters above sea level (the authors, based on weather information of ANACAFE 2014).

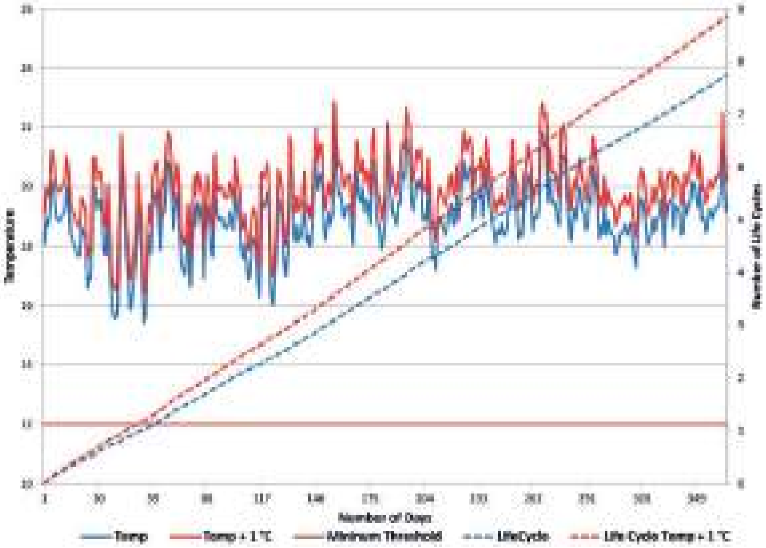

Figure 9. Number of medfly life cycles expected in a year in a coffee farm in the suppression area in Guatemala at 1600 meters above sea level in relation to an average daily temperature increase of 1°C (the authors, based on weather information of ANACAFE 2014).

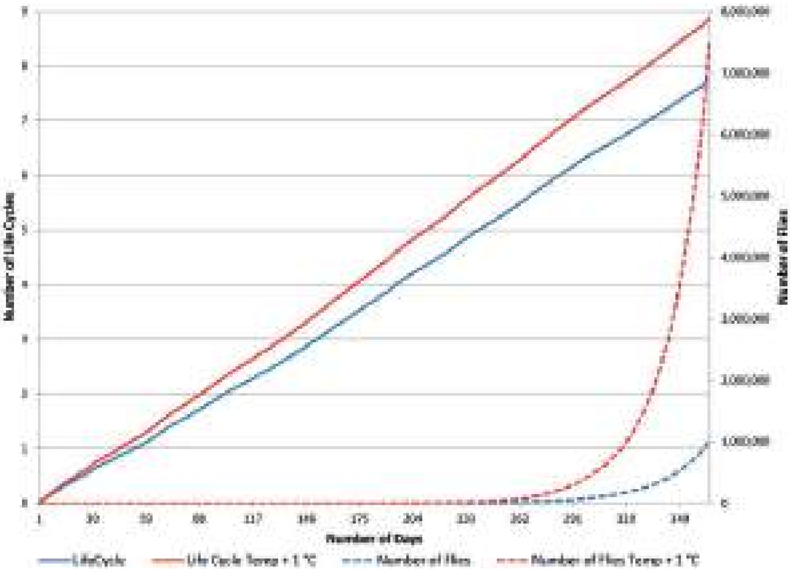

Figure 10. Number of medfly life cycles and number of medflies (offspring from one wild female fly on day one) expected in a year with an average daily temperature increase of 1°C (the authors, based on weather information of ANACAFE 2014).

6.3. Soil Texture

The last factor of the three factors considered here is soil. Under similar conditions of host availability and temperature, differences in the size of medfly populations have been found. Those differences might be explained by factors such as soil types. Larval and, mainly, pupal stages of the medfly occur in the soil, so soil conditions will affect medfly pupae survival. Eskafi and Fernandez (1999) found that pupal survival was negatively correlated with the soil bulk density, but positively with percentage of soil porous space and percentage of water saturation.

To estimate the relationship between soil texture and the presence of medfly 17 014 traps in Guatemala were used. For each trap, the maximum number of flies captured from 2004 to 2016 was obtained and the traps were overlaid with a map of soil textures (Simmons et al. 1959; MAGA 2000). The textures were classified from 1 to 10, according to the content of sand. In this classification, 1 included very clayey soils (almost no sand and high-bulk density) and 10 included very sandy soils (almost only sand and low high-bulk density). The result of overlaying the traps with the classified soil textures was that each trap had a texture class and the maximum number of flies captured. The average of the maximum number of flies captured per texture class classified by sand content was calculated and plotted indicating a positive relationship between fly captures and the content of sand (Fig. 11).

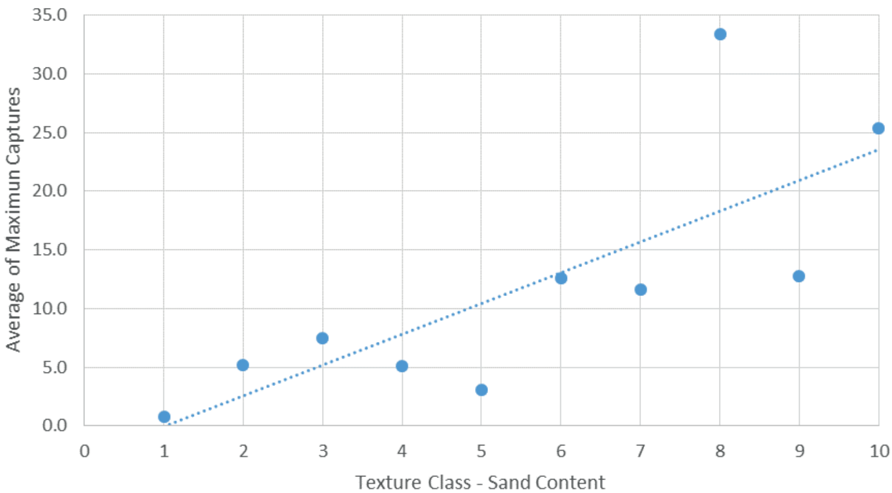

Figure 11. Relationship between medfly captures and soil texture classes (1 almost no sand and 10 very sandy soils) (the authors, based on data of Moscamed and the soil information of MAGA 2001).

From the three factors analysed, we can infer that the maximum potential for presence of medfly occurs in coffee production areas with yearly average temperatures of around 20°C, and sandy-loam soils; being the coffee availability for oviposition the main factor, either a) promoting population growth or b) restricting and decreasing population growth.

7. MEDITERRANEAN FRUIT FLY CAPTURES FROM 2004 TO 2016

Even though the described population curve is observed every year, the difference from one medfly-year to another is that the maximum population size might be higher or lower. Fig. 12 presents a sequence of the yearly average fly per trap per day (FTD) of the wild populations from 2004 to 2016.

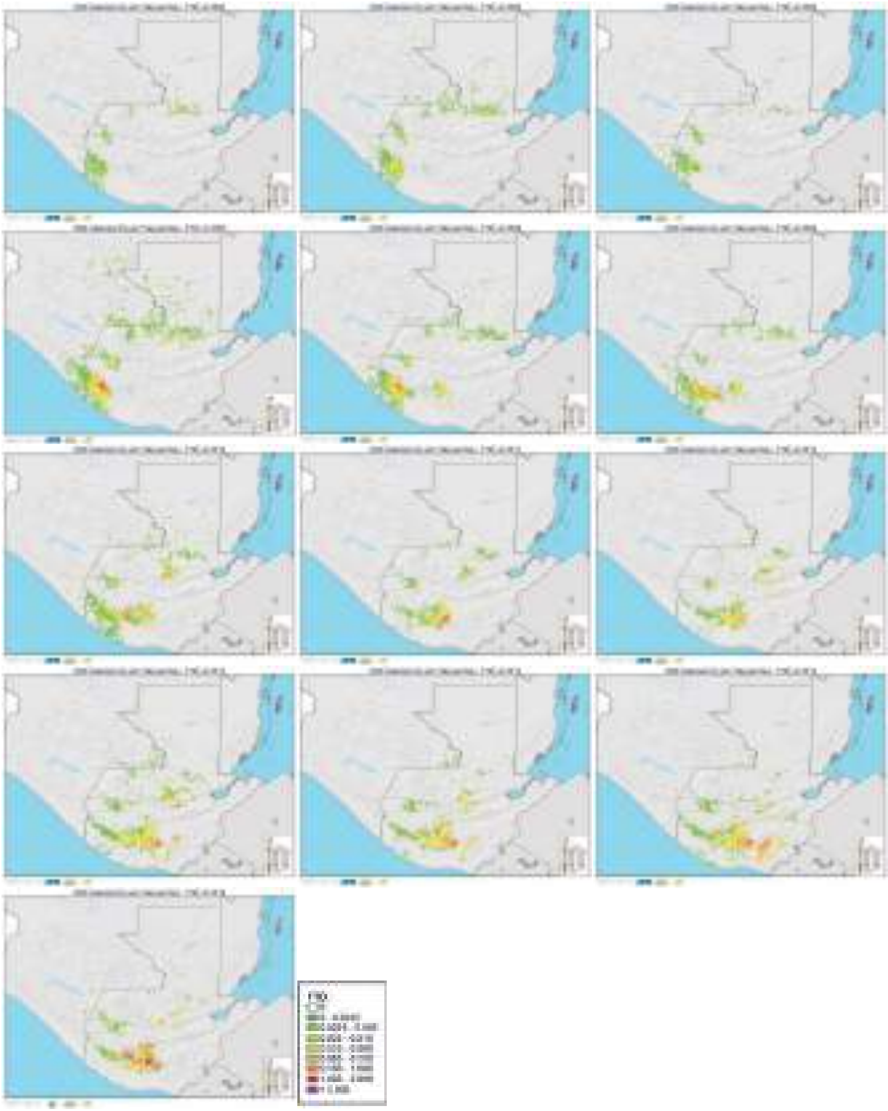

Figure 12. Average Fly per Trap per Day (FTD) numbers per year, from 2004 to 2016 in Guatemala and southern Mexico (credit Moscamed).

During this 13-year period it has been observed that there have been “good” and “bad” years regarding the number of flies captured. A “good-medfly-year” occurs when the maximum population size is low, as measured by relatively few captures in the infested areas, and as a consequence few or no finds in the neighbouring low prevalence and free areas. In the sequence shown in Fig. 12, 2004, 2006, 2012 are considered as “good” years. In contrast, a “bad-medfly-year” occurs when the maximum population size is higher than normal, and the number of captures is very high in the infested areas, spreading into the low prevalence and free areas. In the period of 2004 to 2016, years 2007 and 2016 are considered “bad” years.

Even though most of the control activities (SIT application, ground and aerial sprays, quarantine, and mechanical control) were conducted in a similar way between 2004 and 2016, a “jump” from one good year to a bad year was observed periodically, with no apparent reason. For example, between 2006 and 2007 a huge population increase occurred (Fig. 13). There are several hypotheses that have been advanced to explain this pattern.

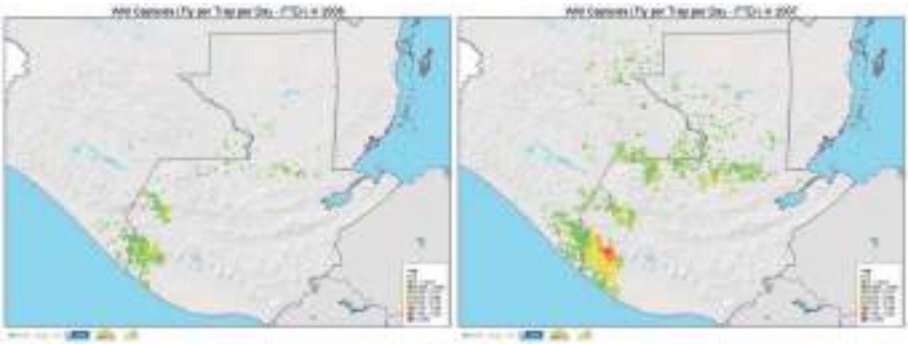

Figure 13. Comparison of wild medfly captures in the years 2006 and 2007, showing a drastic increase in the number of captures in 2007 (credit Moscamed 2017).

Auclair et al. (2008), suggested that the periodic changes are related to the “El Niño” pattern (El Niño Southern Oscillation or ENSO) (Wang et al. 2017). They analysed the trapping information and related it with temperature and rainfall, finding a correlation between the weather conditions in the “lead-in” year (6 months previous to the peak of the captures) and medfly population dynamics. The “bad” years were classified as “outbreak years” or “medfly storm years”, and the “good” years as normal years. These relationships indicated that dry and hot “lead-in” years will produce a “medfly-storm” or an “outbreak year”, while wet and cool “lead-in” years will produce lower than average trap captures or normal years. Auclair et al. (2008) concluded that before a medfly-storm year:

> *“rainfall was less and temperature was greater on average during the key months of population growth during the lead in years compared to average”.*

These conditions, in the area in which Moscamed operates, are generated by the El Niño/La Niña cycle, with dry/hot years occurring with the El Niño phenomenon. In summary, an "El Niño Lead-in Year" will drive to a "medfly-storm year". With this pattern detected, Auclair et al. (2008), generated the "El Niño Forecast Plume", which basically suggests that before a year of interest that is expected to be a "medfly-storm" year, the signal of El Niño will increase.

This model, generated in 2008, was executed again in 2015 (Allan Auclair, personal communication). An updated version of the model, together with the ENSO data for 2015 led to a prediction that 2016 was going to be an outbreak year. The prediction by Auclair was borne out in 2016, which was indeed a fly-storm year. The maximum number of captures in 2016 was much above the normal captures and much higher compared with 2014 and 2015 (Fig. 14).

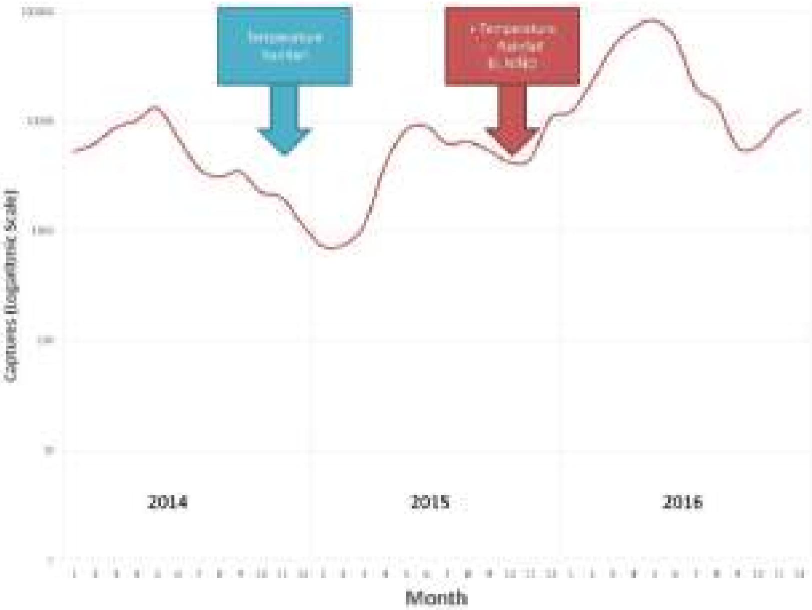

Figure 14. Number of fertile medfly captures per month from 2014 to 2016 in the region (the authors, based on the information of Moscamed).

By overlaying the medfly captures with the ENSO Anomalies from 2015 to 2017 and the Forecast Plume, it can be observed that what Auclair predicted in 2015 was correct; as shown in Fig. 15.

8. DISTRIBUTION AND PREDICTION MODELS

In this Section we generate medfly distribution models based on the information generated by Moscamed, and analysis of population demographics due to the ecological variables mentioned above (host, temperature and soil texture).

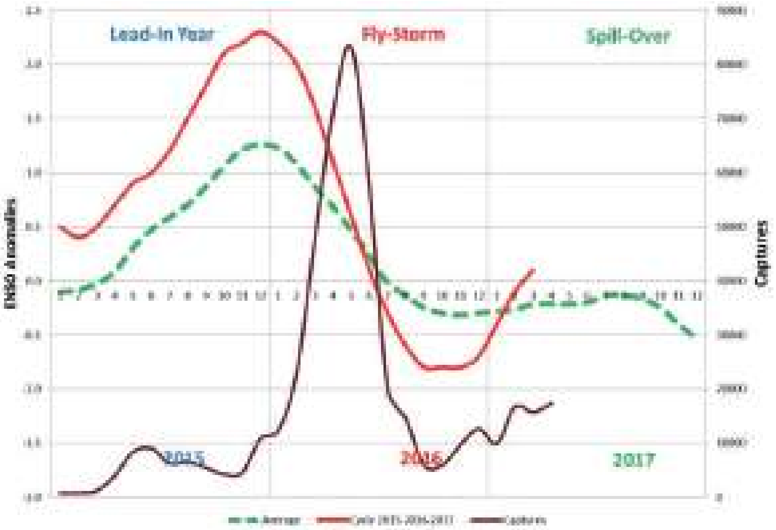

Figure 15. El Niño signal (left y-axis), outbreak years and medfly capture from 2015 to 2017 (right y-axis). The green dotted line is the "El Niño Forecast Plume" for an outbreak year generated by Auclair et al. (2008). The red solid line is the El Niño signal as reported by NOAA (2017). The brown continuous line is the total number of captures for medfly in the region from 2015 to 2017 (the authors, based on information of Moscamed, Auclair et al. 2008 and NOAA 2017).

Trapping information (a dataset of 17 014 traps serviced from 2004 to 2015) was overlaid with the ecological factors in order to estimate the distribution of the medfly in areas with no traps in Guatemala, using the maximum entropy software (Maxent) (Phillips et al. 2006). Maxent is a software widely used for modelling species distribution. It uses machine learning methods to statistically estimate the relationships within species presence locations (response variable) and a set of environmental predictors (explanatory variables). The response variable selected was the maximum number of flies captures in one trap in one week. Moscamed uses Jackson (trimedlure attractant) and Phase IV (open-bottom baited with a dry food-based synthetic attractant) traps for monitoring the wild populations.

According to Midgarden et al. (2004) there is no significant difference in the total number of wild flies captured for these two types of traps. So, both trap types were included in the analysis. This variable represents the maximum level of infestation in one site. The explanatory variables selected were:

1. Distance to coffee – as a measurement of the main host, generated using the coffee production areas from the land use map of Guatemala (GIMBOT 2014).
2. Temperature – variable related with the life cycle, generated from the INSIVUMEH weather stations in the digital database of MAGA (2001).
3. Soil texture – classified for clay to sandy, as a measurement of the effect of this condition on the larval/pupal stage, obtained from the soil maps of Guatemala (MAGA 2001).

With the GIS, the information was prepared to be able to use it in Maxent. The results of the modelling are presented in Fig. 16. The output is the logistic probability of presence of medfly, ranging between values from 0 to 1.

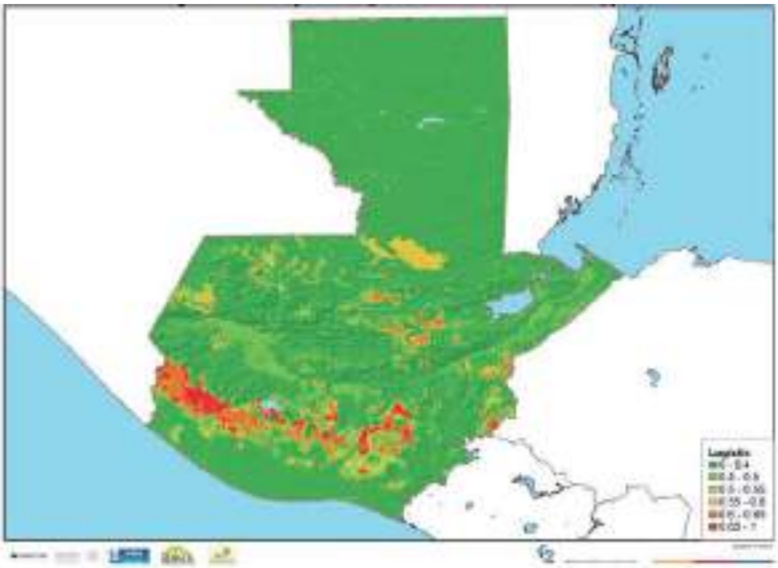

Figure 16. Logistic probability of medfly occurrence in Guatemala using the maximum entropy (Maxent) method (the authors, based on information of Moscamed).

The IPCC observations regarding temperature indicate that the total temperature increase from 1850–1899 to 2001–2005 is 0.76°C [0.57°C to 0.95°C] (IPCC 2007). Hansen et al. (2013) observed that the global surface temperature in 2012 was +0.56°C (1°F) warmer than the 1951-1980 base period average. Rahmstorf et al. (2012) observed that global mean temperature has been increasing due to climate change at a rate of 0.16°C/decade.

With these observations of consistent temperature increases and the wide range of medfly tolerances to temperatures (minimum and maximum), it is expected that fly populations will increase each year under normal conditions. To estimate the effect of increasing temperature due the climate change, the temperature in Maxent was modified by adding 1°C. The results of that estimation are shown in Fig. 17.

According to the modelling conducted, and the prediction of the increase of temperature, it seems that in some areas the probability of occurrence of medfly will increase at higher altitudes, mainly in the temperate areas, but in lower altitudes (subtropical areas) this probability will decrease. This prediction might be explained by the fact that medfly has lower and higher temperature thresholds. As indicated before, it is expected that the maximum potential for presence of medfly will occur in areas with yearly average temperatures of around 20°C.

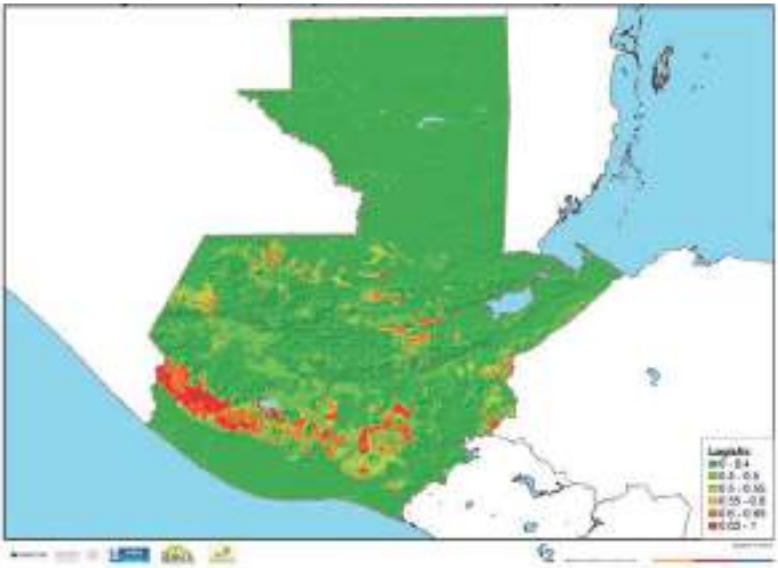

Figure 17. Logistic probability of medfly occurrence in Guatemala using the maximum entropy (Maxent) method and considering an increase in temperature of 1 °C (the authors, based on information of Moscamed).

In the subtropical areas, the temperature is higher than this temperature, in consequence the increase in temperature might decrease the probability of medfly occurrence. In contrast, in the temperate areas, the temperature is below the optimal temperature of 20 °C, and the expected increase in temperature might also increase the probability of medfly occurrence, since the temperature will be closer to the optimal. Fig. 18 shows the expanded area of south-western Guatemala, where this contrast can be appreciated.

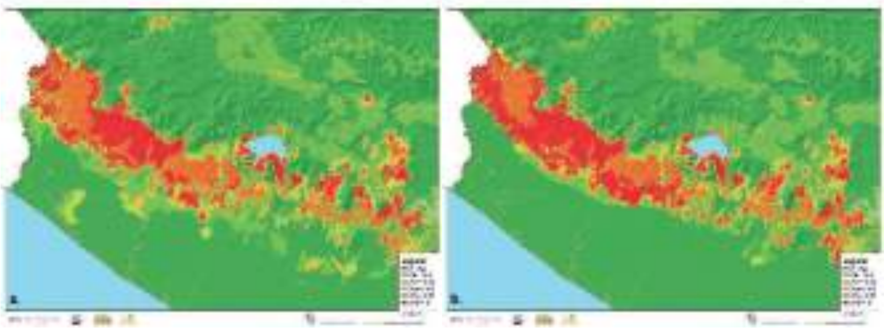

Figure 18. "Zoom-in" to the south-western area of Guatemala to see the differences between the modelling with current temperature (a.) and with an increase of temperature by 1°C (b.) (the authors, based on information of Moscamed).

Further analyses should include other levels of temperature increases and the effect of increased variance of temperature. Future analysis should also consider other explanatory variables, as well as using other modelling techniques for species distribution.

9. CONCLUSIONS

Climate change including temperature increase appears inevitable. Nevertheless, understanding how this will affect the population ecology of a pest will provide programme managers with key information for decisions on insect pest management that can minimize the negative effects of these changes.

Knowledge about the effects of climate, in particular temperature and other ecological factors, such as host phenology and the population trends of medfly, has allowed us to develop a predictive model that can be applied as a decision-making tool in support of effective medfly programme management. Temperature shifts from climate change have a direct impact on medfly populations. Furthermore, hot and dry El Niño years will increase the reproductive rate of the pest, resulting in overall population increase, whereas cold La Niña years will have the opposite effect, resulting in population reduction. Well-coordinated AW-IPM activities based on information analysis is crucial to avoid the increases of medfly populations. With the prediction models generated, early warnings can be provided to high-level decision-makers and programme managers to act in an effective and timely-manner, including shifting programme strategies and assigning larger budgetary resources to the programme when expecting difficult years.

10. ACKNOWLEDGEMENTS

The authors would like to thank Nick C. Manoukis and Walther Enkerlin for many suggestions that significantly improved this manuscript.

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TRENDS IN ARTHROPOD ERADICATION PROGRAMMES FROM THE GLOBAL ERADICATION DATABASE, GERDA

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SUMMARY

The Global Eradication and Response Database (GERDA, http://b3.net.nz/gerda) documents representative incursion responses and eradication attempts against tephritid fruit flies of economic importance, Lepidoptera, tsetse flies, screwworm flies, mosquitoes, ants, beetles and other particular taxa of invasive arthropods since 1869. It includes cases where governments were quickly resigned to the inability to eradicate, as well as cases where a positive outcome was sought in a declared eradication programme. The distribution of pests is expanding well beyond what has been recorded in GERDA, but this information contains useful trends. The rate of eradication attempts continued to rise during the 20th and into the 21st century. In the case of Lepidoptera other than gypsy moth, 75% of programmes were started in the last 20 years. This is evidence for the rapid geographic range expansion under globalisation. It also indicates how active risk analysis and improved technology are increasingly enabling governments to attempt eradication to avoid projected substantial long-term costs of pest establishment. More than 80% of eradication programmes have been successful for arthropods in the database. For certain groups such as tephritid fruit flies of economic importance, the success rate is even higher, due to the experience gained from previous similar programmes, as well as the progress in the development of lures and suppression tools. A steady increase in the number of eradication programmes globally suggests that current exclusion measures for constraining the spread of invasive species are not adequate. Cost-benefit analysis based on prior pest behaviour indicates that additional mitigation against certain taxa are warranted (if possible). It is likely that all these reasons have led to this increase in the number of eradication programmes over time as a consequence of increases in travel and trade volumes from an expanding number of countries, a desire to maintain or reduce pest pressure on exotic and native commodities, and the development of new tools to increase the technical feasibility of eradication attempts. It is notable that arthropod eradication programmes still rely significantly on insecticides, but their importance is steadily decreasing when compared to the application of other tools.

J. Hendrichs, R. Pereira and M. J. B. Vreysen (eds.), Area-Wide Integrated Pest Management: Development and Field Application, pp. 505–518. CRC Press, Boca Raton, Florida, USA.

Key Words: GERDA, eradication attempts, incursion responses, globalisation, invasive species, arthropods, alien, non-indigenous, risk analysis

1. INTRODUCTION

Invasive insect pest species are spreading as a consequence of increasing global trade and continue to emerge as a threat to food production and ecosystem health (Liebhold et al. 2016). This includes insect pests that need to be controlled to avoid significant losses in cropping systems in all regions of the world (Vreysen et al. 2016). Failure to manage these species would have serious consequences for food production worldwide (Vreysen et al. 2007). Some pests have already become ubiquitous global pests, but many are still undergoing geographic range expansion (EPPO 2018). There are sometimes arguments over what constitutes the current range of some species, such as the debate over whether tephritid fruit flies have established below detectable levels in California (McInnis et al. 2017; Carey et al. 2017; Shelly et al. 2017). There is also evidence of a problem of "fake news" in at least one eradication programme in California (Lindeman 2013).

Government-led incursion response programmes can have either eradication or sometimes just delimitation and containment as the goal. Governments often conduct a risk analysis to assess whether the establishment of the unwanted organism is likely to exceed an economic, environmental or social impact threshold and require an attempt to eradicate (Tobin et al. 2014). As part of a project identifying factors affecting outcomes from arthropod eradication efforts (Tobin et al. 2014; Liebhold et al. 2016), a global eradication database called "GERDA" (Kean et al. 2017) has been collating official incursion response programmes that can range from doing nothing through attempting eradication.

GERDA input is based on volunteerism, and registration for a login to access the data is free. GERDA contains information on 1139 incursion responses, of which 1037 led to eradication attempts (Kean et al. 2017). While this is not a complete list of all global incursion response data, data are continuously being verified and entered into the online database. More than 430 registered users of GERDA are listed, from 43 countries. The base data are available along with references so that entries can be checked.

The GERDA data have been contributed by many individuals, who share the vision of everyone having access to information that will facilitate better decision-making with respect to incursion responses. The data, scope and definitions used in the database are available (e.g. Box 1, Kean et al. 2017) and have been used to review global trends (Tobin et al. 2014), as well as details for particular taxa. For example, 28 lepidopteran species were the target of 144 known government-led incursion responses, with effort spread across 12 moth families, dominated by the Lymantriinae and Tortricidae (Suckling et al. 2017). Likewise, Suckling et al. (2016) reviewed the eradication of fruit flies of economic importance covering more than 200 programmes across 16 species.

In this paper, we reinvestigated the database for trends in 811 arthropod eradications in 94 countries, with an additional 63 programmes added since Tobin et al. (2014).

2. RESULTS

2.1. Summary of Known Arthropod Eradications

To August 4, 2017, the database reported 1093 incursion responses including 972 eradication programmes in 105 countries, targeting 309 taxa, of which 166 were arthropods. A total of 768 arthropod eradications have been recorded. Of the 634 arthropod programmes for which the outcome is known, 514 (81%) were successful and 120 (19%) failed. The number of arthropod eradication programmes initiated climbed rapidly through the second half of the 20th century (Fig. 1).

Box 1. GERDA: Frequently Asked Questions
(Kean et al. 2017 (GERDA, http://b3.net.nz/gerda/faq.php)

The word "eradicate" originates from the Latin "to uproot" (*eradicatus*). In ecology, eradication is the intentional local extinction, or extirpation, of a particular taxon. This involves the killing or complete removal of every individual of a population of the target taxon from a defined area, i.e. achieving population size zero.

The target taxon is most often a population of a species but may sometimes be a subspecies or more than one closely related species. Eradication programmes almost always target populations of pestiferous invasive species in part of their invaded range.

The target area for an eradication programme may vary greatly in size. Often eradications are carried out in geographically-isolated areas, such as islands, to minimise the risk of reintroduction. Sometimes, however, eradications may target a particular part of a species' range because of the environmental, economic, or political benefits of removal, even if the species is likely to reinvade.

One of the biggest challenges of any eradication programme is demonstrating success. The International Plant Protection Convention (IPPC) specifies standards for plant pest eradications in its International Standards for Phytosanitary Measures No. 9 (FAO 2016a), but these are largely descriptive. Current international practice specifies that, provided that adequate surveillance activity has been carried out, eradication of most plant pests can be declared once there have been no detections for at least three times the normal generation time of the target taxon (FAO 2016b; Kean et al. 2017).

Of the 768 arthropod eradication programmes recorded so far in GERDA, the method of pest detection is known for 42% of the entries. A range of detection methods led to the start of these programmes (Fig. 2), of which more than half were based on specific traps and lures (e.g. pheromones). In contrast, insect traps without specific lures (e.g. a light trap) have not been the primary tool for detection of a pest that has subsequently been subjected to an eradication programme.

2.2. Clustering of Arthropod Eradications

Certain orders of insects were more frequently targeted for eradication, especially Diptera (Tephritidae and Culicidae in particular), followed by Coleoptera and Lepidoptera (Table 1). This is likely due to the potential significant impact that species from these groups have on primary agricultural production and human health, as well as the availability of eradication tools (Suckling 2015).

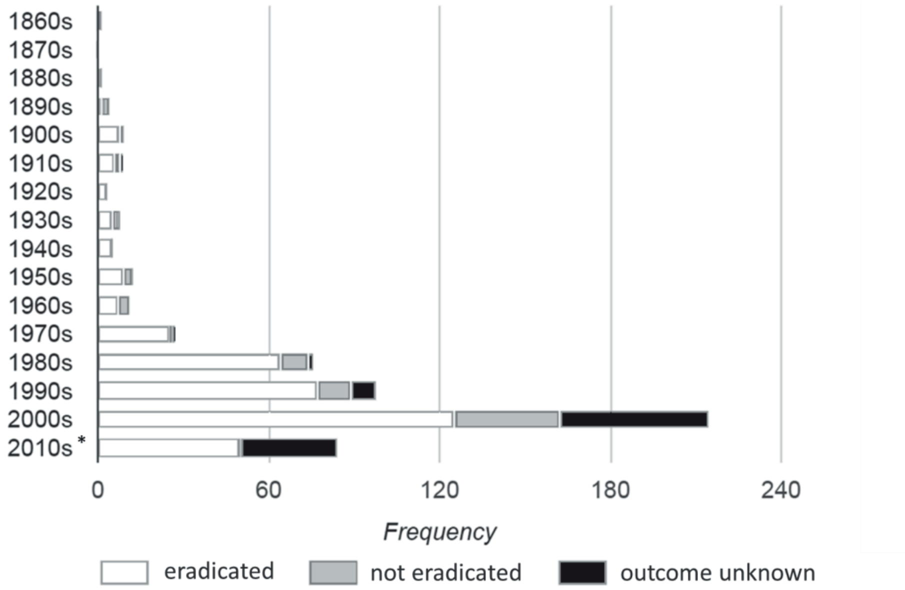

*Figure 1. Arthropod eradication programmes initiated each decade, reported in the Global Eradication and Response Database, GERDA (http://b3.net.nz/gerda) (accessed August 4, 2017). *Data for this decade are from January 2010 until August 4, 2017.*

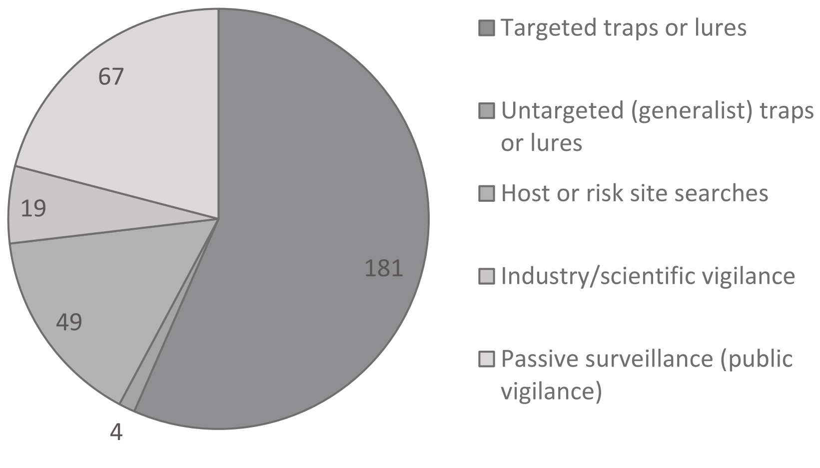

Figure 2. The number of times various detection methods led to the initiation of arthropod eradication programmes stated in the Global Eradication and Response Database (updated from Kean et al. 2017).

GERDA shows evidence of the same clusters forming around similar arthropod taxa as can be found in a database on attractants for pest management (Suckling 2015; El-Sayed 2018). GERDA illustrates the complexity of the different life histories that must be sufficiently understood before engaging in eradication attempts.

Once detection trapping systems are developed, it is frequently possible to use knowledge from previous programmes against similar threats to gain efficiencies. Some methods are applicable over a range of different taxa, whereas in other cases, methods available for closely related species can be easily adapted.

A number of major taxa showed a high degree of re-occurrence as targets of eradication programmes (Table 1; Fig. 3).

Table 1. Number of eradication programmes so far recorded in the Global Eradication and Response Database (GERDA) and success rate by insect order (August 4, 2017)

Order	Count	% Likely or Confirmed Eradication
Diptera	331	77.6
Coleoptera	139	42.4
Lepidoptera	135	75.5
Hymenoptera	70	62.8
Hemiptera	34	50.0
Isoptera	18	38.9
Thysanoptera	11	64.0
Other	33	72.0
Total	768	

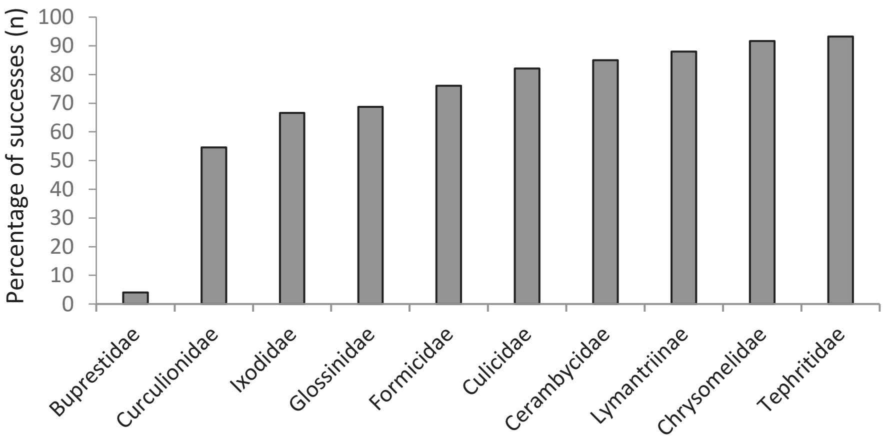

Figure 3. Percentage of successful arthropod eradication programmes by major target taxon (from GERDA, updated from Kean et al. 2017).

The eradication success rate was relatively high for most major target taxa. However, success rates were lower for weevils and buprestid beetles, notably the emerald ash borer, *Agrilus planipennis* Fairmaire (Buprestidae), which has proven difficult to eradicate with the current tools available. About 60% of tick (Ixodidae) and tsetse fly (Glossinidae) eradication programmes were successful, followed by ants (Formicidae) and mosquitoes (Culicidae), longhorn beetles (Cerambycidae), tussock moths (Erebidae), leaf beetles (Chrysomelidae) and fruit flies (Tephritidae) (Fig. 3). The few thrips were largely in glasshouse situations.

We acknowledge that the GERDA data probably contain some reporting bias, but contend that the results are nevertheless indicative of a trend whereby some insect taxa are more easily eradicated than others, due to their biology, invasion dynamics or the tools available to detect and manage them.

The clustering of certain targets at different taxonomic levels, such as the Tephritidae within the Diptera, rather than representatives of all families within the Diptera, indicates the patchiness of pests in certain taxonomic and economic clusters. Even though flies have a broad range of hosts, the vast majority are not pests, apart from those with fruit, animals or humans as hosts, which are well represented in the eradication data as targets on multiple occasions.

2.3. Increase in the Number of Arthropod Eradication Programmes

The annual number of eradication programmes across all invasive arthropods has increased steeply in recent decades (Fig. 1), but this has been accompanied by the development of more specific, environmentally-friendly and cost-effective tools. In fact, the sub-family Lymantriinae demonstrate how, with the development of new tools, patterns of eradications attempts can change. The 74 *Lymantria dispar* L. entries in GERDA are USA-dominated due to the "Slow the Spread Programme" for *L. dispar* in the USA (Sharov et al. 2002). For the 61 programmes against this pest for which the control tools are known, initial eradication and management attempts in the late 19th and early 20th centuries consisted of picking of egg masses by hand as one of the few options available (Myers et al. 2000). This was followed by the spraying of persistent insecticides, which showed a steady increase until the 1960s, when efforts were made to develop alternative control methods, such as mass-trapping approaches (Fig. 4).

The synthesis of the sex pheromone for *L. dispar* enabled the delimitation and monitoring of populations through the trapping of male moths attracted to traps (Bierl et al. 1970). Then in the 1980s, the biopesticide, *Bacillus thuringiensis kurstaki,* was extensively trialled in the USA for use against Lepidoptera (USFS 1994). Also, at this time, mating disruption became more readily available (Cardé, this volume), after being tested and reported from the late 1970s (Schwalbe et al. 1979). In addition, a number of Sterile Insect Technique (SIT) field trials were successfully conducted against gypsy moth in the 1970s and 1980's, but it was concluded that the method was not cost-effective (Simmons et al. 2021).

In the 1970's and 1980's there was a rapid increase in the number of *L. dispar* eradications attempted (Fig. 4). The biopesticide is now the only tool recorded as used for eradication for the past 20 years, probably because it is cheap to apply, and a large amount of the moth's range is over forested areas, so few people are affected by application, thus not opposed to its use. The effectiveness of the biopesticide and the acceptability of its use, is probably the reason why there has been a shift from multiple tools used in earlier years, to a single tool used in recent years for the eradication of *L. dispar* (Fig. 4).

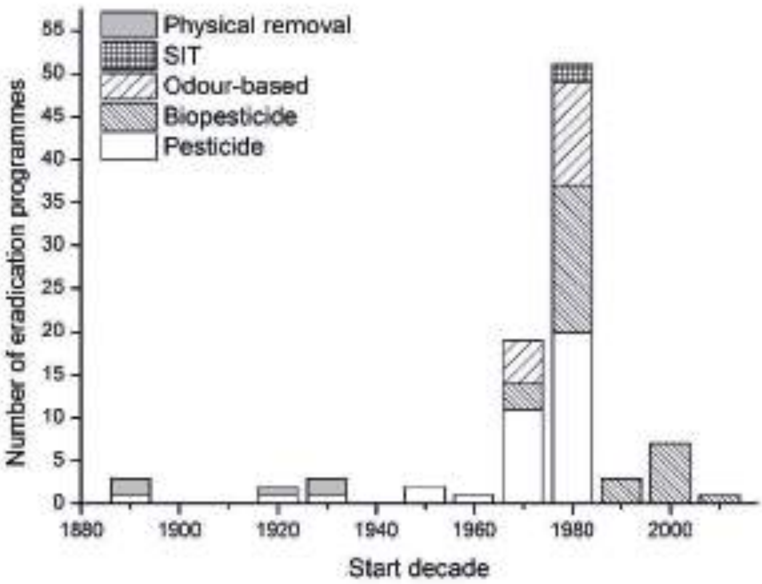

Figure 4. The type of suppression tools used for 61 Lymantria dispar *eradication programmes over time. Physical removal includes both removal of host and hand removal of the pest; odour-based includes mass-trapping, lure and kill, and mating disruption (from GERDA, updated from Kean et al. 2017).*

However, urban-based eradications can face public opposition to aerial use of the biopesticide, so mass-trapping, mating disruption used with reduced rates (Tcheslavskaia et al. 2005), or sterile insect release can present more favourable options (Gamble et al. 2010). In fact, mating disruption is widely used in the "Slow the Spread Programme" (Tcheslavskaia et al. 2005; Liebhold et al. this volume), although details of this suppression programme on the leading edge of gypsy moth infestation are not reported in GERDA due to its focus on eradication programmes.

It is not possible to identify a single cause of the increase in the number of arthropod eradication and response programmes, but it is likely due to a combination of several factors, including the ability to monitor and detect introduced pest populations with their sex pheromone, from the 1970s.

With the development of better or more publicly-accessible pest control technologies throughout time, a corresponding change in the type of management methods used is expected, and this appears to be the case (Fig. 5).

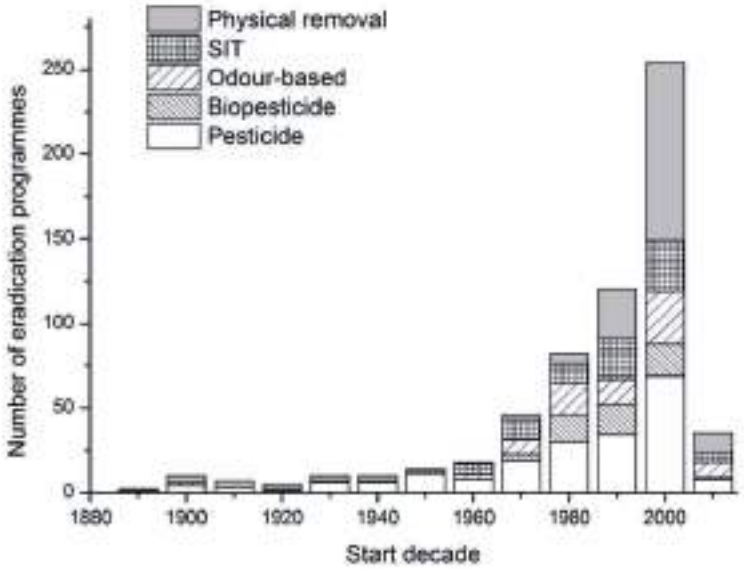

Figure 5. The number of programmes using different tools to eradicate populations of arthropods. Note some programmes used multiple tools. Physical removal includes both removal of host and hand removal of the pest; odour-based includes mass-trapping, lure and kill, and mating disruption (from GERDA, updated from Kean et al. 2017).

Insecticides still feature heavily in arthropod eradications, but they are steadily decreasing percentage-wise (for example, see 1930-1950s in Fig. 5 where they represented most of the tools used in the past versus today). Failed eradications suggest that pest management costs and area of insecticide treated crops is likely rising over time (ca. 20% of programmes). In the case of newly established pests, the new applications of insecticides can disrupt existing integrated pest management (IPM) programmes using biological control (Cameron et al. 2009) and force the return or initial establishment of broad-spectrum insecticide programmes (Berry et al. 2009; Vereijssen et al. 2015). This pattern has been repeated many times and one of the impacts of such invasive species is to remove the future opportunity for agricultural production using organic means, where demand and opportunities do exist in Western countries.

Unexpectedly, removal by hand and host removal was the primary tool in the early 2000s. This may be due to new pests being targeted, for which there was little information on alternatives, including tree-killing beetles, such as the emerald ash borer *A. planipennis* (Fig. 5).

With the development of odour-based lures, control options for greener technologies have increased primarily for Lepidoptera, but this approach has also been used for Coleoptera and Diptera species. The SIT is a technology without non-target impacts, but the need to maintain colonies of the target pest species and security requirements for radiation sources has likely led to the limited number of lepidopteran, coleopteran and dipteran species for which SIT has been used (Klassen et al. 2021). Nevertheless, this number is gradually increasing and recent studies found that it might be feasible to tackle other pest taxa with SIT integration in the future, such as the brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae) (Welsh et al. 2017), or *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae) (Lanouette et al. 2017).

New sources of radiation that can be switched off, such as X-ray, remove the need to secure or replenish decaying radioactive sources, an expensive exercise (Mastrangelo et al. 2010; Mehta and Parker 2011). This technology is also increasingly being used for post-harvest disinfestation (Follett and Weinert 2012), but there still remain issues of reliability, which are of serious concern for the SIT component of these programmes.

The cost of achieving eradication is positively related to the size of the infested area (Fig. 6), with successful outcomes more likely when the detected population is still small and at low density, but this is not necessarily guaranteed. However, the availability of detection tools (Fig. 2) probably allows for the earlier detection of the pest, better delimitation, and thus a quicker eradication (Tobin et al. 2014).

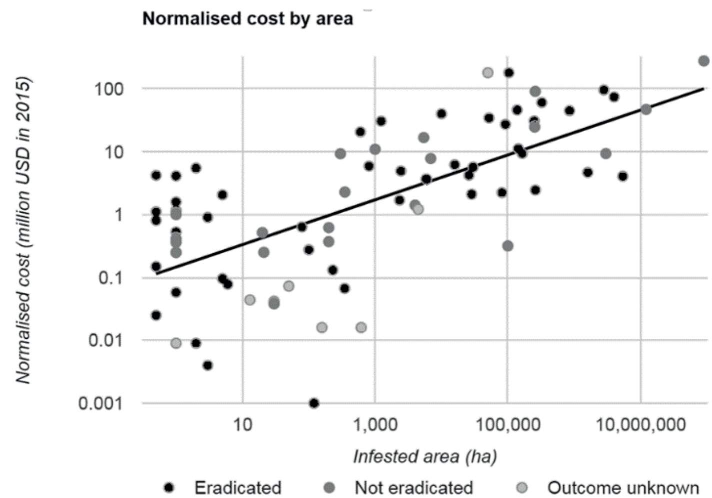

Figure 6. Rise in normalised cost of eradication with infested area for arthropod eradication programmes where the outcome is known or unknown (USD in 2015) (from GERDA, updated from Kean et al. 2017).

3. DISCUSSION

The rapid rise in non-native arthropod incursions and eradications is a concerning trend, because it has been clear for more than 10 years that passive vectoring from international travel and trade volumes, including non-commercial postal shipments, has risen to the stage where current biosecurity processes in most jurisdictions are inadequate to prevent or even reduce incursion frequencies (Liebhold et al. 2006). This has potential implications for food production in the cases of some of the worst invaders (Vreysen et al. 2007). In part, access to nutritious food supply becomes more challenging wherever horticultural crops become scarce due to fruit fly or other insect attacks and the diet shifts towards cereals which lack some of the 20 or so micronutrients required (Broadley and White 2010). The expansion of oriental fruit fly *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae) into Africa and islands of the Pacific region, and onto additional host plants (Grové et al. 2017) illustrates the point.

On the positive side, there has been a rapid rise in government-led eradication programmes, along with a rise in countries undertaking eradication efforts (to at least 90), which is encouraging in view that in the past there was often only resignation and no attempt to contain and eliminate an incursion. GERDA does not document all of the cases where governments were quickly resigned to the inability to eradicate, but it represents cases where a positive outcome was sought in a declared eradication programme. These undeclared cases add to the increasing burden of pests discussed here, and it should be noted that the distribution of some pests have expanded well beyond what has been recorded in GERDA, due to its focus on eradication, not pest management.

A number of trends affecting the probability of success are clear in the data. The type of invasive organism makes a difference to the outcome, which is directly linked to the type of surveillance that is possible. Tobin et al. (2014) reported that the availability of lures was an enormous (>22-fold) factor increasing the likelihood of early detection followed by eradication. The type of organisms that warrant eradication are clustered in groups, which frequently turn out to be targets of pest management in other jurisdictions (Suckling 2015). This implies recognized pest status rather than new offender status, although both cases exist. Novel and unwanted tussock moths (Lepidoptera: Erebidae: Lymantriinae) were detected in New Zealand, which led to several large-scale aerial urban biopesticide-based eradication programmes, but the particular species involved in the incursions were not anticipated (Brockerhoff et al. 2010).

The ability to conduct delimitation of an incursion is essential to the eradication success, so perhaps it is unsurprising that there is investment in developing and using insect attractants in many countries, although their commercial availability often lags behind the scientific reports (Baker et al. 2016). Across all arthropods, more than 80% of eradication programmes have been successful, although for certain groups, such as fruit flies of economic importance, the success rate is even higher (~90%). All sectors have been affected by invasive arthropods, although some have had a lot more experience than others, particularly sectors related to food production in horticulture or urban gardens, and human and animal health.

One of the species with a high colonisation rate as well as a record of eradication success is *B. dorsalis,* a tephritid fruit fly for which effective lures are available. In addition, the *Lymantria* species were well represented in this group, and they too have been eradicated many times. Attractants used to lure these two species, as well as other damaging pests, to traps have been identified as well as a number of control strategies. The advanced state of detection and control tools for *B. dorsalis* and *Lymantria* species is probably because of the large damage they cause and the rate at which they spread in the new range, which has prioritised research in this area. This has probably led to the unexpected result that a high dispersal rate is not a factor limiting success rate. As Tobin et al. (2014) highlighted, the existence of a detection tool, and thus likely a detection network programme, has had a bigger impact on success rate. Generally, the availability of multiple tools that can be used for eradications can lead to faster successful outcomes, but there are examples, such as a single or a few applications of *B. thuringiensis kurstaki* that resulted in successful eradication of *L. dispar* populations.

Tobin et al. (2014) reported 672 eradication programmes against arthropods (to 2010), and we have been able to compile additional cases, although of course current entries are best checked directly on the GERDA database, where users can find simple summary tools (Kean et al. 2017). Tobin et al. (2014) discussed several biases of data compiled in this database, e.g. more recent data are easier to locate and compile, and that successful programmes are reported more often due to the reluctance to publicize failures.

We contend, however, that the evolving database GERDA is robust to indicate the trends and drivers of eradication success and failure. For Lepidoptera other than gypsy moth, 75% of programmes were started in the last 20 years, suggesting rapid geographic range expansion under globalisation (Suckling et al. 2017). This entails that regular reviews of the trends in new data will be warranted, and/or the need of regulatory agencies to input their eradication data and use GERDA in order to remain updated. Operational biosecurity agencies involved in arthropod eradication are already invited to contribute their data to GERDA, to strengthen the evidence for conclusions and policy over time.

A fast increase in the number of eradication programmes globally suggests that current exclusion measures are not adequate to manage an increasing risk to global food security, due to an unrelenting supply of invasive species (Seebens et al. 2017). An increase in the biodiversity of invasive pests is emerging, increasing the challenge considerably. However, pest incursions have motivated the development of newer technologies that will make incursion responses and eradication success a more likely outcome in the future.

The role of public support cannot be over-stated, and as Lindeman (2013) states:

> "*the California Department of Food and Agriculture (CDFA) lost the battle over aerial spraying against the invasive light brown apple moth (LBAM,* Epiphyas postvittana *(Walker)) largely because of a report and other supporting grey literature documents that expressed highly disputable facts, evidence, and conclusions*."

Vigilance over the facts is clearly needed by the scientific community.

4. ACKNOWLEDGMENTS

We thank the Better Border Biosecurity collaboration (www.b3nz.org), other sponsors including the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, and others listed online who have contributed data to GERDA, as well as two anonymous reviewers.

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SUCCESSFUL AREA-WIDE ERADICATION OF THE INVADING MEDITERRANEAN FRUIT FLY IN THE DOMINICAN REPUBLIC

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SUMMARY

The presence of the Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) (Tephritidae) in the Dominican Republic was officially reported in March 2015. Subsequent delimitation found that the pest had already spread to 2053 km^2 in the eastern part of the country, constituting a major outbreak. Trading partners imposed an immediate ban on most exports of fruit and vegetables listed as hosts of the pest, resulting in a loss of over USD 40 million over the remaining nine months of 2015. The outbreak was centred on Punta Cana, one of the busiest tourist destinations in the Caribbean. The agricultural production sites affected by the ban were more than 200 km away from the outbreak. The Dominican Government established the Moscamed Programme (Moscamed-RD) through its Ministry of Agriculture as an emergency response. This programme received the financial and operational support to carry out all required surveillance and control activities. The Food and Agriculture Organization of the United Nations (FAO), the International Atomic Energy Agency (IAEA), and the United States Department of Agriculture-Animal and Plant Health Inspection Service (USDA-APHIS) cooperated to assist the country in establishing a national monitoring network to determine the geographic extent of the outbreak and to initiate an eradication campaign with support from regional organizations such as the Organismo Internacional Regional de Sanidad Agropecuaria (OIRSA) and the Interamerican Institute for Cooperación on Agriculture (IICA). The regional Guatemala-México-USA Moscamed Programme played a major role in assisting through technology transfer, which included the application of the Sterile Insect Technique (SIT) and other integrated pest management components. An international Technical Advisory Committee (TAC), chaired by FAO/IAEA, provided technical oversight beginning in September 2015. The last fly was detected in January 2017 and official eradication was announced in July 2017 after six generations had passed with no detections of the pest. The Dominican Republic is now on the list of countries that have successfully eradicated the Mediterranean fruit fly and has substantially strengthened its fruit fly surveillance system and emergency response capacity.

J. Hendrichs, R. Pereira and M. J. B. Vreysen (eds.), Area-Wide Integrated Pest Management: Development and Field Application, pp. 519–537. CRC Press, Boca Raton, Florida, USA.

Key Words: *Ceratitis capitata*, medfly, Tephritidae, Sterile Insect Technique, SIT, IPM, fruit exports, Caribbean, invasive pest

1. INTRODUCTION

Agriculture contributes substantially to the Dominican Republic's GDP and is the primary employer of the labour force, as well as among the main sources of foreign currency. Fruit and vegetable production and exports make up a significant portion of these benefits, including the production of avocados, bell peppers, mangoes, and tomatoes. Exotic pests and diseases present a risk to agricultural production and exports, and international phytosanitary standards recommend continuous vigilance to prevent negative impacts on this sector of the economy. The Dominican Republic experienced the repercussions of the presence of an invasive pest for which it was largely unprepared.

The incursion of Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) into Dominican Republic was of high importance, not only for the country, but for all other countries of the Caribbean Basin that are free of this major pest. Its presence was suspected by the Dominican Republic's Ministry of Agriculture in October 2014. After accurate identification was confirmed, the detection was officially reported in March 2015. Exports of listed Mediterranean fruit fly host fruit and vegetables were banned immediately by trading partners as the lack of an operational national detection system caused uncertainty about the extent and the distribution of the pest in the country. This reduction of exports resulted in a loss of more than USD 40 million over the remaining nine months of 2015, putting some 30 000 jobs at risk (Gil 2016).

1.1. Characteristics of the Outbreak

The outbreak was located in the Punta Cana region in the eastern Dominican Republic (Fig.1), one of the most visited tourist destinations in the Caribbean, and therefore the pest was suspected to have been brought by tourists. Delimitation trapping confirmed high densities of the pest in the coastal areas of Punta Cana and adjacent Bávaro, with sporadic detections in several contiguous provinces within the surrounding area of 2053 km^2.

Fortunately, agricultural production of Mediterranean fruit fly hosts for export was non-existent in the affected area, with the major fruit and vegetable production sites affected by the ban located more than 200 km away from the outbreak. An additional characteristic of the outbreak was that certain known hosts, which are typically moved through commerce, such as mangos, citrus, guavas, cherries (acerola), and other host fruits common in backyards throughout the region were not attacked. Rather, larval finds were limited to three species of wild or ornamental fruits of no agricultural importance (see Section 2.2.2.).

1.2. Establishment of the Moscamed Programme in the Dominican Republic

The Government of the Dominican Republic, through its Ministry of Agriculture, responded to this emergency with the establishment of the Moscamed Programme in the Dominican Republic (Moscamed-RD), providing the required financial and operational support to perform all recommended delimitation and eradication activities.

The initial challenges were, among others: social and economic effects of the export ban; pressure of the media and private sector; answers demanded by stakeholders; questions by some on the need for eradication; mobilizing for financial and human resources; and streamlining external support, as assistance was being offered by a number of entities.

Figure 1. Map of the island of Hispaniola showing the Mediterranean fruit fly-infested area in 2015 in the eastern part of the Dominican Republic, covering parts of the provinces of La Altagracia, La Romana, San Pedro de Macorís, El Seibo and Hato Mayor (red= infested area; yellow= buffer area; green= free area).

The Food and Agriculture Organization of the United Nations (FAO), the International Atomic Energy Agency (IAEA), and the United States Department of Agriculture (USDA), through its Animal and Plant Health Inspection Service (APHIS), collaborated to assist the Ministry of Agriculture in establishing a national monitoring network to delimit the distribution of the outbreak and to initiate an eradication campaign. First steps were begun by USDA-APHIS, followed by a series of technical assistance and capacity building missions by the Guatemala-Mexico-USA Moscamed Programme (Enkerlin et al. 2015, 2017).

In view of the potential devastating damage of the Mediterranean fruit fly to the Dominican Republic and neighbouring countries of the Caribbean Basin, an international coordination meeting took place in Santo Domingo in May 2015 with the participation of FAO, IAEA, regional organizations such as the Instituto Interamericano de Cooperación para la Agricultura (IICA) and the Organismo Internacional Regional de Sanidad Agropecuaria (OIRSA), as well as USDA-APHIS. The objective was to coordinate technical and financial support, as well as the supply of some critical equipment and resources. In September the technical assistance was formalized under FAO/IAEA, which established and coordinated a Technical Advisory Committee (TAC) composed of international experts.

Authorities of the Ministry of Agriculture of the Dominican Republic, with encouragement of the USDA-APHIS and the FAO/IAEA, agreed to collaborate under a Cooperative Agreement with the Moscamed Regional Programme (Guatemala-Mexico-USA). The Letter of Understanding validating the agreement was signed in July 2015 taking into consideration the potential devastating damage of the Mediterranean fruit fly and the expertise available in this regional programme to help manage the pest outbreak.

This agreement facilitated not only continued training, but also equipment and supplies (some loaned or donated by USDA-APHIS) for trapping as well as the release of sterile male flies, also supplied on a cost recovery basis by the Mediterranean fruit fly mass-production facility in El Pino, Guatemala. This synergistic cooperation played a major role in assisting the Moscamed-RD Programme through technology transfer of all components of an area-wide integrated pest management (AW-IPM) approach that included the Sterile Insect Technique (SIT) as a major component in the final eradication phase (Dyck et al. 2021).

2. DELIMITATION OF OUTBREAK AND PREPARATORY ACTIVITIES

The eradication process followed during the 2015-2017 campaign, which is broadly summarized in Fig. 2, included these phases and actions:

2.1. Preparatory Pre-eradication Phase

Immediately after reporting the detection of the Mediterranean fruit fly in the eastern part of the Dominican Republic, trade restrictions were imposed on the export of Dominican fruit and vegetable host material. This was mainly due to the absence of a solid operational trapping network and resulting uncertainty about the geographic distribution of the pest.

Through the above-mentioned Cooperative Agreement, technology transfer and capacity building efforts were strengthened, and training of Moscamed-RD personnel continued in subjects such as detection, identification (taxonomic as well as sterile vs. wild), pest suppression and eradication, public relations, quarantine and other activities related to the implementation of AW-IPM programmes.

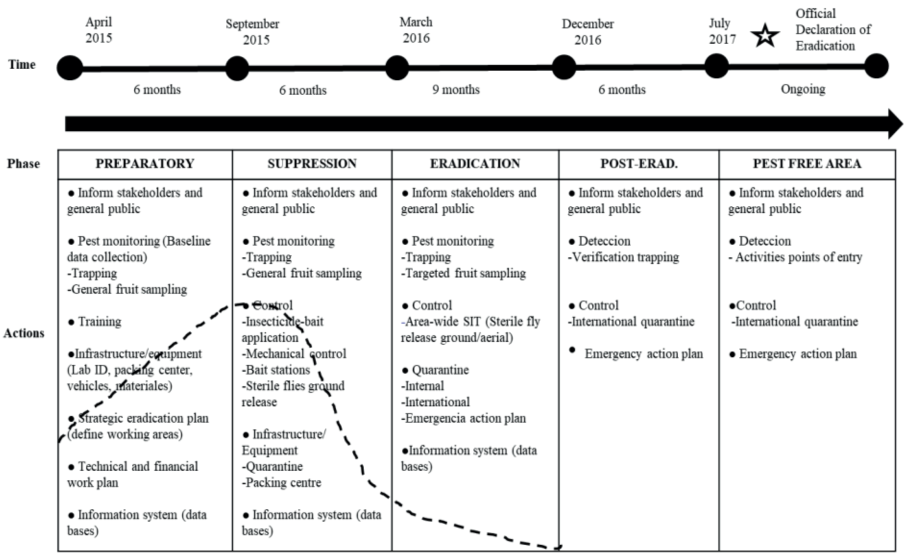

Figure 2. Phases and actions of the eradication process followed during the Mediterranean fruit fly eradication campaign 2015-2017 in the Dominican Republic (dotted line is a theoretical representation of population density) (source Walther Enkerlin, FAO/IAEA Insect Pest Control Section).

The detection system was gradually enhanced from the original limited and occasional trapping to an effective national surveillance system. Trap types used included Jackson traps baited with the male-attractant trimedlure, the female-biased Phase IV traps baited with the synthetic food lure Biolure, and Multilure traps baited with the more generic liquid protein baits such torula yeast and Ceratrap.

The trapping network during the preparatory or pre-eradication phase rapidly expanded from 1006 traps, mainly at points of entry (every two weeks with inspection levels of only about 25% of traps), to 14 589 traps country-wide (9936 male-specific Jackson traps and 4653 female biased Phase IV traps) that remained in place during 2015 (Table 1 and Fig. 3).

The country-wide trapping reached inspection levels of over 95% (weekly in the buffer and infested areas, or every two weeks in the Mediterranean fruit fly-free areas and points of entry).

Trapping and fruit sampling were significantly increased in the eastern region, aimed at accurately determining the distribution and potential spread of the infestation, locating any remnants of the infestation that may have been missed, as well as enabling sound decision-making and planning of suppression and eradication activities. The majority of traps in the country, 64% (or 9936 traps) were placed in the eastern region, where the initial detection occurred, consisting of 4687 Jackson Traps and 5249 food-based traps (Fig. 4).

Table 1. Maximum number of traps in the national Mediterranean fruit fly trapping network established in 2015 in the Dominican Republic

Traps/ Attractant	La Altagracia	La Romana	El Seibo	Hato Mayor	San Pedro de Macorís	Rest of Dominican Republic	Total
Jackson/ Trimedlure	2797	363	605	476	446	5249	9936
Phase IV/ Biolure	3015	430	577	372	259	0	4653
Total	5812	793	1182	848	705	5249	14 589

Figure 3. National Mediterranean fruit fly trapping network established in 2015 in the Dominican Republic (yellow triangles= Jackson traps, green circles= Phase IV/Biolure traps).

Figure 4. Trapping network in the eastern region of the Dominican Republic (yellow triangles= Jackson traps, green circles= Phase IV/Biolure traps).

During this preparatory phase, fruit sampling activities followed a general approach, systematically collecting a wide range of soft-skinned fruit species that could potentially be susceptible to Mediterranean fruit fly infestation. A total of 10 589 fruit samples were collected and dissected. Once the host range had been assessed for the Dominican Republic, a targeted stratified sampling protocol was implemented as explained in Section 2.2.2. (FAO/IAEA 2017a, and FAO/IAEA 2018).

The results of the surveillance system indicated that the infestation was concentrated in and around the coastal touristic areas of Punta Cana and Bávaro, with sporadic wide-spread detections throughout the eastern provinces. Most adult (1572) and immature stages of the fly (1189 larvae in 225 infested samples) were found in the 8 weeks after initial activities were begun in March 2015. The pest was found not only in the Punta Cana and Bávaro area, but later also in other areas in the Province of La Altagracia, and subsequently also in the nearby provinces of El Seibo, San Pedro

Macorís, and Hato Mayor (see Fig. 7). A reproducing and recurring population was also found in a popular tourist area in the Province of La Romana.

The group of international experts commissioned by the FAO/IAEA under the external TAC first met on-site in January 2016 and reviewed activities and results so far achieved during the initial months of the programme. The TAC confirmed that eradication was still feasible and recommended that an area-wide programme be established, integrating the SIT, as the core eradication activity, with other control methods.

The cooperation with several stakeholders, in particular experts from the Guatemala-México-USA Moscamed Programme and the FAO/IAEA, as well as the recommendations of the TAC (September 2015, January 2016, October 2016 and July 2017), served to guide the implementation of all activities and provide continuous technical back-stopping.

2.2. Suppression and Eradication Phase

The new surveillance system (trapping and fruit sampling) allowed the programme to develop and implement the strategies for the immediate suppression and ultimate eradication of the established Mediterranean fruit fly populations.

2.2.1. Detection - Trapping Networks

The goal during this suppression phase was a trap density of 2 traps per km^2 at a 1:1 ratio (Jackson trap to Phase IV/Multilure trap) in areas with host presence, as well as achieving high trap servicing levels (Fig. 5). Once the SIT was initiated, the trap ratio was adjusted in release areas to a 1:9 ratio to focus on wild female detection and to minimize sterile male recapture. Trap service intervals were changed to once every two weeks in the Mediterranean fruit fly-free areas and remained at once per week in the infested and buffer areas of the eastern region (Fig. 5).

For each Mediterranean fruit fly find, a high-density delimitation trapping was installed in a 9 km^2 area around the find for three life cycles, as indicated by international trapping protocols (FAO 2016).

Once the infestation on the island was well delimited and aerial sterile fly releases initiated in 2016, the total number of traps in the Mediterranean fruit fly-free areas of the eastern region was gradually reduced to allow concentrating more of the available resources on areas with suppression/eradication activities.

Overall, there was no real trapping network in the first quarter of 2015, and from 5 April 2015 to 14 January 2017, 4174 adults (3938 males and 236 females) were caught in 594 traps out of a total of 14 589 traps deployed country-wide. Adult detections were higher during the second and third quarter of the year, both in 2015 and 2016 (Fig. 6).

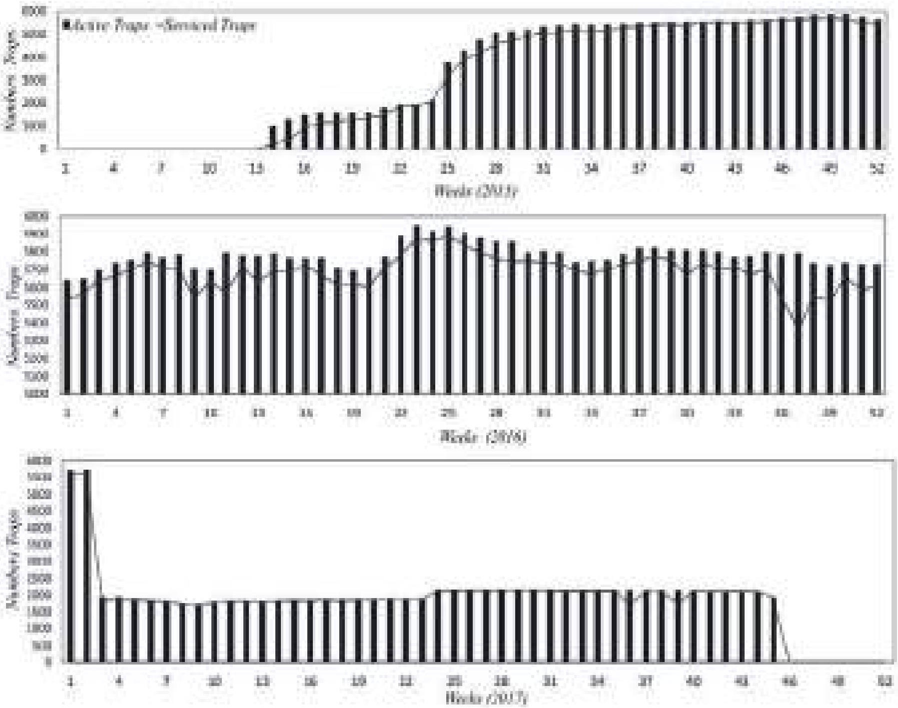

Figure 5. Numbers of installed traps (solid bars) and servicing levels of these traps (line) in the eastern region, including La Altagracia Province, during the 2015-2017 eradication campaign.

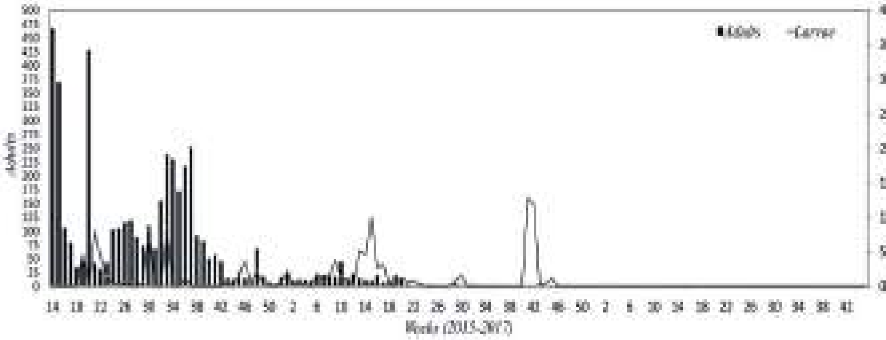

Figure 6. Numbers of detected wild adult flies (black bars) and larvae (line) of Ceratitis capitata *per week during the 2015-2017 eradication campaign in the eastern region of the Dominican Republic.*

The trapping network also provided valuable information on the spatial distribution of the pest, clearly showing that the population was concentrated on the eastern part of the country, mainly within the La Altagracia Province, with the highest numbers present in Punta Cana where the epicentre of the outbreak was located (Fig. 7). A second, incipient outbreak was also found in the Province of La Romana.

Figure 7. Locations where all Mediterranean fruit flies were captured in the Dominican Republic between 2015 and 2017 in the Provinces of La Altagracia, La Romana, El Seibo, Pedro de Macorís, and Hato Mayor. Colours represent the absolute numbers of wild fly detections per location (green dot= 1-2 flies; yellow= 3-5 flies; orange = 10 to 25 flies; red = >150 flies).

2.2.2. Detection - Fruit Sampling

As was done for the trapping, fruit sampling was adjusted during this phase to mainly target or direct sampling to the confirmed hosts. The general fruit sampling data indicated 95 infested samples of tropical almond *Terminalia catappa* L. and 19 infested samples of yellow caya *Sideroxylon foetidissimum* Jacq., locally known as "yellow caya" which therefore were the major *C. capitata* hosts, though larvae were also found in three samples of another wild host *Simarouba berteroana* Krug & Urb, locally known as "aceitunas = olives" or "black caya", with 3 infested samples. Based on this information, fruit sampling efforts in the infested area were mainly targeted to these three host species to increase the probability of detection.

Overall, 1189 larvae were detected in 10 589 fruit samples with a total mass of 34 789 kg of fruits. Consistent with the trapping results, the majority of larvae were detected during the second and third quarter of the year, both in 2015 and 2016 (Fig. 8). This figure shows that the peak infestation occurred during week 21 of the year 2015 with an average of 7.4 larvae per sample, although the highest number of larvae was obtained in week 41 of 2016 in a large localized infestation in the Bávaro area. The last larva was detected in week 46 of 2016.

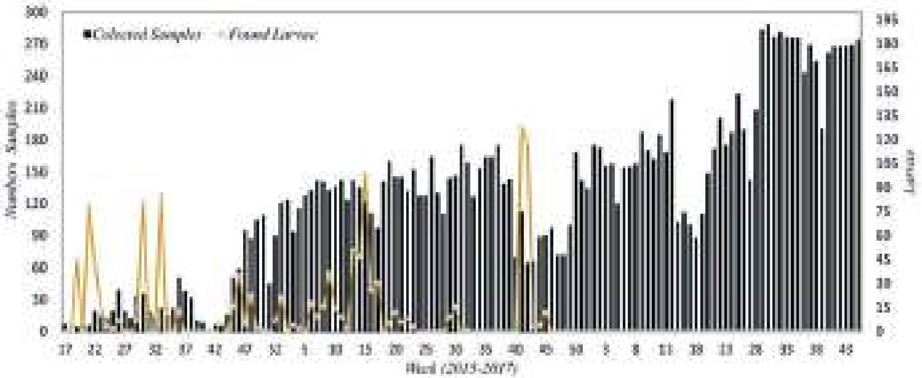

Figure 8. Numbers of fruit samples collected (black bars) and Mediterranean fruit fly larvae detected (brown line) during 2015-2017.

2.2.3. Mechanical/Cultural Control

Mechanical/cultural control consisted of the collection and disposal of *C. capitata* host fruit (on the ground and in the tree), as well as the elimination or severe pruning of host trees, mainly tropical almond, yellow caya and black caya, in the infested areas. A total of 1200 tons of fruit were collected and destroyed, mainly from tropical almond and yellow caya (Fig. 9).

2.2.4. Bait Spray Application

Bait sprays were mainly applied by ground to an area of one square kilometre surrounding hot spots (where repeated detections were made) in 2016 and 2017, although limited aerial bait spraying was also carried out in hot spot areas in 2015 (Fig. 10).

In addition, three scenarios for the aerial application of bait spray were proposed in preparation for the first quarter of 2016 in case of an increase in detections during the March-May period:

a) application of the bait spray on 32 241 ha, which covered all accumulated outbreaks,

b) only on 4342 ha, which covered active outbreaks, and

c) only on 1883 ha, which covered outbreaks from the last 4 weeks.

Due to reasons beyond the control of the programme, such as inadequate supply of GF-120, arrival of a large tourist population for Easter, and the socio-political situation in the area, it was not possible to carry out the aerial bait sprays as planned to expedite the eradication process.

Figure 9. Mechanical /cultural control activities consisting of the destruction of host fruit and the pruning or elimination of wild hosts in the infested area.

Figure 10. Aerial and ground insecticide-bait spray activities and placement of bait stations.

2.2.5. Bait Stations

Bait stations were used as part of the AW-IPM approach to support the ground sprays within the one square kilometre core area of the delimitation trapping area and to cover some locations outside of the core area (Piñero et al. 2014). They were used as a complement when the infested area could not be sprayed, where there was a lack of host trees to be treated, in the surrounding areas in cases of dense vegetation that was difficult to penetrate, and also when ground sprays were ineffective because of the heavy rains.

In total 28 176 stations baited with Ceratrap, 21 133 stations baited with GF-120, and 1513 prototype bait stations developed in Guatemala were installed in areas neighbouring outbreaks (Fig. 10). They were also used as a preventive measure in areas where larvae had been detected in fruit.

2.2.6. Quarantine and Exclusion Activities

A network of quarantine road stations was placed strategically on the main highways and exit points from the La Altagracia Province to prevent the movement of the pest through infested fruit to Mediterranean fruit fly-free areas (Fig. 11).

Apart from the internal quarantine stations, inspection at international points of entry was upgraded due to the large number of tourists (ca. 5 million per year) visiting the country. X-ray machines were installed at seaports and airports, with particular attention to the Punta Cana and La Romana airports. Careful supervision of exclusion activities at these points of entry continues to be crucial to prevent new fruit fly incursions into the country in consignments or in passenger luggage.

2.2.7. Sterile Insect Technique

Sterile male fly releases began in October 2015 after the Mediterranean fruit fly infestation was delimited and the populations in hot spots suppressed. For the first six months, the flies were emerged in paper bags and released by ground, beginning with 1 million pupae per week, increasing gradually to 15 million per week. Aerial release of sterile flies was initiated in March 2016, using the chilled adult release system following an area-wide approach in release blocks (FAO/IAEA 2017b). An existing Ministry of Agriculture building in Higuey (one-hour drive to the airport) was adapted to host the fly emergence and release facility. A cold room was installed adjacent in the facility and an average of 72 million good quality sterile male flies were emerged, chilled, packed and released each week (average of 82.1% of emergence, 91.7% flight ability and 87.3 absolute fliers).

The sterile flies were distributed by air over eight release blocks or polygons, covering a total of 42 000 ha in the provinces of La Altagracia and La Romana (Barclay et al. 2016; FAO/IAEA/USDA 2019). The total number of sterile males released throughout the campaign was 4062 million. USDA chilled release machines (single-box) were loaned to the programme from the APHIS Aircraft and Equipment Operations facility in Edinburg, Texas. Each machine was installed in a Beechcraft King Air 90 and loaded with a single 1 m tall release box with a maximum capacity of 14 million sterile medflies per flight.

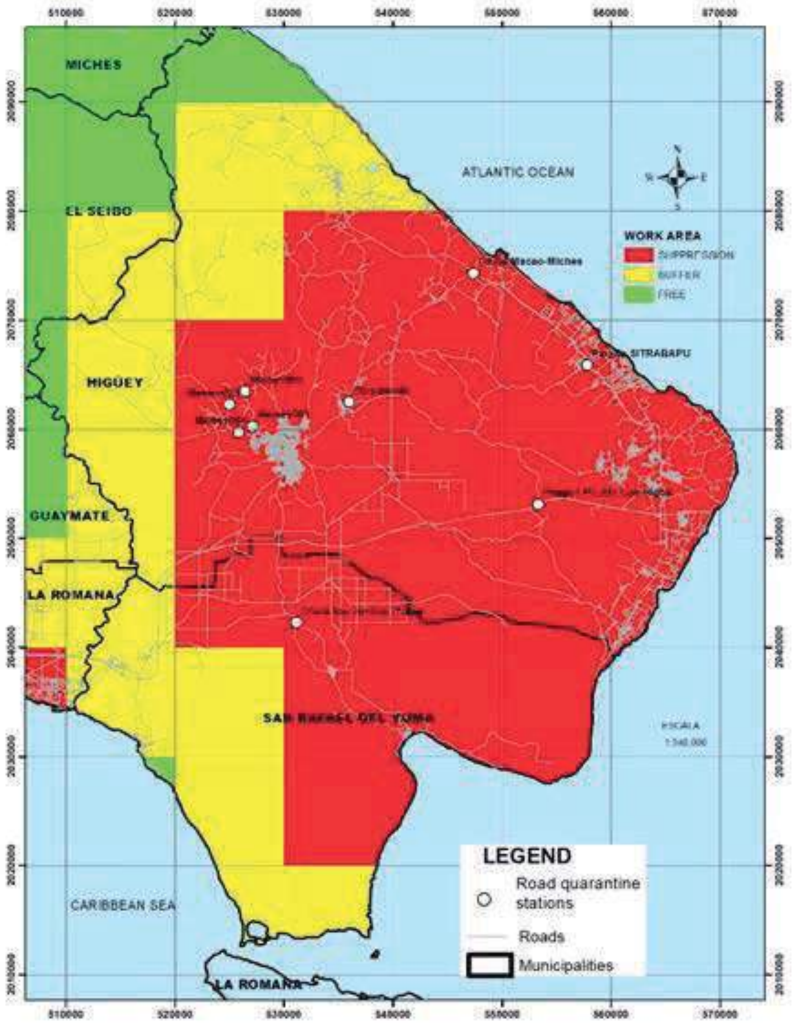

Figure 11. Distribution of road quarantine stations in the eastern part of Dominican Republic during the Mediterranean fruit fly eradication phase.

The distribution of the recaptured sterile flies (% traps with at least one capture) averaged 60%, which is below the recommended level of 85%. Release blocks located along the coastline were affected by strong dominant winds from the east, likely causing sterile fly drift (Fig. 12). Therefore, 15 million additional sterile male flies were released weekly by ground, on average, along the coast of Bávaro, Punta Cana and La Romana to achieve effective sterile to wild fly ratios in the main outbreak areas. Blocks showing low sterile fly distribution were further reinforced through ground releases specifically focussed on detection and outbreak sites.

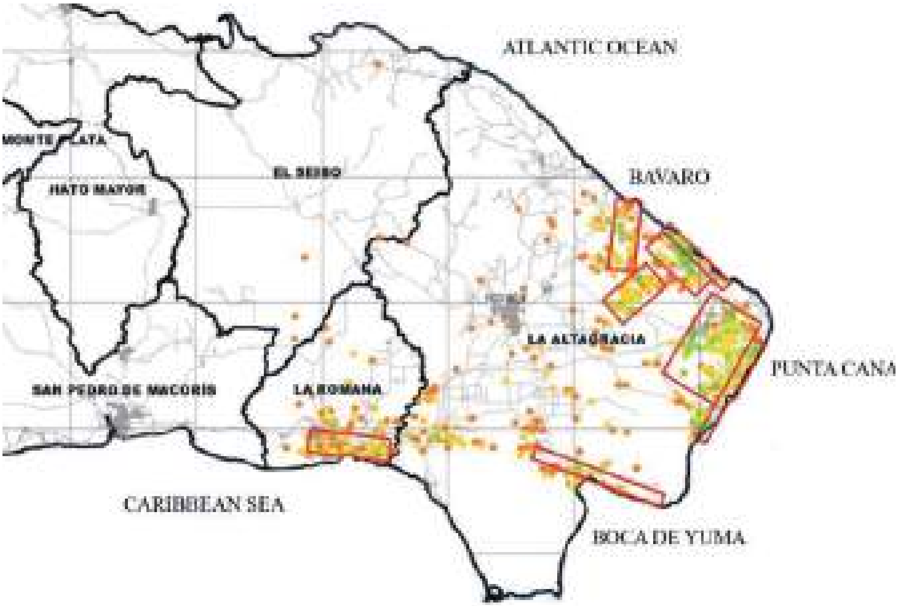

Figure 12. Blocks of aerial and ground release of sterile flies and example of average sterile fly recapture in a week (red dot= 0-1 sterile fly; orange= 2-5; yellow= 6-10 sterile flies; light green= 11-25 sterile flies; green= >26 sterile flies).

The last fertile adult Mediterranean fruit fly was detected the second week of January 2017 after less than two years of beginning intensive control measures against the pest (Programa Moscamed-RD 2017). In May 2017, sterile releases were suspended once three fly generations had passed since the last wild fly catch, which was equivalent to at least 12 weeks or ca. 3 fly generations of zero catches after the last detection.

2.3. Post-Eradication Phase

Following another risk mapping analysis at the end of 2016, a further re-arrangement of the trapping network was carried out. The total number of traps in service was reduced to a total country-wide of 4630 in early 2017, of which 2835 were deployed in the eastern region and 1795 in the rest of the country (Fig. 5 and Table 2). In addition, Phase IV traps were replaced by Multilure and McPhail traps baited with torula yeast in view of their better performance under the conditions of the Dominican Republic.

In addition, verification trapping was conducted during the post-eradication phase after sterile male releases were terminated. Verification trapping implies that traps were placed at a higher density (5/km^2) in areas where infestations had previously been confirmed. More sensitive traps such as C&C (Cook & Cunningham) and yellow panel traps (Programa Regional Moscamed 2012) were included in the verification trapping (FAO/IAEA 2018). This was implemented in May-June 2017 as a final confirmation to support official declaration of eradication in July 2017, and then continued through October 2017 at the request of USDA-APHIS.

Table 2. Number of traps deployed in the relevant provinces in 2017 after the risk analysis

Traps (Attractant)	La Altagracia	La Romana	El Seibo	Hato Mayor	San Pedro de Macorís	Rest of Domi-nican Republic	Total
Jackson (Trimedlure)	734	204	75	56	123	1730	2922
Mc Phail (Torula yeast)	656	0	0	0	0	65	721
C&C	0	22	0	0	0	0	22
Yellow Panel	0	11	0	0	0	0	11
Multilure (Ceratrap)	489	201	79	72	113	0	954
Total	1879	438	154	128	236	175	4630

As a result of the successful implementation of the programme, the export ban for horticultural products in most western and central areas of the country was lifted in early 2016, only 9 months after intensive surveillance and suppression activities were begun. USDA-APHIS lifted the export ban for 23 provinces in January 7, 2016 and later for another 2 provinces in August 10, 2016.

The benefits of the programme in confining the invading pest to the eastern part of the country, which allowed opening some export markets, and then achieving eradication in early 2017 were immediate, with exports nearly recovering to pre-outbreak levels in 2016, and even significantly increasing in 2017 (Fig. 13).

Now that Mediterranean fruit fly has been eradicated, a reliable surveillance network is being maintained to detect future *C. capitata* and other fruit fly populations early, and trained personnel and supplies are in place to provide a rapid response to any future detection or outbreak.

International quarantines and trapping at ports of entry, suitable host areas, tourist sites, markets and those locations where pest presence was recurrent during the outbreak are also being strengthened to protect the Mediterranean fruit fly-free status and prevent further introductions.

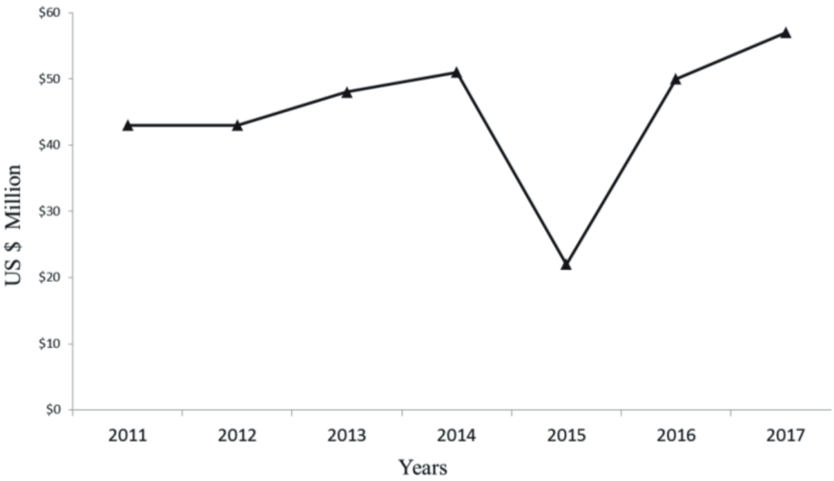

Figure 13. Exports of horticultural products from the Dominican Republic to the USA between 2011 and 2017, including the export ban in March 2015 because of the Mediterranean fruit fly invasion.

3. CONCLUSIONS

The last adult Mediterranean fruit fly was detected in the Dominican Republic in the second week of January 2017. Eradication of the pest from the Dominican Republic using an IPM approach including area-wide SIT application was confirmed in April 2017 after a period of at least three full life cycles with zero captures. Nevertheless, the official declaration of eradication took place in July 2017 after six generations of zero catches and an additional verification trapping network established in high risk areas, including previous detection sites. These additional detection efforts confirmed the absence of the pest.

Most importantly, the country has strengthened its quarantine procedures and developed the capacity for early detection and emergency response for invasive fruit fly pest incursions, as well as for area-wide application of the SIT. This valuable experience can now be shared with Haiti and other countries throughout the Caribbean region to strengthen their quarantine and surveillance systems for invasive fruit flies and other pests, and to prevent similar situations, which can result in serious economic and social losses for the whole region.

The Dominican Republic is now on the list of countries that have successfully eradicated the Mediterranean fruit fly, along with Chile, Mexico, and the USA, and others that have established Mediterranean fruit fly-free areas including Argentina, Australia, Guatemala and Peru on the American continent.

In view of the experience, the Dominican Republic has established a National Fruit Fly Programme with an assigned annual budget to maintain the gained expertise, manage native *Anastrepha* fruit flies, and maintain the surveillance and response capacities for invasive fruit flies and other pests.

4. ACKNOWLEDGEMENTS

The authors wish to acknowledge the highly qualified technical staff of the Moscamed Programme of the Governments of Guatemala, Mexico and the USA that played a major role in the transfer and area-wide implementation of the Sterile Insect Technique in the Dominican Republic.

Also, our appreciation of the valuable contributions of Walther Enkerlin, Jorge Hendrichs, Don McInnis, David Midgarden, Pedro Rendón, Jesus Reyes, and Ricardo Rodriguez, members of the Technical Advisory Committee that provided technical and strategic guidance throughout the eradication process.

Important in-kind contributions of national and international organizations including FAO, IAEA, IICA, OIRSA and USDA are also acknowledged. Our thanks to Jorge Melvin Arias from the Programa Moscamed–RD for the compilation and analysis of data. The valuable assistance improving an earlier version of the manuscript by David Midgarden, and in editing of figures and graphs by Alberto Gonzalez Lara from the Moscamed Programme in Mexico, is also acknowledged.

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THE ERADICATION OF THE INVASIVE RED PALM WEEVIL IN THE CANARY ISLANDS

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SUMMARY

After the first detection in 2005 of the Red Palm Weevil (RPW), *Rhynchophorus ferrugineus,* in the Canary Islands, the Government of the archipelago established and implemented the RPW regional eradication programme. The area-wide application of different control measures in a coordinated and integrated way for 10 years has resulted in the eradication of this invasive pest in the archipelago. The last pest focus, located on the Island of Fuerteventura, was declared eradicated in May 2016. In this paper, the different control measures that were applied, as well as the way they were executed, are discussed. Special attention is given to the factors considered key to success. It is concluded that, with the knowledge and techniques available, the eradication of RPW is possible under favourable political and financial circumstances. The biggest threats to the success of this programme originated in human factors, rather than in intrinsic characters of the insect or the techniques used.

Key Words: Rhynchophorus ferrugineus, Phoenix spp., date palms, eradication programme, Gran Canaria, Fuerteventura, Tenerife, geographic information system, Spain

1. INTRODUCTION

The Canary Islands date palm, *Phoenix canariensis* hort. ex Chabaud is endemic to the Canary Islands, where it can be found naturally in valleys and ravines and as an ornamental tree in public and private gardens and parks. It is one of the most emblematic elements of biodiversity in the Canary Islands landscape.

In the first decade of the 21st century, real estate boomed in the Canary Islands and this led to a drastic increase in the import of adult palm trees, especially the date palm, *Phoenix dactylifera* L. This is how the red palm weevil (*Rhynchophorus ferrugineus* Olivier) (RPW) entered the Canary Islands, posing a serious threat to the conservation of *P. canariensis.*

J. Hendrichs, R. Pereira and M. J. B. Vreysen (eds.), Area-Wide Integrated Pest Management: Development and Field Application, pp. 539–550. CRC Press, Boca Raton, Florida, USA.

The RPW was first detected on the Island of Fuerteventura in September 2005 (Martín et al. 2013). This introduction most likely originated from the import of date palms from Egypt for ornamental purposes. Subsequently, inspections begun in the areas where *P. dactylifera* imports had taken place in the previous 6 years. In this way 11 new infested areas were found, 7 in Gran Canaria and 4 in Fuerteventura. Inside these 11 areas different phytosanitary measures were implemented, including surveillance (palm tree inspection and maintenance of a RPW trapping network) and removal and destruction of infested palm trees. However, the programme as outlined below was more than a sum of these activities.

The RPW regional eradication programme was initiated in September 2006. It was implemented by the Canary Islands Government public company 'Gestión del Medio Rural de Canarias', and co-funded by the Spanish Ministry of Agriculture.

2. THE PROGRAMME

2.1. Centralised Coordination and Organigramme

Especially in projects that involve separate and different geographic areas (e.g. different islands), each one with their responsible administration, there is always a tendency of projects to be implemented in a different way according to local ideas. Therefore, a centralised coordination unit, as well as a programme structure that was transparent, proved to be vital to reach the objectives of the project.

The organogram of the programme is shown in Fig. 1. The entire team consisted up to 35 people and each team on each of the three affected islands with RPW infestations (Gran Canaria, Fuerteventura and Tenerife, where the only RPW focus was detected in 2007) was headed by an island team leader. Efficient programme management proved to be the most difficult challenge and that was already obvious during the initial phases of the implementation of the project. Different aspects of project management and implementation resulted more challenging than the technical-scientific knowledge of the pest. These included establishing an efficient team, keeping track of the project objectives, efficient communication, effective coordination between institutions, and strict adherence to established protocols.

2.2. Legislative Measures

Since the detection of the RPW in Europe, all Governments, including the Canary Islands Government and the Island Councils, made legislative efforts, within the scope of their responsibilities, to arm themselves with legal instruments to control RPW. During de development of the eradication programme, the basic framework for the adopted measures was derived from:

APA/94/2006, 26 January, amending the Order of 12 March 1987 to prohibit the importation of plants of palm species (Palmae) of more than 5 cm of base diameter into the Autonomous Community of the Canary Islands (BOE No. 24 of 1/28/2006) (APA 2006).

Commission Decision 2007/365/EC of 25 May 2007 adopting emergency measures to prevent the introduction into and the spread within the European

Community of *Rhynchophorus ferrugineus* (Olivier) and its subsequent amendments. (OJ L139 / 24 of 31/05/2007) (OJ L266 / 14 of 07/10/2008) (17/08/2010 DOCE L) (European Commission 2007).

Decree of 29 October 2007 declaring the existence of pests produced by the harmful agents *Rhynchophorus ferrugineus* (Olivier) and *Diocalandra frumenti* (Fabricius) and establishing the phytosanitary measures for their control and eradication (Boletín Oficial de Canarias no. 222, dated 6.11.2007) from the Council of Agriculture, Livestock, Fisheries and Food of the Canary Government (BOC 2007).

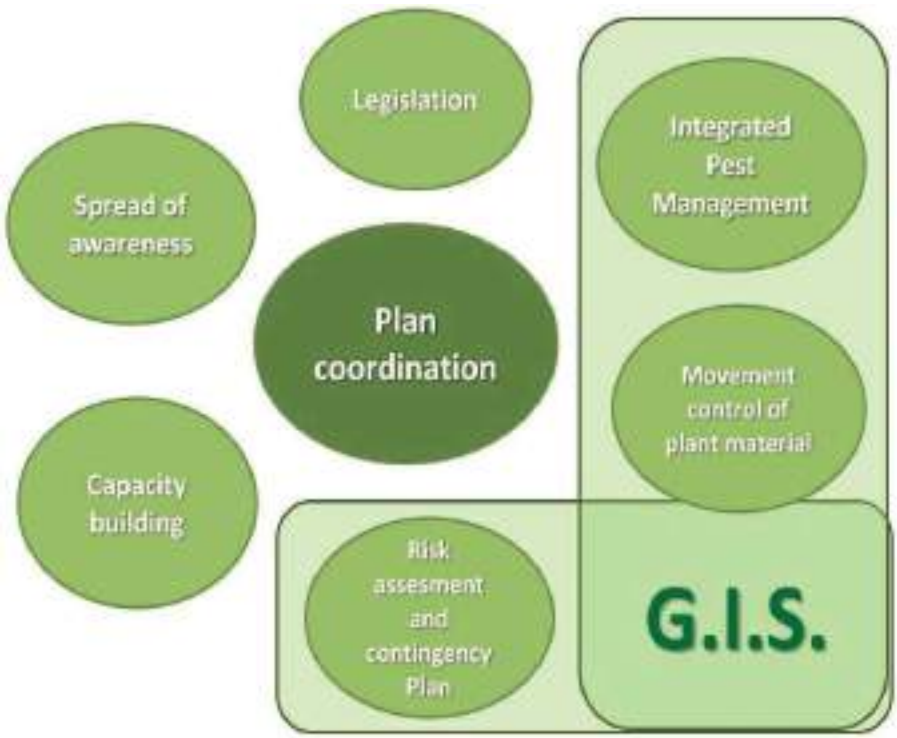

Figure 1. Red Palm Weevil Programme's organigramme.

The measures included in the regulations, at all levels, can be divided into two major groups (Gobierno de Canarias 2019a):

1. Measures that aimed at reducing man-assisted insect dispersal, including the prohibition of import of plants for planting, quarantine measures and regulations for the movement of plant material, and imposing related obligatory measures for nurseries and farmers, and

2. Measures that aimed at reducing the establishment of the pest and its natural spread after detection in a certain area.

The measures of the first group include the control of movement of plants for planting, promotion of stakeholder awareness, and stimulation of increased cooperation between institutions. Although these measures were the most difficult to enforce, they were crucial for the success of the programme. To ensure compliance with these regulatory measures, it was necessary to include staff with legal experience on phytosanitary regulations in the multidisciplinary teams of the eradication programme.

The global economic crisis resulting from the great recession of 2008, which affected Spain particularly hard, proved indirectly to be a bonus that made the implementation of the RPW quarantine and eradication measures easier. In the pre-crisis period, the Spanish economy was increasingly biased towards the construction sector because of a credit and real estate bubble (Jimeno and Santos 2014). The bursting of this bubble drastically reduced the number of requested permits for the construction of new real estate in Spain from close to a million per year before the crisis to less than 200 000 per year following the crisis. As a result, the demand for importing, transplanting and moving of palms from nurseries to new real estate sites was significantly reduced (Fig. 2).

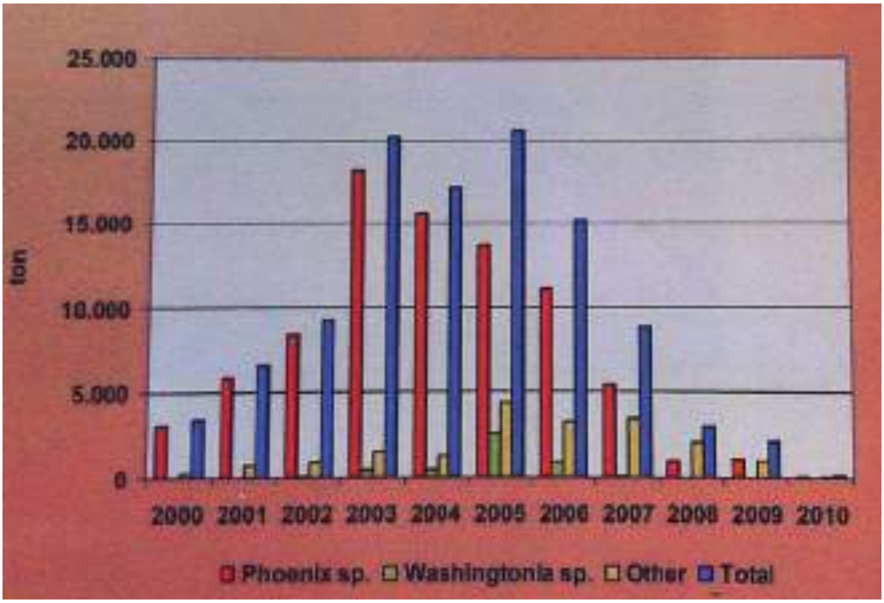

Figure 2. Tons of imported palm trees into Spain (source: Jose Maria Cobos, Spanish Ministry of Agriculture).

2.3. Awareness Campaigns

To involve as many people as possible in the eradication campaign, several information and awareness campaigns accompanied the programme to provide training and information to all stakeholders and citizens. These stakeholders included engineers, technicians and staff of the different public administrations, as well as gardeners in hotels, gardening companies, plant nurseries and the general public. The main goal was to achieve optimal support from the public in reporting and alerting the programme management board immediately when observing a palm tree with suspicious symptoms. This reporting system of the general public was crucial to implement quick follow-up actions. The following communication tools were used:

- A specific web page (Gobierno de Canarias 2019b)
- TV advertising campaigns
- Information on DVDs
- Conferences and special workshops held on each one of the islands
- Brochures.

One of the crucial factors in this communication campaign was complete transparency, and to openly disclose all available information. In this way, all stakeholders became "co-owners" of the programme and felt confident and involved.

2.4. Specific Training

The Order of October 2007 stipulated that anybody working on palm trees should be accredited as "*Specialist on labour on palm trees*". The objective of this accreditation was to ensure that any person or company carrying out any type of work on palm trees was conversant with all methods and protocols described in the legislation and had received the necessary training to ensure proper palm tree management. To achieve this goal, several courses were organized to train-the-trainers, who obtained thereafter the necessary accreditation. The programme encouraged all official administrations and relevant academic institutions to include courses on palm tree management in their curricula. The RPW programme edited and produced the "*Manual of good practices in palm trees*", which was used as textbook in these courses.

2.5. Movement of Plant Material

Import or movement of infested plants for planting is the main route of introduction and spread of the pest over long distances. Therefore, the programme deemed it crucial to restrict and control the movement of plants. In addition, to manage the movement of palm trees from nurseries, the programme required all nurseries to be registered. Nurseries were inspected periodically with emphasis on:

- The registration of the entry and exit of palm trees
- Visual inspections of possible RPW damage and symptoms
- Application of the mandatory chemical treatments.

A "*Phytosanitary Accreditation*" was created, consisting of a 6-month valid movement authorization for palms susceptible to RPW, except *P. canariensis, P. dactylifera* and *Washingtonia* spp., for which authorizations were requested for every single movement. It was mandatory to have an authorization of the Canary Islands Plant Protection Organization to perform transplantations of *Phoenix* spp. and *Washingtonia* spp. These could only be carried out by accredited companies. All requests for transplantation of palm trees located within a range of 5 km from infested plants were denied.

2.6. Integrated Pest Management Programme

The following activities were included in the integrated pest management programme: visual inspection of trees, chemical treatments, destruction of RPW-infested palms, monitoring/mass-trapping of RPW, and cultural measures such as pruning, which was only authorized for public safety reasons and should include the application of an oil painting or pruning mastic on the pruning scars. All of these are common measures implemented in control programmes world-wide (Abraham et al. 1998; Faleiro 2006; Dembilio and Jaques 2015).

2.6.1. Delimitation

Upon detection of a RPW infestation in a palm tree, or a group of palm trees, a new pest focus was declared, which was defined by two main areas:

Intensive surveillance area: The area with a 1 km radius from the outermost affected palm trees in the focus. All palm trees within this area were registered into batch, and only palms trees that were positively diagnosed with RPW were registered individually.

Guided surveillance area: The area within a 3 km radius from the border of the intensive surveillance area.

2.6.2. Inspection of Palm Trees

After testing all possible tree inspection methods available, intensive visual inspection was found to be the most effective detection method. The method consisted of a thorough observation of the stipe and all the bases of the crown's fronds. This type of inspection was performed by specialized personnel.

2.6.2.1. Inspection Inside Intensive Surveillance Area. In addition to regular inspections (about 3 inspection/palm/year) of all palm trees within the intensive surveillance area, visual inspections were carried out around each trap where RPW adults were caught, as well as around newly detected infested palm trees.

2.6.2.2. "Guided Inspections". Specialised technicians, responsible for the guided surveillance, carried out the visual inspections within the guided surveillance areas. These inspections allowed marking the location of affected palm trees outside the intensive surveillance areas that prevented the dispersal of the pest from infested areas.

2.6.2.3. Alert System. The programme established an alert system in which any citizen could report observations of palm trees with apparent symptoms of the RPW. Through this system, five new RPW outbreaks were detected very early, which made it very easy to bring these outbreaks under control. The success of the alert system measure was facilitated by the public outreach and awareness campaigns (see above in point 2.3.).

2.6.3. Removal of Infested Palm Trees

All palm trees suspected of being infested with RPW were removed. In most cases, the removal took place within 24 hours after detection. In those cases where this was not possible, palms were treated and enmeshed until removal.

The removal process followed a strict disposal protocol to avoid dispersal of adult weevils during the process. The tree stump was guarded and inspected for several days after the removal and a trap was deployed next to it for at least a week.

2.6.4. Chemical Treatments

Chemical treatments aimed to control the immature stages of RPW found in the most superficial part of the palms. Insecticides such as chlorpyrifos 48%, imidacloprid 20% and thiamethoxam 25% were sprayed on the tree at very low pressure, using about 15 litres of the mixture per palm.

Throughout the programme, chemical treatments were routinely applied (about 2 treatments/year) to all palm trees inside the intensive surveillance area, but also to palm trees around each newly detected affected palm, as well as around traps when adult specimens were caught.

2.6.5. Trapping Networks

Food and pheromone baited traps were deployed to maintain a trapping network following different strategies and objectives:

- Mass-trapping
- Adult weevil attraction to the centre of each pest foci
- Population monitoring
- Detection of new pest foci.

The traps were baited with 700 mg of *R. ferrugineus* attractant (4-methyl-5 nonanol 90% and 4-methyl-5-nonanon 10%, both purity>95%) and either ethyl acetate (kairomone) or fresh palm tissue. They were checked for weevils and serviced once a week. At an average temperature of 28ºC the attractant is released at a rate of 11mg/day making the trap effective for a period of 6 to 8 weeks (product label information). The self-made four window (4 cm diameter) 10 litre bucket traps with no opening on the lid were placed at more than 15 meters from any palm tree, and if possible, were buried half in the ground. At the onset of the programme, white traps were used, but starting in 2011 these were painted black (Ávalos and Soto 2010).

Different strategies were followed to manage the trapping networks. As recommended by Oehlschlager (1994), the programme started using a grid of 1 trap/ha in pest foci and surrounding guided surveillance areas. This was later replaced by 'dynamic micro-networks of traps', where traps were deployed at a density of 4 traps/ha in the polygons of the affected palm trees. Following this approach, no traps were deployed in areas around pest foci and their surrounding guided surveillance areas, where the presence of the pest was not proven. The objective was not to attract the weevils away from affected areas by placing traps into areas where they had not yet been observed. These networks were 'dynamic' and continuously adjusted and adapted in size based on (a) new detections of affected palms, (b) increased catches in certain areas, (c) the absence of newly infested palm trees, and (d) the absence of weevil catches. On islands with known RPW foci, traps were also placed around the areas where the infested palm trees had been disposed of.

In islands that had remained free of RPW, traps were placed in areas where imported date palm trees had been planted in the last 5 years, e.g. golf courses, hotels, newly constructed real estate projects, nurseries, etc. Using this approach, the 2007 outbreak in the Island of Tenerife was detected early.

2.7. Contingency Planning

As soon as a new focus was detected, a contingency plan was developed and implemented. The purpose of this contingency plan was to determine the origin of the outbreak, as well as to determine the location and to remove all infested palm trees. All human resources of the programme were dedicated to the new focus until the situation was brought under control.

3. A TOOL: GEOGRAPHIC INFORMATION SYSTEM (GIS)

A geographic information system (GIS) is a system designed to capture, store, manipulate, analyse, manage, and present spatial or geographic data (Foote and Lynch 1995). The eradication programme included a programming team (ITs), responsible for the development of the used GIS applications.

The GIS was the main tool supporting the decision-making process for three of the main activities of the programme (Fig. 1), i.e. the IPM programme, the control of movement of all plant material, and contingency plans.

The GIS was considered an essential tool for the planning and effective coordination of the eradication pest programme that allowed:

- Data and spatial analysis for optimal decision-making
- Efficient planning and use of resources
- Assessment of the programme (results, achievement of objectives) and workers from readily available quality information
- Improvement of the programme's internal and external communications.

The GIS consisted of four important elements: mobile applications, a database, a web application and a web viewer.

3.1. Database

The main objective of the database was to store and centralise all relevant information:

- Elements of the programme, e.g. pest foci, groups of palm trees, individual palm trees, traps, nurseries
- Activities of the programme, e.g. removal of infested palm trees, inspections, chemical treatments
- Results of the programme, e.g. trap catches, inspection data etc.
- Resources of the programme, e.g. workers, type of chemical products, type of traps, pheromones.

All this information was conveniently organized and related. All other software applications developed interacted with the database, either to introduce new values (e.g. field-collected data with the mobile application) or for the processing of information (web viewer, web application) to generate reports, customized maps, etc.

3.2. Mobile Application

An application for mobile devices was developed to facilitate data collection in the field. It was designed to avoid mistakes when entering data resulting in great efficiency, accuracy and high data quality.

Usually, at the end of each week, each island team leader summarized the collected data using the internet. These data were stored on a web server and automatically imported into the central database of the project.

3.3. Web Application

A web application was developed to use the database in a more friendly and efficient way. This application allowed:

- Data entry
- Data editing
- Performing queries
- Generation of tables
- Generating graphics and reports.

3.4. Web Viewer

The web viewer allowed observing and analysing all the spatial information collected by the field teams. As a result, it was possible to show on a map:

- Stored data, such as lots, affected palm trees, traps, farmers and nurseries
- Customized queries, e.g. palm trees removed by date ranges, palm lots in a range of 100 meter around a trap with catches, traps categorised by the number of catches or by a date range
- New layers, e.g. areas occupied by infested palm trees and traps.

4. MANAGEMENT OF HUMAN RESOURCES

The eradication programme as described above offered a framework to reach the eradication objectives. Nevertheless, for the correct implementation of all measures, it was essential to have an efficient management team. Probably the biggest challenge of any programme direction is to establish and manage this team.

The team was composed of members whose attitude towards work and internal training was considered exemplary. Efficiency in the programme was maintained as each team member was aware of the relevance of his/her role in the implementation of the programme and its ultimate success. This entailed that the objectives and procedures of each task had to be clearly defined.

To achieve the programme's objectives, great attention was given to continuous training, improved motivation of the group members and to always create and maintain a positive team spirit. At all times it was emphasised that the group members were the protagonists of the obtained results. A team member could always make suggestions and the proposals were always evaluated and sometimes incorporated into the procedures.

5. RESULTS

On three islands (Gran Canaria, Fuerteventura and Tenerife), sixteen RPW foci were detected and eradicated (Fig. 3). More than 70 000 palm trees were registered, 706 081 visual inspections were made, and 209 547 chemical treatments were carried out. A total of 681 RPW adults were caught in traps (Fig. 4) and 660 palm trees removed. In May 2016, 11 years after the pest was first detected, and after three years without finding affected palm trees or catching RPW in traps, the Canary Islands were declared free of the pest.

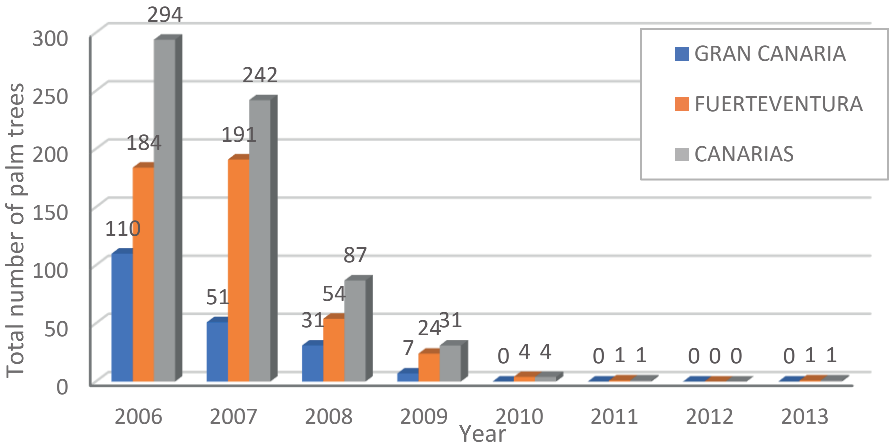

Figure 3. Affected palm trees between 2006 and 2013 on the islands of Gran Canaria and Fuerteventura, as well as total numbers for the Canaries.

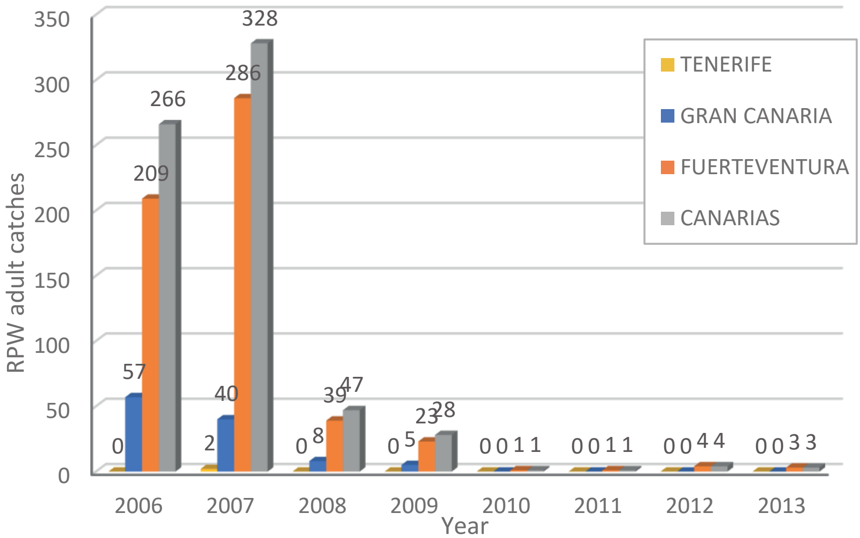

Figure 4. Red Palm Weevil adult catches in traps between 2006 and 2013 in Tenerife, Gran Canaria, and Fuerteventura, as well as total numbers for the Canaries.

The Canary Islands example shows that the presently available knowledge and control tactics can successfully eradicate the RPW. The main issue is not the lack of technical know-how, but the establishment of an efficient organization and its management to reach the objectives. The Canary Islands are now facing a new challenge and that is to maintain the motivation and support to prevent and detect early any new introduction of the RPW.

Taking into account the results and positive experience gained in the eradication programme of RPW in the Canary Islands, the minimum requirements for a successful eradication programme are as follows:

- Applying a programme in areas of recent introduction or where the RPW has been kept under control
- Identifying areas isolated from affected areas by a buffer zone with no susceptible palms or that are at least 10 km away from the nearest RPW focus, where no programme activities have to be applied
- Including adequate legislative measures and their enforcement aiming to avoid new introductions and the movement of plant material
- Correct design and integrated implementation of all programme´s activities and components
- Adequate budget available according to the number of pest foci and other requirements
- Centralised coordination (e.g. communication, decision-making) of area-wide programme activities
- Adequate human resources available and their management (e.g. training, attitude, motivation, constancy procedures)

- Effective use of GIS in support of data management and decision-making
- Public education and engagement, and involvement of all stakeholders
- Cooperation and coordination with public (Provinces, Autonomous Communities and affected Municipalities) and private entities (e.g. nurseries, gardening companies, hotels, farmers).

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