CHAPTER 2.1.

AREA-WIDE INTEGRATED PEST MANAGEMENT AND THE STERILE INSECT TECHNIQUE

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SUMMARY

Area-wide integrated pest management (AW-IPM) focuses on the preventive management of pest populations throughout the ecosystem. It seeks to treat all habitats of the pest population in space and time so that none produces migrants to re-establish significant infestations in areas of concern. In contrast, the conventional strategy focuses narrowly on defending the valued entity (crop, livestock, people, buildings, etc.) from direct attack by pests. AW-IPM requires multi-year planning and commitment, coordination among stakeholders, and an organization dedicated exclusively to its implementation, whereas conventional pest management involves minimal forward planning, tends to be reactive, and is implemented independently by individual producers, businesses, or households. AW-IPM tends to integrate advanced technologies, whereas the conventional strategy tends to rely on traditional tactics and tools. The sterile insect technique (SIT) is a species-specific form of birth control imposed to suppress or contain target pest populations, although it is a very powerful tool for “mopping up” sparse and isolated pest populations. On environmental, economic and biological grounds, in many situations the case for the SIT is compelling. While only some area-wide programmes integrate the SIT, deployment as part of an area-wide management system is essential for the SIT to be effective.

1. AREA-WIDE INTEGRATED PEST MANAGEMENT STRATEGY

The area-wide concept is a modernizing strategy of providing services efficiently wherever needed. Area-wide management takes advantage of the power of organization and coordination intelligently applied. In older societies, many services were provided on an individual basis by the family, e.g. collecting water and fuel, protection of the family, disposal of waste and sewage, etc., and independently of the activities of the neighbours. These services proved to be rather unreliable, ineffective, and were obtained at great individual expense. Reduced costs, better physical protection, and increased effectiveness were the drivers towards more effective delivery services. As a result, many of these services evolved from an individual to area-wide provision (Hendrichs et al. 2007). Today, many of these services, such as police protection, potable water, garbage and sewage removal, mail service, retailing, ambulance, fire protection, public health, electrical supply, high-speed transport, telephone, and internet services are being provided on an area-wide basis (Lindquist 2001; Hendrichs et al. 2007).

Area-wide approaches to deal with insect pests have ancient roots in coping with locust plagues and vector-borne diseases (Klassen 2000; Faust 2008). By systematic use of quarantines, Venice and Milan in 1347–1350 contained bubonic plague transmitted by the oriental rat flea *Xenopsylla cheopis* (Rothschild), and this approach was gradually adopted throughout Europe.

Area-wide integrated pest management (AW-IPM) came into a degree of prominence in the late 19th and early 20th centuries with the development of classical biological control (1888) (Caltagirone 1981), the use of pest-resistant plants (such as the grafting of all European grapes on phylloxera-resistant American rootstocks in the 1870s) (NAS 1969), campaigns to eradicate the gypsy moth *Lymantria dispar* (L.) in Massachusetts (1890–1901) (Liebhold et al. 2021) and *Boophilus* spp. cattle ticks from the southern USA (1906–1943) (Rutherford 2007), the suppression of yellow fever and malaria vectors in Havana, Cuba (1898) (Lechuga and Castro 2016) and in the Panama Canal Zone (1904) (Stern 2005), and the organization of mosquito-abatement districts, first in West Africa and then in several continents (1900) (AMCA 2004; Foley IV et al. 2021).

The area-wide approach is one of several major strategies for coping with pest problems (Kogan 2000). Various pest management strategies have evolved in response to differences in the challenges presented by various pests (Hendrichs, Vreysen et al., this volume). The strategy for coping locally with a pest problem on an empirical basis gives only temporary alleviation. As methods of control, and guidelines for their use, are developed and refined, they form the basis of the conventional strategy of localized management of only fractions of pest populations. This is the most widely used strategy, and individual producers, businesses and households practice it independently and with no coordination with other stakeholders. However, in response to individual producers or households not being able to adequately meet the challenge of certain very mobile and dangerous pests, the need for total population management or an AW-IPM strategy emerged (Rabb 1972). Mobile pests include not only those that fly long distances, but also those transported passively on wind, water, or animal hosts, or in infested commodities traded locally or internationally.

Edward F. Knipling, the “father” of the sterile insect technique (SIT), was a strong proponent of the area-wide concept to manage many of the major pest problems, independent of the SIT (Klassen 2003). Therefore, area-wide management is often incorrectly associated with the SIT. However, while area-wide management is essential for effectiveness of SIT use, it applies equally to the effective implementation of other control tactics against many other pest insects that are not the target of SIT application. Table 1 lists examples of area-wide programmes not involving the integration of the SIT.

1.1. *Defining Area-Wide Integrated Pest Management*

For the purposes of this book, AW-IPM is defined as:

IPM applied against an entire pest population within a delimited geographic area, with a minimum size large enough or protected by a buffer zone so that natural dispersal of the population occurs only within this area.

The common thread that runs through all AW-IPM programmes is the strong emphasis on the preventive control over space and time of foci of infestation from which recruits emerge to re-establish damaging densities of the pest population in areas of concern.

A few scientists have attempted to define the AW-IPM strategy. Knipling, as cited by Dickerson et al. (2001), stated:

Area-wide pest management is the systematic reduction of a target key pest(s) to predetermined population levels through the use of uniformly applied control measures over large geographical areas clearly defined by biologically based criteria.

Lindquist (2000) wrote:

An area-wide insect control programme is a long-term planned campaign against a pest insect population in a relatively large predefined area with the objective of reducing the insect population to a non-economic status.

Table 1. Examples of area-wide programmes to suppress or eradicate insect pests without integration of the SIT

Programme	References
Preventive anti-locust programmes in Africa, Asia and China — some coordinated by the FAO	Showler 1997, 2002; van Huis 2007; Cressman 2021
Area-wide biocontrol of the cassava mealybug <i>Phenacoccus manihoti</i> Matile-Ferrero with the parasitoid <i>Epidinocarsis lopezi</i> (De Santis) in 38 countries of sub-Saharan Africa	Herren and Neuenschwander 1991
Area-wide biocontrol of the pink hibiscus mealybug <i>Maconellicoccus hirsutus</i> (Green) with two parasitoid species in the Caribbean Basin, Florida and California	Meyerdirk 1999
Area-wide control of the brown planthopper <i>Nilaparvata lugens</i> (Stål) and rice stem borers in China, Japan and South Asia by asynchronous rice planting and the conservation of the natural enemy fauna through landscape engineering	Oka 1991; Ives and Settle 1997; Kiritani 2007; Zhu et al. 2007; Heong et al. 2021
<i>Dendroctonus</i> pine bark beetles: long-term landscape level management aimed at age and species mosaics unfavourable for large outbreaks in western USA and Canada	Keen 1952; Carroll 2007
Global Malaria Eradication Campaign, initiated by the WHO in 1955, but disintegrated in 1969; malaria was eradicated in 37 countries, and in the end 74% of the people at risk were protected	Wright et al. 1972; Nájera et al. 2011
Mosquito control districts first implemented in West Africa in the 1890s against malaria vectors; ~260 districts in USA, many in other countries	AMCA 2004
Area-wide management of silverleaf whitefly <i>Bemisia tabaci</i> (Gennadius) in Australia based on elimination of weed hosts, preservation of natural enemies, and tight-planting windows	Schellhorn et al. 2008
Area-wide management and containment of the gypsy moth <i>Lymantria dispar</i> (L.) in the north-eastern USA -- Bt sprays and mating disruption.	Liebholt et al. 2021
African Programme for Onchocerciasis Control to eliminate river blindness; insecticides used to kill <i>Simulium</i> spp. larvae in rivers, and ivermectin to treat infections	WHO 1994; Hougard 2000; Tekle et al. 2016
Caribbean <i>Amblyomma</i> Programme to eradicate the tropical bont tick <i>Amblyomma variegatum</i> (F.), Bridgetown, Barbados; treatment of all ruminant livestock with pour-on Bayticol [®]	Pegram et al. 2000, 2007
Buffalo flies <i>Haematobia exigua</i> de Meijere in Australia	James et al. 2021
Chagas' disease, reduviid vectors in Latin America; spray infested homes, eliminate habitat, screen blood banks for trypanosomes	Schofield 2000; Hashimoto and Schofield 2012
Boll weevil <i>Anthonomus grandis grandis</i> Boheman eradication; pheromone trapping, insecticide treatment, and cultural control	Dickerson et al. 2001; El-Lissy and Grefenstette 2007; Allen 2008
Corn rootworm (<i>Diabrotica</i> spp.) management programmes in the US; Bt hybrid corn planting with resistance management, and local soil insecticide or foliar sprays applications in high-rootworm-density fields	Chandler 2002; Chandler et al. 2008; Quinn 2018
Area-wide biointensive management plan for the brown marmorated stink bug <i>Halyomorpha halyis</i> (Stål)	Leskey et al. 2016
Codling moth <i>Cydia pomonella</i> (L.) suppression through the area-wide use of pheromone-mediated mating disruption in Washington State, Oregon and California	Calkins et al. 2000; Coop et al. 2000

Table 1. Continued

Programme	References
Codling moth eradication by integrating area-wide male annihilation and removal of all host and potential host trees in urban areas	Kovaleski and Mumford 2007
Fruit fly AW-IPM in dragon fruit in Binh Thuan Province, Viet Nam	Hien et al. 2020
Area-wide use of encapsulated semiochemicals in lure-and-kill sprays against the olive fruit fly <i>Bactrocera oleae</i> (Rossi) in Greece and Spain	Jones and Casagrande 2000
Eradication of the oriental fruit fly <i>Bactrocera dorsalis</i> (Hendel) from Mauritius using male annihilation and bait application technique	Seewooruthun et al. 2000
Eradication of <i>Bactrocera papayae</i> Drew and Hancock from northern Queensland, Australia, by male annihilation and strategic foliage baiting	Hancock et al. 2000
Area-wide treatment of all properties to suppress Formosan subterranean termite <i>Coptotermes formosanus</i> Shiraki infestations of structures	Lax et al. 2007
Eradication of the red palm weevil <i>Rhynchophorus ferrugineus</i> (Olivier) in the Canaries, Spain -- strict quarantines, palm treatment, and removals	Fajardo et al. 2021
Regional management of <i>Helicoverpa armigera</i> (Hübner) in China	Wu 2007
Eradication of <i>Hypoderma</i> spp. warbles from livestock in France using pour-on insecticides	Amouroux 2000
Management of Russian wheat aphid <i>Diuraphis noxia</i> (Kurdjumov) and the greenbug <i>Schizaphis graminum</i> (Rondani) on wheat in the US Great Plains based on cultural practices, pest-resistant cultivars, and biological control agents	Keenan et al. 2007; Giles et al. 2008
Area-wide augmentative biological control of the green peach aphid <i>Myzus persicae</i> (Sulzer) on tobacco in China	Yu et al. 2021
Area-wide suppression of invasive <i>Solenopsis</i> spp. fire ants using insecticide-baits and self-sustaining biological control agents	Vander Meer et al. 2007; Aubuchon and Vander Meer 2008
Stored-grain insect area-wide integrated pest management based on systematic sampling and decision-support software to guide fumigations	Flinn et al. 2007; Hagstrum et al. 2008
Grape moths <i>Lobesia botrana</i> (Denis and Schiffermüller), and <i>Eupoecilia ambiguella</i> Hübner, area-wide pest management in Italy based on pheromone mating disruption	Ioriatti et al. 2008
Area-wide application cultural method for the control of western tarnished plant bug <i>Lygus hesperus</i> Knight in cotton	Carrière et al. 2006; Abel et al. 2007
Area-wide mosquito abatement or management districts to suppress mosquito populations by integrating physical and biological management, with larviciding, and adulticiding	Fonseca et al. 2013; Foley IV et al. 2021
Cattle fever tick eradication programme operating since 1906, first to eradicate <i>Rhipicephalus annulatus</i> (Say) and <i>Rhipicephalus microplus</i> (Canestrini) from the USA (1943), and since then to contain incursions along the border with Mexico	George 1989; Rutherford 2007
Area-wide suppression of the Asian citrus psyllid <i>Diaphorina citri</i> Kuwayama in Florida based on coordination of insecticide sprays to protect against this vector of devastating citrus greening (huanglongbing)	NAS 2010; Singerman et al. 2017
Navel orangeworm <i>Amyelois transitella</i> (Walker) area-wide management in California almonds, pistachios and walnuts through sanitation, mating disruption and integration of selective pesticides and/or biological agents	USDA/ARS 2018
Glassy-winged sharpshooter <i>Homalodisca vitripennis</i> (Germar) area-wide management in California based on coordinated insecticide sprays	USDA/APHIS 2015

Both of these definitions have considerable merit, and they fit the majority of area-wide programmes. However, slightly different definitions may be needed to describe programmes on the conservation of natural enemies (Schellhorn et al. 2015; Heong et al. 2021), and on classical biological control where the adaptation of the introduced biological agent to all new environments cannot be known in advance of release (Knipling 1992a; Wyckhuys et al. 2021). Also, it may not be possible to clearly define the boundary of the pest population. In a similar vein, Showler (2002) stated:

Locust swarms can be highly variable, influenced by many factors, including geography, vegetative conditions, land-use patterns, environmental sensitivity, availability of resources and tactics, prevailing winds, insecure areas, and rainfall patterns. Reliance on a single control strategy is therefore unrealistic [Showler 1997]. A more appropriate approach would be to develop specific strategies that will fit with projected scenarios, mostly by harmonizing them with national contingency plans.

1.2. Characteristics of Area-Wide Integrated Pest Management

It is intuitively obvious that the immigration of individuals of a target pest into a managed ecosystem prevents the effective suppression or eradication of a population of that pest. Indeed, the dispersal and migration of pests, usually from small untreated foci into a managed area, have a tremendous impact, and is often underestimated (Byrne 2008). For example, very few codling moths develop in well-managed commercial orchards. Butt et al. (1973) found that the number of codling moths that overwintered in the Wenas Valley of Washington State, USA, dropped by 96% when a few abandoned orchards and neglected non-commercial apple trees were either removed or sprayed with insecticide. This study indicated that most of the moths originated from untreated trees that in aggregate were less than 5% of the host resources of the moth. Similarly, experiences in coping with the pink bollworm *Pectinophora gossypiella* (Saunders) and the boll weevil have shown that the few growers (who do not destroy crop residues immediately after harvest) provide food for these pests to reproduce and to enter diapause (Allen 2008; Staten and Walters 2021). This lapse in field sanitation can be the direct cause of devastating levels of these pests appearing in the following season on neighbouring farms.

Knipling (1972) graphically pointed out the drastic implications of allowing a small fraction of a population of a major pest to reproduce without control (Fig. 1). Knipling showed that more pest individuals would be produced if 1% of the total population was allowed to reproduce without control, while 100% control was applied to 99% of the population, than if only 90% control was imposed uniformly on the total population. Thus Knipling (1972) elaborated the basic principle of total population suppression:

Uniform suppressive pressure applied against the total population of the pest over a period of generations will achieve greater suppression than a higher level of control on most, but not all, of the population, each generation.

Currently, for the most part, individual producers, who often rely heavily on the use of insecticides, carry out defensively the control of highly mobile and very destructive pests. Although other control technologies are often incorporated into the

producer's IPM system, these technologies are also usually applied by the individual producer independently of other producers. This conventional uncoordinated and localized farm-by-farm or field-by-field strategy provides opportunities for the pest population to build-up and to infest well-managed neighbouring fields. Consequently, on most farms, insect pest populations increase to damaging levels each year, and the farmer is forced to apply broad-spectrum fast-acting insecticides as a rescue treatment. This defeats the primary goal of the IPM system, which is to take maximum advantage of naturally occurring biological control agents (Rohwer and Knipling 1992; Heong et al. 2021). Moreover, the application of insecticides, when an insect pest population reaches the economic threshold, does not prevent the losses that occur before the threshold has been reached. For commodities that are planted on vast areas, such losses are immense. For example, the world production of maize (corn) was roughly 1134 million metric tons in 2017 (World Data Atlas 2017). Avoidance of a loss of only 3% would make available 34 million metric tons, which could be a major factor in alleviating hunger.

Figure 1. Results of a model that shows the outcome of neglecting to suppress a small fraction of a pest population in an agroecosystem versus the effect of uniformly suppressing the entire pest population. Left: 10% of the population is untreated, and in four generations it produces a large number of individuals, while the 90% of the population that is treated declines. Right: Entire pest population in the agroecosystem is suppressed uniformly, and its numbers decline from generation to generation. (Figure adapted from Knipling 1972, reproduced with permission.)

AW-IPM differs from conventional pest management of local pest populations in several important ways (Lindquist 2000; Koul et al. 2008):

1. It focuses on the preventive management of pest populations throughout the ecosystem, while the conventional strategy focuses narrowly on defending a valued entity (crop, livestock, people, buildings, etc.) from direct attack by pests.
2. It requires multi-year planning and commitment, and an organization dedicated exclusively to implementing the strategy; the conventional strategy involves only

minimal forward planning, tends to be reactive, and is implemented independently by individual producers, businesses, or households.

3. It tends to utilize advanced “high-tech” technologies, whereas the conventional strategy tends to rely on traditional “low-tech” tactics and tools that can be reliably implemented by non-specialists (Lindquist 2000, 2001).

Community-based control can be considered as a special case of localized control whereby local communities are responsible not only for the implementation of the control activities but are also involved in their development and management (Vreysen 2001). There have been many examples of community-based control in Africa against tsetse fly populations, and these have shown that these operations can be successful in small areas and when the farmers have access to expertise and initial “seed money” (Dransfield et al. 1991). However, none of these community-based control activities has proven to be sustainable as exemplified by such efforts against the vectors of human sleeping sickness in Ivory Coast (Laveissière et al. 1985) and Uganda (Lancien 1991), or the vectors of nagana in Kenya (Dransfield et al. 1991). The reasons for the unsustainability of this approach are multiple, e.g. lack of scale and central coordination, various sociological factors (e.g. theft of the suppression devices, sustaining the interest of the farmers, willingness to contribute, etc.), inaccessibility of some habitats, and the need to deploy the suppression tools at high densities in some habitats (Vreysen 2006). Despite the quick localized benefits these approaches can bring, they cannot be sustained indefinitely by communities, becoming ineffective in the long run (Vreysen 2001).

Indeed, it is the use of organizations dedicated to coordinate and conduct area-wide programmes that provides the opportunities to employ sophisticated technologies and professional management. Computer-based models are utilized in planning and management (Bouyer et al., this volume), and satellite imagery is used to identify localities of alternate hosts that can be treated to reduce the number of migrants that cause the damage in commercial production areas. Area-wide programmes acquire or develop highly sensitive detection systems, use spatial tools such as the global positioning system (GPS), geographic information systems (GIS), and satellite remote sensing (RS), and employ specialised software for data management to ensure efficient implementation of these programmes.

Also, they may implement area-wide approaches to resistance management to prevent or retard the development of resistance to insecticides or the loss of host-plant resistance (Prasad et al. 2009). Computer programmes and real-time environmental data to predict insect populations can be used effectively in an area-wide programme, but usually not on an individual farm basis. Thus, modelling of pest distribution and immigration patterns, analysis of weather to predict increases or decreases of populations, genetic analysis to determine and forecast resistance levels, or to assess the level of isolation of targeted insect pest populations, etc., are utilized in area-wide programmes (Elliott et al. 2008; Bakhoun et al. 2021; Bouyer et al., this volume).

Most insect populations are not distributed uniformly in time and space (Vreysen, this volume). Metapopulation and landscape ecology are approaches that have been used to study or characterize spatially structured insect populations, and the basic concept of these dynamics is the heterogeneity of the environment (Levins 1969; Clark 2010). This heterogeneity results in discrete patches that are suitable or

unsuitable, as well as persistent or unstable, for inhabitation of the pest insect (Elliott et al. 2008). The main difference between the two approaches involves the role of the matrix in the dynamics of the population patches, i.e. uninhabitable but consistent effects on the dynamics of the population in the metapopulation approach versus the matrix having varying effects on the local populations in the landscape ecology approach, which can influence within-patch dynamics (Hanski 1998). These approaches are important predictive modelling tools for a better understanding of the dynamics of the pest populations and, hence, allow for better planning of AW-IPM programmes.

Efficient implementation of AW-IPM requires defining the temporal and spatial scales that must account for the behaviour and longevity of the target pest. The minimum time-unit for analysis is likely to be the generation time of the target insect, whereas the minimal spatial unit should be the average two- or three-dimensional scale that a target insect can disperse within a generation (Elliott et al. 2008), and should be large enough to encompass all normal movement of the average individual insect (Schneider 1989; Barclay et al. 2011).

Finally, area-wide programmes can take advantage of the power and selectivity of specialized methods to manage insect pests that, for the most part, are not effective when used on a farm-by-farm basis. These include the SIT, inundative releases of parasitoids, the use of semiochemicals, mating inhibitors, large-scale trap cropping, treatment of hosts on public lands and in private gardens, etc.

1.3. Benefits of Area-Wide Integrated Pest Management

Suppressing highly mobile pests on an area-wide basis is usually more benign environmentally, more effective, and more profitable, than on a farm-by-farm basis because of economies of scale (Carlson and Wetzstein 1993; Keenan and Burgener 2008). Also, AW-IPM is better at capturing the benefits of mobile natural enemies (Knipling 1992a; Ives and Settle 1997).

Area-wide programmes enable many producers and other stakeholders to pool resources to utilize technologies and expertise that are too expensive for individual producers. These may include mass-rearing facilities, aircraft services, information technologies, and highly trained specialists. In addition, a coordinated area-wide programme can avoid or internalize external costs. External costs (externalities) are the harmful effects arising from pest control operations, which affect parties other than the pest control decision-maker, but for which no compensation is paid to the persons harmed (Reichelderfer et al. 1984). Spray drift onto neighbouring properties frequently provokes disputes. Also, insecticide use to protect agricultural crops has caused resistance to develop in other insects, including vectors of disease. This has been an important factor in the resurgence of malaria.

AW-IPM is more likely to succeed when the number of farmers involved is small and the crops are similar. In addition, the suppression of the pest under the leadership of a third party makes it easier for a heterogeneous group of farmers to collaborate. Farmers who cultivate crops with a high economic value and low-pest tolerance suffer greater losses than farmers who cultivate a crop of lower economic value but with a higher pest tolerance (Yu and Leung 2006). Therefore, it is much

easier to encourage the former to participate in an area-wide programme as compared with the latter (Stonehouse 2007).

AW-IPM provides imperfect public goods, and is prone to free-riding, and therefore most successful programmes depend on government funding, coordination, and management (Hendrichs et al. 2007). However, joint funding by federal/state governments and growers can enhance implementation because growers are stakeholders (Ervin and Frisvold 2016). The contributions of the producers and/or the general public (Halasa et al. 2012; Mumford, this volume) are often obtained by levying taxes, e.g. the codling moth programme in Canada (Nelson et al. 2021), or through contracts between farmers and a private entity, e.g. the false codling moth *Thaumatotibia leucotreta* (Meyrick) programme in South Africa (Boersma 2021). Sometimes, unexpected economic outcomes are obtained, e.g. results from an AW-IPM programme against the Queensland fruit fly *Bactrocera tryoni* (Froggatt) in Australia indicated that returns from tighter roadblocks were greater than returns from increased surveillance or enhanced eradication capacity (Floreac et al. 2013).

Benefit/cost analyses have become important and valuable tools to assess the direct and indirect benefits of AW-IPM programmes; they provide consistency, flexibility, objectivity, and comprehensiveness at the decision-making stage (Enkerlin et al. 2007; Quinlan and Larcher-Carvahlo 2007; Mumford, this volume). Direct benefits are easy to assess because they result from increased crop yield and crop quality, increased livestock productivity, and reduced insecticide use and control costs. Indirect benefits are more difficult to quantify because they often relate to reduced environmental or human-health costs (Quinlan and Larcher-Carvahlo 2007; Enkerlin, this volume).

As evidenced by the few examples below, the benefits of properly executed AW-IPM programmes can be enormous:

1. The boll weevil, since its introduction into the USA in the 1890s, has cost the cotton industry more than USD 2300 million in economic losses. As exemplified in Georgia, its eradication provided significant benefits to growers; the average gross crop revenues increased from USD 70 million per year (prior to eradication) to USD 400 million per year (afterwards) (USDA/APHIS 2013).
2. The eradication of the New World screwworm *Cochliomyia hominivorax* (Coquerel) in North and Central America resulted in annual benefits to livestock keepers amounting to USD 1300 million, despite an investment of the same amount to eradicate the pest over 45 years. The eradication of the same pest when it invaded Libya resulted in a benefit/cost ratio of 5:1 for the infested area and 10:1 for the whole of Libya (Vargas-Terán et al., this volume).
3. A recent benefit/cost analysis of the Moscamed containment programme, assuming that the Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) is eradicated in Guatemala and the containment barrier is moved to the border with El Salvador and Honduras, indicated a benefit/cost ratio of 140:1 for Belize, 16:1 for Guatemala, and 127:1 for Mexico (Enkerlin et al. 2017).
4. An economic analysis of an AW-IPM programme against the Asian tiger mosquito *Aedes albopictus* (Skuse) in New Jersey, USA (based on adulticiding, larviciding, and resource reduction) indicated that the incremental cost of the programme was USD 41 per person per year. Over a period of 3 years, a benefit/cost ratio of 8.6:1 was obtained, indicating that for every USD spent, the

programme gave adults additional time outdoors worth USD 8 (Shepard et al. 2014).

Finally, economies of scale can be captured in area-wide programmes, although complex trade-offs may be involved. The more mobile the pest, and the more uniform the damage caused by the pest, the larger the area under coordinated management should be (Barclay et al. 2011). The total cost of pest detection, monitoring, and suppression per hectare of crop usually declines as the size of the managed area increases. However, as the project size increases, the per-hectare organizational cost usually increases because of the increased need for coordination and other communication costs. For these reasons, in very large programmes such as the effort to eradicate the boll weevil or the pink bollworm in the USA, the vast area was subdivided into several operational zones (Allen 2008; Staten and Walters 2021). Also, considerable organizational cost savings may be realized in instances where towns, municipalities, or cooperatives already have structures in place for decision-making and communication.

1.4. Contingencies Often Dictate Changes in Strategy

Contingencies often arise that require replacement of one strategy with another (Geier 1970; Hendrichs, Vreysen et al., this volume). For example, at various times during the 45-year campaign to remove the New World screwworm from the USA, Mexico and Central America, different pest management strategies had to be selected. This programme began when an unusual series of frosts, beginning early in December 1957, killed all screwworms in the south-eastern USA north of a line from Tampa to Vero Beach in southern Florida. Sexually sterile flies, from a culture in a research laboratory, were released in a broad band north of this line to contain the pest population. In the summer of 1958, this exclusion or containment strategy was replaced by the strategy of eradication; the sterile flies were derived from a recently constructed mass-rearing facility that was able to produce 50 million sterile flies per week. Eradication was accomplished in 1959; in 1966 the New World screwworm was officially declared eradicated in the USA. However, it was obvious that, unless the insect was removed from northern Mexico, it would reinvade the USA. Nevertheless, the programme to eradicate the screwworm from northern Mexico could not commence immediately because, until 1972, there was no agreement between the Governments of the USA and Mexico. Therefore, in 1966, the programme strategy had to change from eradication to exclusion in the form of a sterile-insect barrier along the entire Mexico-USA border. Sterile flies were released in a zone that was about 130-km wide. Unfortunately, this barrier proved to be too narrow to exclude female screwworms from entering the USA and causing many cases of screwworm myiasis (Graham 1985). Finally, operations began in Mexico in 1974. The last screwworm case in the USA occurred in 1982 (Vargas-Terán et al., this volume).

1.5. Legal Authority for Area-Wide Integrated Pest Management

Legal authority to implement area-wide and other regulatory programmes is absolutely essential, but is still evolving (Dyck, Reyes Flores et al., this volume). Without explicit legal authority, the organization implementing an area-wide programme would not be able to conduct operations on private property, nor operate quarantines.

In about 1860 the grape phylloxera *Daktulosphaira vitifoliae* (Fitch) was introduced into France from the USA. Within 25 years of its arrival, this insect had destroyed one million ha of vineyards (fully one-third of the production capacity). To protect the German wine industry, in 1873 the Government of Germany passed the first law that provided for quarantines and regulatory control of agricultural pests (NAS 1969). Other governments quickly followed the example, and in 1881 representatives of many European countries together developed a set of regulations governing the movement of grape-propagating material.

In about 1880 the establishment of the San Jose scale *Quadraspidiotus perniciosus* Comstock in California, its rapid spread on nursery stock throughout the country, and the failure of a programme to eradicate it, caused Canada, Germany, and Austria-Hungary in 1898 to prohibit the importation of American fruit and living plants (Klassen 1989). This crisis in the USA led to the passage in 1905 of federal legislation on quarantine and the regulation of interstate shipments (Plant Quarantine Act) (Womach 2005).

Indeed, now many countries have legislation on: (1) prevention of the introduction of new pests from foreign countries, (2) prevention of the spread of established pests within the country or state, and (3) enforcement of the application of control measures against exotic pests to prevent their introduction and establishment, eradicate their outbreaks, retard their advance or prevent damage by them. In some countries the law allows people, who wish to organize a programme against a pest, to hold a referendum. If the referendum passes by a certain margin (usually 67% in US counties), then all parties at interest must cooperate in the venture (Boll Weevil Eradication Law 1992; Grefenstette et al. 2009; Ervin and Frisvold 2016).

The programme to eradicate the citrus canker disease in Florida was initiated in 2000 but was hampered for 4 years because of insufficient legal authority. This pathogen is carried considerable distances on driving rain, and to achieve eradication the Division of Plant Industry decided to destroy all citrus trees within a radius of 578 m from an infected tree. Homeowners in urban areas, who did not understand the need for such drastic action, felt that their rights were violated by workers who, as part of the eradication programme, entered residential yards and destroyed citrus trees. Thus, the Broward County Circuit Court ruled that programme employees must have a separate court-issued warrant to enter each privately-owned property. The need to apply for tens of thousands of warrants prompted the Florida Department of Agriculture and Consumer Services to appeal this ruling; in 2004 the Florida Supreme Court overturned it. Nevertheless, as a result of all these delays, during which three major hurricanes traversed infected areas, the disease was spread widely, and the mandatory eradication programme had to be abandoned in January 2006 (Centner and Ferreira 2012).

1.6. Apathy, Outrage, and Area-Wide Integrated Pest Management

The strategy of eradication emerged just over a century ago as the brainchild of C. H. Fernald of the University of Massachusetts, USA. Under Fernald's leadership, Massachusetts attempted to eradicate an introduced pest, the gypsy moth, in an 11-year campaign from 1890 to 1901. Initially, the primary eradicator was Paris green, but this insecticide, of only modest efficacy and phytotoxicity, had to be abandoned because of adverse public reaction. Forbush and Fernald (1896) noted:

Considerable opposition to the use of Paris green for spraying was manifested by many people living in the infested towns. A mass-meeting of opponents of the spraying was held in Medford. One citizen, who attempted to cut the hose attached to one of the spraying tanks, and threatened with violence the employees of the Board who had entered upon his land, was arrested and fined. Others neutralized the effects of the spraying by turning the garden hose upon trees and shrubs that had been sprayed, and washing off the solution. The opposition to the spraying affected the results of the work unfavourably to a considerable extent.

Clearly, apathy by many members of the public had turned into outrage.

If not concerned primarily with the economic dimension of the pest problem, stakeholders tend to be highly concerned with ecological, environmental, social, and human-health implications of area-wide programmes (Rabb 1972; Dreistadt 1983; Scribner 1983; Myers et al. 1998). Therefore, leaders of AW-IPM programmes need to be very sensitive to the perceptions and attitudes of the public toward certain programme operations (Dyck, Regidor Fernández et al., this volume). Often, eradication efforts must be conducted by the ground rules of the urban, rather than rural, setting. In programmes to eradicate outbreaks of the Mediterranean fruit fly in California and Florida, members of the urban public strongly protested against the aerial malathion bait-spray applications (Scribner 1989), even though the same insecticide was used without dissent for mosquito abatement. On the other hand, the same public has usually applauded the release of sexually sterile male flies.

As explained by Sandman (1987), the public is usually apathetic towards technological programmes. However, certain factors inherent in programmes, and in the manner in which they are managed, can precipitate an almost irreversible shift in the public's attitude from apathy to outrage. A sense of outrage can be evoked by involuntary exposure to pesticide residues, imposed levies of fees, quarantines, right of trespass, unfair and inequitable sharing of risks, costs and benefits, temporary loss of control of one's property or field operations, the perception that endangered species may be harmed, etc. Starr (1985) asserted that:

Public acceptance of risk is more dependent on public confidence in risk management than on the quantitative estimates of risk consequences, probabilities and magnitudes.

He noted that, when a zoo wishes to acquire a tiger, the public does not demand a refined assessment of the risk that the tiger might escape and kill someone. Instead, the public wants assurance that the zookeeper can be trusted to prevent the tiger from escaping, and that, if the tiger should escape, the zoo is fully prepared to implement an emergency plan to meet this contingency. Similarly, the public's confidence in the management of an area-wide programme is of paramount importance.

In each area-wide programme, a special effort must be made to anticipate and identify those factors that may be emotionally upsetting to various stakeholders, and take pre-emptive actions to avoid or mitigate adverse reactions. Public officials must be kept apprised, public education materials produced (FAO/IAEA 2017), fora must be created for effective two-way communication with the public, surrogates of the public must be included in oversight and decision-making processes, and referenda may have to be conducted to secure support and funding for the programme (Batra and Klassen 1987; Klassen 1989; Dyck, Regidor Fernández et al., this volume).

1.7. Invasive Pests, Global Trade, and Area-Wide Integrated Pest Management

The rapid globalization of trade in agricultural products, and increasing tourism, have dramatically increased the spread of invasive harmful organisms (Klassen et al. 2002; Hendrichs, Enkerlin et al., this volume). We have entered an era of an unprecedented level of travel by exotic invasive organisms. Native flora and fauna on islands are sustaining great harm from non-indigenous invasive organisms, and major pests are becoming established with increasing frequency on all continents, except Antarctica.

For about a century many countries relied on the inspection of arriving cargo and passengers at the port of entry as the primary exclusion strategy. However, the volume of arriving cargo is doubling every 5 or 6 years (Zadig 1999), and it is not possible to increase similarly the human and other resources devoted to inspection at ports of entry. Clearly exclusion at the port of entry is no longer sufficient to protect plant resources, even though a number of emerging technologies are likely to facilitate safeguarding activities (Batkin 1999). Thus, to stem the influx of exotic pests into the USA, the National Plant Board asserted that the most important change needed in the US safeguarding system is to shift primary reliance from exclusion at the port of entry to offshore actions, i.e. pest-risk mitigation in the areas of production, certification at the point of origin, and pre-clearance at the port of export (NPB 1999).

An important approach to offshore risk mitigation is the creation of pest free areas. Indeed, countries that export raw agricultural commodities can effectively remove the threat of exotic pests to the importing country by creating and maintaining pest free areas (Rohwer 1992; Malavasi et al. 1994; Dalal et al. 2017; Enkerlin, this volume; Hendrichs, Vreysen et al., this volume). A pest free area is an area in which a specific pest does not occur as demonstrated by scientific evidence and in which, where appropriate, this condition is being officially maintained (FAO 2019). There are two kinds of pest free areas: (1) pest free zones — large geographic areas, including entire countries such as Chile, Japan or New Zealand — that are certified free of tropical fruit flies of economic importance, and (2) pest free production fields or areas that require demonstration of non-host-status or the demonstrated suppression of quarantine pests to non-detectable levels. In addition, there are low-prevalence areas that are established by means of a systems approach through the application of a series of preharvest and postharvest suppression and mitigating measures.

According to Griffin (2000), both the International Plant Protection Convention (IPPC) and the World Trade Organization (WTO) Agreement on Sanitary and Phytosanitary Measures (Devorshak 2007):

... are structured to accept and encourage area-wide pest management as a tool for promoting safe trade and contributing as much as possible to the complementary goals of food security and economic security for all countries.

The first US-recognized pest free area was established in 1988 in Sonora, Mexico (SARH/DGSV-USDA/APHIS 1990), and since then Mexico has been ridding large additional sections of its territory of all fruit fly species of economic importance (CNCMF 2002). The Mexican states of Baja California, Chihuahua, and Sonora have been freed of all economically important species of fruit flies. Citrus, stone fruits, apples, and vegetables are being exported from these states without any suppression or postharvest treatment. In other parts of Mexico, low-prevalence fruit fly areas are being established by means of a systems approach (Reyes F. et al. 2000; Enkerlin, this volume; Hendrichs, Vreysen et al., this volume). Chile rid the entire country of the invasive Mediterranean fruit fly by 1995 (SAG 1995), and since then large volumes of Chilean fruits have been exported to the USA and other markets without the need for any quarantine treatments. Also, other countries have created fruit fly-free areas (Rendón and Enkerlin 2021; Enkerlin, this volume).

Other examples of successfully preventing the establishment of invasive insect pests are the eradication of outbreaks of the European grapevine moth *L. botrana* in California (Simmons et al. 2021), the red palm weevil *R. ferrugineus* in the Canary Islands (Fajardo et al. 2021), the painted apple moth *Teia anartoides* Walker in New Zealand, and the cactus moth *Cactoblastis cactorum* (Berg) in Mexico (Hendrichs, Enkerlin et al., this volume; Simmons et al., this volume).

An area of low pest prevalence is an area (whether the entire country, part of a country, or all or parts of several countries), identified as such by the competent authorities, in which a specific pest occurs at low levels, and which is subject to effective surveillance, suppression or eradication measures (FAO 2019; Hendrichs, Vreysen et al., this volume). Requirements to establish low-prevalence areas include a sensitive detection programme, suppression of the quarantine-significant pest to non-detectable-levels, strict sanitation and control of the fields, and safeguards to prevent infestation during packing and transit to the port of export (Riherd 1993; Simpson 1993; Malavasi et al. 1994; Riherd et al. 1994).

Florida is able to export grapefruit to Japan by creating pest free grapefruit groves in about 22 counties. Regulatory experts from Japan inspect the entire process of production, packing, and transit. Official protocols for pest free fields can be found in Gomez (1999). Similarly, fruit groves free of the South American cucurbit fruit fly *Anastrepha grandis* (Macquart) have been created in Mossoro, Brazil, and Guayaquil, Ecuador, through demonstration of non-host status under appropriate crop management (Malavasi et al. 1994).

The concept of low prevalence, using bait sprays and the SIT, was pioneered during the early 1960s against the Mexican fruit fly *Anastrepha ludens* (Loew) along the Mexico-USA border (Knippling 1979). Also, in the early 1960s, the Citrus Marketing Board of Israel developed a bait-spray-based area-wide programme

against the Mediterranean fruit fly that has been able to meet the certified quarantine security requirements of fruit-importing countries (Cohen and Cohen 1967).

A significant development has been a preventive approach involving the continuous area-wide release of sexually sterile male Mediterranean fruit flies in the Los Angeles Basin (Dowell et al. 2000; USDA/APHIS 2004; Enkerlin, this volume), and around high-risk ports in southern Florida, to prevent Mediterranean fruit fly establishment resulting from recurrent introductions in ports of entry (USDA/APHIS 1998; Hendrichs, Enkerlin et al., this volume).

1.8. Area-Wide Integrated Pest Management – Future Directions

Despite the fact that AW-IPM programmes are technically complex and managerially challenging (Vreysen et al. 2007), this strategic approach bears great promise for the future. Over the last two decades, interest in this strategy has been mounting, especially considering the substantial benefits obtained when area-wide programmes are properly executed. However, it should be emphasized that these programmes require long-term planning, i.e. from stakeholder commitment to feasibility studies, pilot trials, and pre-operational and operational phases (Vreysen et al. 2007; Bouyer et al. 2020; Vreysen et al. 2021; Vreysen, this volume); they also need close collaboration among researchers, farmers, extension workers, community leaders, local and regional governments, and the general public (Liu and Yan 1998).

AW-IPM is probably most appropriate for high-value crops, key livestock pests, and major human-disease vectors; it is also appropriate for those rural areas where the number of farmers is small, agroecological heterogeneity is low, and only a few key pests need to be addressed (Hendrichs et al. 2007). However, the approach may not be applicable to very mobile or migratory insects or to all animal- or human-disease vectors.

A major obstacle to the successful implementation of AW-IPM is the lack of trained extension workers -- that may lead to even increased insecticide inputs. In Asia, many state-employed extension workers are also involved in marketing insecticides, and their advice to farmers becomes biased against IPM approaches (Koul and Cuperus 2008; Heong et al. 2021). Better education of farmers and the general public will remain key to better implementation of AW-IPM programmes, and also to better understand economic trade-offs among treatment alternatives.

Another major limitation in implementing AW-IPM, as advocated by E. F. Knipling, is the lack of sufficient knowledge about the spatial and temporal dynamics of the target pest insects (Levandowsky and White 1977). Recent advances in landscape ecology (Pickett and Cadenasso 1995) and ecological modelling (Carrière et al. 2006) can help explore the temporal and spatial dynamics of the pest insect. In addition, landscape genetics, an innovative emerging approach (that associates population genetics of the target insect with spatial tools) enables an understanding of how geographic and environmental features structure genetic variations at the population level (Bakhoum et al. 2021). This approach not only increases ecological knowledge but also explains spatial genetic patterns, isolation by distance, genetic boundaries to gene flow, etc. (Manel et al. 2003). All of these new tools and approaches can facilitate conceptualizing AW-IPM programmes.

Improved lifestyles and higher gross domestic products will result in increased aversion to insecticide use, and consumers will be increasingly prepared to pay a higher price for clean biological commodities. Major opportunities to promote AW-IPM will be closely linked with consumers' demand for food safety, and with increased support for research, extension services, and legislation (Koul and Cuperus 2008).

2. BASIC ELEMENTS OF THE SIT

The SIT is an autocidal genetic control tactic that interferes with the reproductive potential of a target pest population. It can be considered as a form of birth control imposed on an insect pest population to reduce its numbers. The SIT harnesses the sex drive of insects. According to the International Plant Protection Convention (IPPC) (FAO 2019), a sterile insect is defined as:

An insect that, as a result of a specific treatment, is unable to reproduce.

and the SIT is defined as:

Method of pest control using area-wide inundative release of sterile insects to reduce reproduction in a field population of the same species.

The SIT requires the rearing of large numbers of the target pest species, exposing them to ionizing radiation to induce sexual sterility, and releasing them into the target pest population on an area-wide basis. A derivative of the SIT avoids the need to mass-rear the target insect pest species by attracting individuals of the wild populations to a chemosterilant, e.g. Mediterranean fruit fly (Navarro-Llopis et al. 2004) and *Glossina* spp. tsetse flies (Hargrove and Langley 1990; Langley 1999). The latter approach, however, has only been used on an experimental basis. Thus, treated insects are prevented from reproducing; they act as biological agents that nullify the biological potential of untreated individuals with which they mate. Both kinds of SIT are effective only against pest species that reproduce sexually (Lance and McInnis, this volume).

2.1. *How Sterile Males Suppress Populations: Numbers Game*

Knipling (1968) recognized that the level of suppression required to stabilize the density of a population depends on its intrinsic rate of increase (Table 2).

Knipling (1968) estimated that an overwintering screwworm population typically increases approximately five-fold for the next two or three generations. For example, if in an area of 100 000 km² 1 000 000 screwworms overwinter, this population will increase to 5 000 000, 25 000 000, and 125 000 000 in the F₁, F₂, and F₃ generations, respectively. To calculate the consequences of releasing sterile screwworms into a population of fertile screwworms, Knipling listed the various types of matings, calculated the frequency of each type of mating, and assigned ten progeny to each mating of an untreated female (UF) with an untreated male (UM). When both sterile males (SM) and sterile females (SF) are released, there are four types of matings possible. Thus the wild population has 500 000 untreated males [UM] and 500 000

untreated females [UF], and 4 500 000 sterile males [SM] and 4 500 000 sterile females [SF] are released. The frequencies of the various matings, and the number of progeny produced, are shown in Table 3. Using this method, Knipling calculated the trend of this hypothetical screwworm population (Table 4).

Table 2. Rates of mortality and survival required to maintain a stable pest population

Intrinsic rate of increase between generations	Number of progeny per female	Number (fraction) that must survive to prevent population from declining.	To prevent population increase		
			Number (fraction) that must die	Percentage that must die	Percentage that may survive
2-fold	4	2 (1/2)	2 (1/2)	50	50
3-fold	6	2 (1/3)	4 (2/3)	67	33
4-fold	8	2 (1/4)	6 (3/4)	75	25
5-fold	10	2 (1/5)	8 (4/5)	80	20
10-fold	20	2 (1/10)	18 (9/10)	90	10
20-fold	40	2 (1/20)	38 (19/20)	95	5

Knipling realized that, to obtain a reduction of the wild population, the degree of sterility introduced into the wild population by releasing sterile males must be sufficiently high to overcome the rate of increase (reproductive success) of the wild females. Knipling (1968) stated:

If we assume that a given insect has a net capacity to increase five-fold each generation, the ratio of fully competitive sterile to fertile insects will have to be 4:1 to keep the natural population stable. Theoretically, an initial ratio as low as five sterile to one fertile will be adequate to start a downward trend in the natural population when the net increase rate is only five-fold. Actually, starting with this lower overflooding ratio, theoretical elimination of the population will be achieved with fewer insects than will be required with a 9:1 ratio. However, in actual practice, the density of insects will vary in different parts of the environment. Moreover the distribution of sterile insects will never be uniform. Therefore, in control operations, the initial ratio should be sufficiently high to be certain that an overall reduction in the population will occur in all parts of the environment from the start. In some instances, the sterility procedures might reduce the vigour and competitiveness of the organism. Allowance must be made for this factor.

As shown in Table 4, the ratio of sterile to fertile insects increases asymptotically as the density of the wild population declines to low levels. Thus, to take advantage of the tremendous power of the SIT against sparse populations of pests, Knipling advocated that the release of sterile insects should be initiated when the wild population was at a seasonal low or immediately after its decimation by adverse weather events, such as freezes and hurricanes. In addition, Knipling (1966, 1979, 1992a) designed pest management systems in which insecticides, biocontrol agents, etc., were used to reduce the density of the target population to a level at which the SIT could manifest its great suppressive power (Fig. 2).

Table 3. Method of calculating frequencies of various types of matings and resultant progeny when sterile males and females are released into a population of untreated males and females (text provides details)

Type of mating	Number of matings	Number of progeny/ mating	Number of progeny
UF X UM	$\frac{500\,000 \times 500\,000}{5\,000\,000} = 50\,000$	10	500 000
UF X SM	$\frac{500\,000 \times 4\,500\,000}{5\,000\,000} = 450\,000$	0	0
SF X UM	$\frac{4\,500\,000 \times 500\,000}{5\,000\,000} = 450\,000$	0	0
SF X SM	$\frac{4\,500\,000 \times 4\,500\,000}{5\,000\,000} = 4\,050\,000$	0	0

Table 4. Trend of an insect population subjected to sterile insect releases when the normal increase rate is five-fold

Generation	Uncontrolled natural population (5 X increase rate)	Controlled population		Ratio of sterile to fertile
		Natural population	Sterile population	
1	1 000 000	1 000 000	9 000 000	9:1
2	5 000 000	500 000	9 000 000	18:1
3	25 000 000	131 625	9 000 000	68:1
4	125 000 000	9535	9 000 000	942:1
5	625 000 000	50	9 000 000	180 000:1

3. USING THE SIT TO IMPLEMENT PEST MANAGEMENT STRATEGIES

The major pest management strategic options or objectives are: (1) suppression, (2) eradication of well-established pest populations, (3) containment (exclusion) and (4) prevention of invasive pest establishment (Hendrichs, Vreysen et al., this volume).

The SIT is a pest-specific tactic that can play a role in implementing all of these area-wide strategies. In this sense, a “tactic” is a method for detecting, monitoring or controlling a pest. A “system” is an assemblage of tactics that are applied simultaneously or sequentially so that the effects of individual tactics on the pest population are either additive or mutually potentiating, and counter-productive

(negative) interactions are avoided or minimized. A pest management “strategy” is a broad overall plan that aims to achieve the specific strategic objective. The merits of a pest management strategy may be judged by its short- and long-term ecological, economic, sociological and political impacts (Rabb 1972; Enkerlin 2003; Enkerlin et al. 2003; Hendrichs, Vreysen et al., this volume).

Figure 2. Schematic representation of the sequential use of methods of suppression that efficiently decimate a pest population followed by using the SIT, which becomes progressively more suppressive as the population declines. The term “efficiency” refers to the ease in further suppressing the population, and not to the cost of eliminating an individual pest (cost per kill). (Figure adapted from Feldmann and Hendrichs 2001.)

To implement a strategy effectively and efficiently, each control tactic has characteristics that need to be considered in the design of a system. The relationship of the density of the pest to the efficiency of the control tactic is of paramount importance. Some tactics (such as insecticide spraying) are most useful only against dense and moderately dense populations, while others, such as the SIT and sex pheromones, are effective only against sparse populations. Also, ecological selectivity is important to avoid the destruction of natural enemies needed to prevent the resurgence of the pest population following a control operation, and to prevent environmental damage. Most conventional insecticides are non-selective, whereas the SIT and other genetic techniques, pheromones, pest-resistant crop varieties, certain insect pathogens, parasitoids and predators, and certain artificial and naturally occurring attractants, are highly selective tactics. Light traps, some attractant baits, “general” predators, parasitoids and pathogens, and certain insecticides, are only moderately selective.

3.1. *Principles of Designing Pest Management Systems*

The design of a pest management system requires information on the selectivity and efficiency of available tactics. When the suppression of populations to a very low level is required, methods that are effective against high populations, and methods that are effective against low populations, should be integrated so that the actions of the former potentiate those of the latter (Fig. 2) (Mangan and Bouyer, this volume). For example, the use of a selective insecticide potentiates the SIT by increasing the sterile:fertile ratio. Moreover, the release of both a pest-specific parasitoid and sterile insects is likely to be mutually potentiating (Simmons et al., this volume). When the economic threshold of the pest is moderately high, several tactics that have additive effects against dense populations may be combined to give much more reliable suppression than from a single method. Knipling (1979) discussed these principles thoroughly (Hendrichs, Vreysen et al., this volume).

3.2. *SIT and Local Suppression of Portions of Populations*

Since 1981, the SIT has been used commercially to suppress locally the onion fly *Delia antiqua* (Meigen) on an area of ca. 10 000 ha in The Netherlands (Loosjes 2000; Everaarts 2016). The flies are reared year-round and stockpiled for release during the onion-growing season. To protect against immigrant flies, sterile flies are constantly maintained in the fields. Individual farmers contract for the SIT independently of their neighbours, many of whom use chemical control. Free-riders (growers in the release area who benefit but do not pay) weaken this local suppression programme, which has only been able to expand gradually over the years to 40% of the onion-producing area. In addition, further efficiency is lost because the onion fields receiving sterile flies do not form a contiguous block (Everaarts 2016).

3.3. *SIT and “Total” Population Suppression*

The SIT can be applied for population suppression rather than eradication (Hendrichs, Vreysen et al., this volume). As a sequel to the 1993/1995 Oslo Accords, AW-IPM programmes using the SIT against the Mediterranean fruit fly were established in some fruit-producing areas of Israel, Jordan, and the Territories under the Jurisdiction of the Palestinian Authority. Enkerlin and Mumford (1997) concluded that, over a 9-year time frame, the net economic benefits from this SIT suppression programme would be greater than from an SIT-based eradication programme, or from an area-wide bait-spray programme. Assuming that sufficient sterile flies can be purchased from existing rearing facilities, SIT suppression is profitable beginning in the first year. In contrast, eradication would have a payback period of 4 years, because of the need for an upfront investment in a rearing facility, high quarantine costs, and the need for more intensive monitoring. Similar SIT suppression programmes are ongoing in the Western Cape of South Africa (Venter et al. 2021), and Valencia, Spain, and Neretva, Croatia, in southern Europe (Bjeliš et al. 2016; Enkerlin, this volume).

The SIT suppression programme against the codling moth in Canada substantially reduced populations of the pest and also the number of insecticidal sprays. Similar success against the false codling moth in South Africa was achieved (Bloem et al. 2001; Boersma 2021; Nelson et al. 2021; Simmons et al., this volume).

3.4. *SIT and Eradication of Well-Established Populations*

Eradication of a pest population is the sustainable removal of every individual of the pest species in an area surrounded by natural or man-made barriers sufficiently effective to prevent reinvasion except through the intervention of man (Newsom 1978; Hendrichs, Vreysen et al., this volume). Although the eradication of a population may not endure forever, the elimination of a pest from a defined area, followed soon after by reinvasion, is not considered to be eradication.

Through an unrelenting effort from 1957 to 2000, the SIT, as part of an AW-IPM strategy, was used to eradicate the New World screwworm in its native range in the southern USA, Mexico, and Central America (Vargas-Terán et al., this volume). An area-wide programme was essential because the screwworm infested wild as well as domestic animals. Similarly, the SIT was an important component of the AW programmes that eradicated the pink bollworm in southern USA and northern Mexico (Staten and Walters 2021), as well as the Mediterranean fruit fly in areas of Argentina, Chile, USA, and Mexico, and the melon fly *Zeugodacus cucurbitae* (Coquillett) in the Okinawa archipelago of Japan (Kuba et al. 1996; Enkerlin, this volume).

The SIT was used as part of an integrated approach to eradicate tsetse populations in Nigeria and Burkina Faso in West Africa, but as the approach was not area-wide, the eradication status could not be sustained (Cuisance et al. 1986; Oladunmade et al. 1990). An AW-IPM approach that included an SIT component was used to permanently remove a tsetse population from the Island of Unguja, Zanzibar (Vreysen et al. 2000). A similar approach has been used in the last decade in the Niayes area of Senegal (Vreysen et al. 2021). However, the goal of creating a number of tsetse-free zones in Africa (Feldmann et al., this volume) will require significant improvements in mass-rearing technology, an in-depth knowledge of the behaviour of released and wild flies, and a careful consideration of the design of pest suppression systems. In addition, besides technical concerns, considerable development of programme management, and political and financial support, is essential for tsetse eradication programmes (Vreysen et al. 2007; Dyck, Reyes Flores et al., this volume).

3.5. *SIT and Containment and Prevention of Pest Populations*

As already noted, the SIT and quarantines are major tactics in systems used to implement the containment (exclusion) and the prevention strategies. Examples of the containment strategy include Panama, where a barrier of sterile New World screwworm flies is maintained to contain the screwworm at the Panama-Columbia border (Vargas-Terán et al., this volume), and a barrier of sterile Mediterranean fruit

flies is maintained to exclude this pest from Mexico (Villaseñor et al. 2000; Enkerlin et al. 2017).

For the prevention strategy, examples include releases of sterile pink bollworms to prevent the pest from establishing on cotton in California's San Joaquin Valley (Staten et al. 1993), preventive releases of the male-only strain of the Mediterranean fruit fly over the Los Angeles Basin in California and major metropolitan areas in Florida, and releases of sterile Mexican fruit flies to prevent immigrant flies from crossing over from Mexico into the lower Rio Grande Valley of Texas (Hendrichs, Enkerlin et al., this volume). The SIT and quarantine stations were used, initially, to prevent the spread of the New World screwworm throughout Africa, and then to eradicate it in the coastal region of Libya (FAO 1992; Lindquist et al. 1993).

3.6. Lessons Learned from Using the SIT to Achieve AW-IPM

In most AW-IPM programmes that integrate the SIT, the goal of containment, suppression or eradication has been threatened by the existence of untreated or inadequately treated refugia or microhabitats unusually favourable for the pest, i.e. "hot spots", from which recruits could come to reinfest cleared areas. In the New World screwworm campaigns, some hot spots were the ranches where livestock wounds were not being treated. Breaches of quarantine lines were very troublesome. The overarching lesson was that absolutely all segments of the population, i.e. the total population, must be suppressed.

More specifically, with respect to the SIT, the following conclusions can be drawn:

- An extended lag period may occur between the initiation of the release of sterile insects and a noticeable effect on the density of the pest. This is inevitable as the wild population will include many already mated females, sexually immature females, pupae, larvae, and eggs. The released sterile males can only prevent the reproduction of unmated females. As the immature forms mature, they become subject to the impact of the sterile flies. However, the time of one generation will pass before the progeny of previously mated females can be affected. Consequently, the release ratio must be sustained over a period of time equivalent to several generations.
- If a high proportion of the wild population is present as eggs and larvae when the release of sterile insects begins, then the wild population will even increase for a time in spite of the releases of sterile insects. However, this period can be shortened if an insecticide application (or any other control tactic that is effective against high-density wild populations) is made to kill females previously mated to wild males.
- Severe weather events, such as periods of cold weather, may reduce the density of the pest population, and also synchronize the development of the population by halting reproduction and killing exposed life stages. In this way the generation overlap may be eliminated.
- An influx of pests into the target area, even a few mated females, will greatly prolong an eradication programme. Great care must be taken not to underestimate the flight range of the pest. For most pest insects one can assume

that an immigrant female will produce 10–20 adult progeny in a small area. However, the progeny may disperse and be thinly distributed, and thus vulnerable to the SIT.

Krafsur (1998) asserted that the SIT is an underutilized and widely misunderstood technology (Whitten and Mahon, this volume). He refuted several misconceptions concerning the evolutionary responses to the SIT, the role of weather in AW-IPM programmes using the SIT, and the occurrence of undetected populations where eradication had been claimed prematurely.

4. REQUIREMENTS AND RESEARCH NEEDED TO ACHIEVE AW-IPM

The requirements for implementing AW-IPM are complex and sophisticated. Of paramount importance is the recognition that AW-IPM must be preventive, offensive, and planned on a multi-year basis (Lindquist 2001; Dyck, Reyes Flores et al., this volume). Requirements include the following (Vreysen et al. 2007):

- The biology, ecology, distribution, population dynamics, etc. of the pest in the target area must be thoroughly understood.
- There must be political support, as well as strong stakeholder cohesiveness and commitment to the campaign (Dyck, Regidor Fernández et al., this volume).
- Adequate funding needs to be available to cover all aspects of the programme.
- An effective and knowledgeable programme leader, supported by an effective organization, preferably independent from the day-to-day government bureaucracy, is needed (Vreysen et al. 2021; Dyck, Reyes Flores et al., this volume). This team must formulate and continuously update both technical and business plans.
- Staff with the proper qualifications, expertise and experience need to be hired for the AW-IPM programme; they should have no other job.
- Relevant monitoring data need to be collected before, during, and after the programme for the managers to be able to make informed decisions. Data need to be analysed properly, and in short intervals, to allow mitigating actions in case of a problem.
- There must be a system of programme review, including by external and independent experts.
- Legal authority is required to execute all aspects of the programme, e.g. conduct operations on private properties, and operate quarantines (section 1.5.).
- Since losses caused by emerging pest situations rapidly mount with the passage of time, the speed required to organize and implement a programme is critically important, especially when it is financed in part by an industry under economic stress (Kruger 2021).

Applied research and methods-development support is essential to backstop ongoing AW-IPM programmes. In addition, there are a number of general research needs that require more attention to further increase applicability, effectiveness, and efficiency of area-wide programmes:

- Apply the integration of species distribution modelling and landscape genetics to facilitate and optimize the management of target populations (Bakhoun et al. 2021).
- Further improve the use of Geographic Information Systems (GIS), Remote Sensing (RS), mathematical modelling, and data bases to facilitate decision-making in operational programmes, and to better manage large volumes of data sets (Barclay, this volume; Bouyer et al., this volume).
- Study the detection and sampling of very sparse populations. Disagreement (on the interpretation of sample data) enveloped area-wide programmes against the boll weevil in an especially bitter and costly controversy (NRC 1975). Similar difficulties have been encountered in programmes against tsetse flies *Glossina* spp., screwworms, the gypsy moth, and fruit flies (McInnis et al. 2017; Shelly et al. 2017).
- Automate the collection of field data, resulting in substantial cost savings in AW-IPM programmes, e.g. insect traps (baited with a species-specific attractant) that send a radio signal when a catch is made (Schellhorn and Jones 2021).
- Identify sociological barriers, and opportunities to surmount them, in implementing AW-IPM programmes (Kruger 2021; Mankad et al. 2021).
- Encourage the investigation of socio-economic impact to assess benefit/cost ratios and other economic indicators of AW-IPM programmes (Bouyer et al. 2014; Singerman et al. 2017).
- Encourage the implementation of environmental-impact studies to accompany AW-IPM programmes to assess the impact of the programme on the ecosystem (USDA/APHIS 2015).

5. KNIPLING'S IMPERATIVE

When the World Food Prize was awarded to E. F. Knipling and R. C. Bushland, Knipling (1992b) stated:

If major advances are to be made in coping with most of the major arthropod pest problems, then the tactics and strategies for managing such insects, ticks and mites must change. They must change from the current, limited scale, reactive, broad-spectrum measures to preventive measures that are target-pest specific and rigidly applied on an area-wide basis.

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