CHAPTER 6.1.

STRATEGIC OPTIONS IN USING STERILE INSECTS FOR AREA-WIDE INTEGRATED PEST MANAGEMENT

J. HENDRICHs, M. J. B. VREYSEN, W. R. ENKERLIN AND
J. P. CAYOL

*Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture,
International Atomic Energy Agency, A-1400 Vienna, Austria
Email: jorgehendrichs@gmail.com*

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V. A. Dyck, J. Hendrichs and A. S. Robinson (eds.), Sterile Insect Technique. Principles and Practice in Area-Wide Integrated Pest Management. Second Edition.

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SUMMARY

The four strategic options, “suppression”, “eradication”, “containment”, and “prevention”, in which the sterile insect technique (SIT) can be deployed as part of area-wide integrated pest management (AW-IPM) programmes, are defined and described in relation to the contexts in which they are applied against non-native invasive or naturally occurring major insect pests. Advantages and disadvantages of these strategic options are analysed, and examples of successful programmes provided. Considerations that affect decision-making in relation to the selection of a strategic option, e.g. pest biology, whether the pest is a disease vector or agricultural pest, the pest’s status in the target area, and the target market for the produced crop or livestock commodities, are reviewed and discussed in terms of a phased conditional approach to programme planning, preparation, and implementation. If an option is changed during implementation of the SIT, unrealistic expectations often result, leading to high political costs and the discrediting of the technology. Before embarking on an AW-IPM programme with an SIT component, the choice of a strategic option needs to be assessed carefully, and preparations should be supported by considerable baseline data, technical and economic feasibility assessments, and detailed planning.

1. INTRODUCTION

E. F. Knipling developed a theoretical model of the sterile insect technique (SIT) in the early 1940s (Klassen 2003; Klassen et al., this volume), but it was not until 1954 that the technique was successfully demonstrated with the elimination of the New World screwworm *Cochliomyia hominivorax* (Coquerel) from the island of Curaçao following continuous releases of sterile insects for 6 months (Baumhover et al. 1955). Since then, in line with Knipling’s basic model, the SIT has on numerous occasions been confirmed in field programmes as an effective and very powerful method of insect pest management. In spite of this history of successful SIT applications, the existence of puzzling terminology, conflicting definitions, and inappropriate utilization of concepts/strategies continue to cause confusion.

Baumhover et al. (1955) referred to the strategy applied in the Curaçao experiment as screwworm “control”. Both Knipling (1955) and Lindquist (1955) proposed “control” and “eradication” as possible strategic options in using the SIT (Lindquist et al. 1990). While Lindquist (1955) used the term “control” to refer to the general use of the SIT, Knipling (1969) defined for the first time “eradication” and “suppression” as the two major strategic options. Knipling suggested that the terms “suppression” and “management” could be used interchangeably (Knipling 1979). During the decade that the screwworm programme in the south-west of the USA was maintaining a “containment” buffer along the Mexican border, he explained that it was erroneously referred to as an “eradication” programme, and argued that, since long-range migrating flies reinvaded the area every year, the term eradication was misleading in this context when compared with the Curaçao and Florida programmes.

Referring to programmes such as the one against the Mexican fruit fly *Anastrepha ludens* (Loew) in southern California, Knipling (1979) described “prevention” as another possible strategic use of the SIT:

As more experience is gained in the use of sterile insects for insect suppression and with greater confidence in the value of this technique, releasing sterile insects routinely in certain areas may be more expedient to prevent establishment of major pests than eliminating them after they become established.

Since 1996, this principle has been applied in the Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) Preventive Release Program in the Los Angeles Basin, California, USA (Dowell et al. 2000) (section 4.1.).

In 2005, the International Plant Protection Convention (IPPC) adopted the revised International Standard of Phytosanitary Measures (ISPM) 3, “*Guidelines for the export, shipment, import and release of biological control agents and other beneficial organisms*”; for the first time sterile insects were included among beneficial organisms (FAO 2017a). The guidelines promote the safe use of biological control agents and beneficial organisms such as sterile insects, but do not involve special regulatory requirements such as those needed for the release of genetically modified insects. The inclusion of the SIT in the revision of ISPM 3 was a consequence of the growing acceptance of its application as part of an area-wide integrated pest management (AW-IPM) approach against key non-native or naturally occurring insect pests. This change in the mindset of decision-makers and stakeholders is driven mainly by the demands of large retailers (who are responding to consumer requests for cleaner food and a safer environment). It is also driven by the need for alternatives to the indiscriminate use of insecticides, and by the increase in globalization and concomitant international agricultural trade, which requires enforcement, through national animal and plant protection organizations, of the Agreement on the Application of Sanitary and Phytosanitary Measures (the “SPS Agreement”) under the World Trade Organization (WTO 1994).

The programmes applying the SIT tend to become grander in scale and scope, thereby increasing their commercial impact and simultaneously reducing their relative operational costs, mainly due to economies of scale and improvements in the technology of rearing and releasing large numbers of sterile insects (Hendrichs 2000). An extreme example of a very large programme is the Moscamed Mediterranean fruit fly containment effort in Guatemala and southern Mexico, which operates on an annual budget of ca. USD 30 million (data from 2003), (Enkerlin et al. 2015, 2017). Within such contexts and under these pressures, the authorities deciding on AW-IPM campaigns are facing crucial choices regarding the inclusion of the SIT, and which strategic option to apply. In fact, as noted by Klassen (2000), “the terms of reference and contingencies have a tremendous influence on the selection of strategies”, which then are “the real decision-makers”.

The objectives of this chapter are to review the terminologies, the main characteristics and strengths and weaknesses of the various strategic options where sterile insects can be used, and to propose definitions in accordance with international agreements. In addition, the chapter reviews briefly the phased conditional approach to programme implementation, and addresses important species and case-specific issues, e.g. biology of the target insect, buffers, release densities, topography, etc., that

require careful analysis before selecting one of the four strategic options under which to integrate the SIT into AW-IPM programmes.

2. FOUR STRATEGIC OPTIONS: DEFINITIONS AND DESCRIPTIONS

The Food and Agriculture Organization of the United Nations (FAO), through its IPPC, whose international phytosanitary standards are accepted by signatory countries under the SPS Agreement of the WTO, defines “control” of a given plant pest (FAO 2017b) as encompassing:

Suppression, containment or eradication of a pest population.

These three strategies would apply to most AW-IPM programmes with an SIT component, including those against insect pests of medical and veterinary importance. However, the most efficient and cost-effective “control” programme is the one that aims at *preventing* the entry of a pest (movement of a pest into an area where it is not yet present (FAO 2017b)) rather than at dedicating resources to suppress, eradicate or contain an *introduction* (the entry of a pest resulting in its establishment (FAO 2017b)) once it has occurred (Knipling 1979). On this basis, four strategic options, i.e. “suppression”, “eradication”, “containment”, and “prevention”, will be discussed.

2.1. *Suppression*

The FAO (2017b) defines suppression as:

The application of phytosanitary measures in an infested area to reduce pest populations.

Thus the main objective of a suppression programme is to maintain the pest population below an agreed and acceptable economic injury level and/or prevalence level. Until the early 1990s, the SIT was generally considered an appropriate technique for eradicating certain insect pests. This view largely resulted from the high visibility of the successful screwworm eradication programme in North and Central America (Baumhover 2002; Klassen et al., this volume), and the assumption that the SIT was too expensive to compete with other control methods for routine pest management. In recent years, however, suppression of a pest population is increasingly being viewed as a suitable strategy to apply the SIT as part of an AW-IPM approach for some pests of agricultural importance (Hendrichs et al. 2007) due to: (1) crucial improvements made in the rearing and release techniques for some key insect species, which have significantly improved the cost-effectiveness of SIT application (Caceres et al. 2004; FAO/IAEA 2017; Parker, Mamai et al., this volume), (2) increased restrictions imposed on the use of insecticides (Matteson 1995) and more stringent regulations on their residues, (3) increasing development of insecticide resistance in arthropods (Whalon et al. 2008), (4) increased intermingling of commercial production areas and human settlements, which complicates the routine use of insecticides, (5) increased customer health consciousness and the demand for low-residue or even “organic” products (Economist 2001; Greene et al. 2017), and (6) difficulties in maintaining effective quarantines to keep an area pest free (Mumford, this volume).

One major advantage of applying a suppression strategy is the significantly lower investment needed to monitor the pest population as compared with the more intensive monitoring required during and after an eradication campaign (Table 1). Moreover, the set-up and rigorous implementation of effective quarantines (which demand legislation and considerable investment) to protect a pest free area (FAO 1999) are not needed or demand less attention and resources when a suppression strategy is applied (Table 2). Another strength of the suppression strategy is the focus on environmental benefits compared with conventional control methods (Table 1). These trends have culminated in the implementation of suppression programmes using the SIT as an environment-friendly replacement for the use of insecticides (no longer disrupting pollination and the biological control of secondary pests) (Hendrichs et al. 1995; Enkerlin et al. 2003). This strategy has gained acceptance mainly for pest insects of phytosanitary importance, since a certain level of “crop damage” to agricultural commodities is usually acceptable. However, this concept has in general been considered less applicable to insect pests of veterinary, and particularly medical, importance. However, a suppression strategy against disease transmitting mosquitoes would be feasible, provided that only sterile males are released, without sexing errors, as the males are not the disease transmitting sex (Bourtzis et al. 2016).

It should be emphasized that implementing a suppression strategy in an area does not preclude exporting agricultural commodities from that area to countries that have a pest free status. Export markets that accept only pest free commodities can be accommodated within the context of a “systems approach” (FAO 2017c), whereby an effective preharvest suppression programme with an SIT component can be integrated with other efficient pest risk-mitigation measures (for example, postharvest treatments) to guarantee pest free agricultural products. This strategic approach is successfully applied, e.g. in the Arava Valley of Israel, where the use of greenhouses, as an additional risk-mitigation measure, has allowed the export of Mediterranean fruit fly-free vegetable commodities from this area to the USA (Cayol et al. 2004).

Whereas eradication aims at eliminating the last individual of a population in the target area, a suppression strategy can tolerate a certain residual pest population, and lead to the establishment of an “area of low pest prevalence” (FAO 2016b). Suppression can be achieved much more quickly than eradication, is less complex, resource demanding, and management intensive, and therefore less expensive in the initial years (Enkerlin and Mumford 1997; Mumford, this volume). Nevertheless, a suppression strategy requires continuing releases of sterile insects, often combined with other suppression measures, to maintain a low pest population level (Table 1). However, adopting a suppression or other strategy does not exclude eventually progressing towards an eradication strategy once low pest populations are maintained sustainably and new situations arise (Suckling et al. 2014; Staten and Walters 2021).

On the other hand, while the permanent application of a suppression strategy, including continuing releases of sterile insects, could be considered disadvantageous when compared with the sustainable elimination of a pest from an area, this permanent need for sterile insects could stimulate and promote investment in, and the commercialization of, the mass production of sterile insects (Enkerlin and Quinlan 2003) (Table 2). A similar demand has already resulted in a rapidly growing augmentative biological control industry (ANPB 2005; IBMA 2017).

Table 1. Strengths and weaknesses of the four strategic control options applied in AW-IPM programmes integrating the SIT, depending on the type of area

Control Strategy				
Suppression (infested area)	Eradication (infested area)	Containment (pest infested and pest free area)	Prevention (pest free area)	Eradication (introduction into pest free area)
Strengths				
Decreased pesticide use	Insecticide use eliminated eventually	Protection of neighbouring pest free areas	Proactive rather than reactive approach (risk mitigation)	Establishment of pest precluded (if action taken immediately)
Lower investment in long-term monitoring and in short-term capital and operational costs	Access to specific pest free export markets ¹ as well as to markets discriminating for low pesticide residues without pre-export treatment	Environmental and economic benefits for protected area	In case of introduction, effective sterile to wild insect ratios (low wild population density)	Much cheaper in medium and long term than having to "live with" new pest forever
No need for quarantine measures	Most activities and costs limited in time	Pest free area can be expanded gradually	No trade disruption in case of outbreak in release area	Infrastructure and experience gained can be applied against other invasive pests
Access to markets discriminating for low pesticide residues	Strengthened quarantine infrastructure also against other pests	Threat of further pest expansion helps to obtain public and political support for activities	Infrastructure for SIT is in place in case of other outbreaks in the region	Success in avoiding pest establishment promotes preparedness plans for other invasive pests
	Strong public and political support for disease vectors	Maintains export markets	Maintains export markets	Maintains export markets

¹ Only for agricultural pests, excluding insect pests of medical importance

Table 1. Continued

Control Strategy				
Suppression (infested area)	Eradication (infested area)	Containment (part infested and part pest free area)	Prevention (pest free area)	Eradication (introduction into pest free area)
Weaknesses				
Permanent control activities	High short-term investment	Cooperation between infested and non-infested areas	Investment while the targeted pest is not present (political aspect)	Species-specific preparedness needed (plan of action, SIT technology and sterile insect supply, etc.)
Post-harvest treatments required for export	Intensive public relations campaign	Intensive public relations campaign	Not all areas at high risk of introduction can be protected	Early detection and quarantine to delimit and isolate incursions
More active participation and better organization of grower associations needed	Long-term investment in permanent monitoring networks	Disruption of trade and free movement of commodities between infested and non-infested areas	Difficult to appreciate benefits of programmes that run for long time frames and thus susceptible to budget cuts when financial situation becomes difficult	Long-term investment in permanent monitoring networks
	Continuous rigorous quarantine set-up			In some situations, temporal disruption of trade.

While insecticide costs have been increasing rapidly following the removal of many older products from the market, and crop protection companies facing higher costs and steeper regulatory hurdles for launching new pesticide products (CropLife 2016), using sterile insects as part of a suppression strategy for some key fruit fly and moth pests has become cost-competitive with conventional or other population reduction methods (Pereira et al. 2013; Vreysen et al. 2016) (Table 3). Examples of suppression programmes are: Mediterranean fruit fly in Israel and Jordan (Bassi et al. 2007), Croatia (Bjelis et al. 2016), South Africa (Venter et al. 2021), and Valencia, Spain (Primo 2003); codling moth *Cydia pomonella* (L.) in British Columbia, Canada (Bloem et al. 1998; Nelson et al. 2021); false codling moth *Thaumatotibia leucotreta* (Meyrick) in South Africa (Boersma 2021); and some are under development for other species of Diptera and Lepidoptera. These programmes are driven by the need to decrease insecticide use to comply with minimum residue levels required for export and/or local markets and communities, or to offer an alternate method of control for pests that have become resistant to many available insecticides, such as the false codling moth and diamondback moth *Plutella xylostella* (L.).

Table 2. Characteristics of the major strategic control options applied in AW-IPM programmes integrating the SIT, depending on the type of area

Adjunct Issues	Control Strategy				
	Suppression (infested area)	Eradication (infested area)	Containment (part infested and part pest free area)	Prevention (pest free area)	Eradication (introduction into pest free area)
Quarantine	No	Yes	Yes	No	Yes
Investment in monitoring	Low	High	Varies along gradient (Fig. 1)	Medium	High
Investment / operational costs	Medium	High	High	Medium	Low
Trade advantage	Low (but postharvest treatments can guarantee pest free products)	High	Medium	High	High
Demand for sterile insects	Continuous	Short term ¹	Medium term (but can be continuous)	Continuous	Short term
Potential for commercialization of SIT	High	Low ¹	Medium	Medium	Low

¹ Nevertheless, where the target area is very large, requiring a division into many blocks or phases, there could be a long-term demand for sterile insects and increased potential for commercialization

2.2. Eradication

Eradication is defined (FAO 2017b) as:

Application of phytosanitary measures to eliminate a pest from an area.

This definition, which is accepted and used by the agricultural community, clearly implies the *elimination of an isolated local population* of a pest. Nevertheless, for public health (used by the World Health Organization (WHO) mostly for human diseases), the term eradication is restricted to *global extinction* of a pest at the species level (WHO 2001). Classical examples are the eradication of small pox (Fenner et al. 1988), rinderpest (OIE 2011), or the current worldwide efforts to eradicate polio (Lahariya 2007).

Table 3. Examples of AW-IPM programmes that have applied the SIT according to major control strategies in relation to the type of area

Control Strategy				
Suppression (infested area)	Eradication (infested area)	Containment (part infested and part pest free area)	Prevention (pest free area)	Eradication introduction into pest free area)
Carob moth ¹ : Tunisia; Diamondback moth ³ : Mauritius	New World screwworm ² : N. and C. America (1958–2003)	New World screwworm: Panama (2004– present)		New World screwworm: Libya and the Florida Keys
Mexican fruit fly ⁴ : North-east Mexico	Mexican fruit fly and West Indian fruit fly ⁵ : North-west Mexico	Mexican fruit fly: Sinaloa, Mexico	Mexican fruit fly: Baja California and Rio Grande Valley (Mexico- USA border)	Codling moth: Brazil
Codling moth ⁶ : British Columbia, Canada	Pink bollworm ⁷ : So. USA and northern Mexico (2001–2012)	Pink bollworm: San Joaq. Valley in California USA (1969–2000)		Cactus moth ⁸ : Yucatán peninsula, Mexico
Mediterranean fruit fly ⁹ : Brazil, Croatia, Ecuador, Israel, Jordan, Morocco, South Africa, Spain	Mediterranean fruit fly: Argentina (Patagonia) (1992–present), Chile (1992– 1995), Mexico (1978–1982), southern Peru 2002–2008)	Mediterranean fruit fly: Guatemala- Mexico (1983– present), Peru- Chile (1996– 2002)	Mediterranean fruit fly: Los Angeles Basin in CA, USA (1996– present), Tampa- Miami in Florida USA (1998– present), Chile- Peru border (2008–present)	Mediterranean fruit fly: Los Angeles Basin in California USA (1980s–1996), Southern Australia, Dominican Republic (2015– 2017)
Oriental fruit fly ¹⁰ : Thailand, Vietnam	Melon fly ¹¹ : Japan (1982– 1994)		Melon fly: Japan (is. near Taiwan) (1995–present)	Painted apple moth ¹² : New Zealand
Onion maggot ¹³ : The Netherlands	Sweetpotato weevil ¹⁴ and West Indian sweetpotato weevil ¹⁵ : Japan	Queensland fruit fly ¹⁶ : South- eastern Australia		Queensland fruit fly: Western Australia
Greenhouse whitefly ¹⁷ , sweetpotato whitefly ¹⁸ , and Amer. serpentine leafminer ¹⁹ : Europe, USA (greenhouses)	Tsetse fly: Unguja Island ²⁰ (Zanzibar) (1993–1998), Niayes ²¹ , Senegal			Old World screwworm ²² : Australia ²³
False codling moth ²⁴ : South Africa				

Table 3. Continued (footnotes)

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- ¹ *Ectomyelois ceratoniae* (Zeller)
 - ² *Cochliomyia hominivorax* (Coquerel)
 - ³ *Plutella xylostella* (L.)
 - ⁴ *Anastrepha ludens* (Loew)
 - ⁵ *Anastrepha obliqua* (Macquart)
 - ⁶ *Cydia pomonella* (L.)
 - ⁷ *Pectinophora gossypiella* (Saunders)
 - ⁸ *Cactoblastis cactorum* (Berg)
 - ⁹ *Ceratitis capitata* (Wiedemann)
 - ¹⁰ *Bactrocera dorsalis* (Hendel)
 - ¹¹ *Zeugodacus cucurbitae* (Coquillett)
 - ¹² *Teia anartoides* Walker
 - ¹³ *Delia antiqua* (Meigen)
 - ¹⁴ *Cylas formicarius* (F.)
 - ¹⁵ *Euscepes postfasciatus* (Fairmaire)
 - ¹⁶ *Bactrocera tryoni* (Froggatt)
 - ¹⁷ *Trialeurodes vaporariorum* (Westwood)
 - ¹⁸ *Bemisia tabaci* (Gennadius)
 - ¹⁹ *Liriomyza trifolii* (Burgess)
 - ²⁰ *Glossina austeni* Newstead
 - ²¹ *Glossina palpalis gambiensis* Vanderplank
 - ²² *Chrysomya bezziana* (Villeneuve)
 - ²³ Although free of the Old World screwworm, Australia maintains a contingency plan against potential incursions of this pest (AFF 2002)
 - ²⁴ *Thaumatotibia leucotreta* (Meyrick)

An eradication strategy also leads to a reduction in the use of insecticides that is often larger and longer-term (once eradication is eventually achieved) as compared with a suppression strategy, although pre-release population reduction and “hot-spot” treatments may temporarily require increased localized use of insecticides. In addition, eradication allows the establishment of internationally recognized “pest free areas” (Malavasi et al. 1994; FAO 2016a, 2017b) which can permit access to otherwise closed export markets. These trade advantages are often the major motivation for eradication programmes against insect pests of agricultural importance. The eradication of the Mediterranean fruit fly in Chile (SAG 1996) opened trade opportunities annually worth several thousand million USD, and the eradication of the Mexican fruit fly and the West Indian fruit fly in north-western Mexico allows fruit trade with the USA without the need for costly postharvest treatments (Reyes F. et al. 2000; Enkerlin, this volume).

In the past, most AW-IPM programmes integrating the SIT aimed at eventual eradication of the target population, and sterile insects were often released only during the last phase of the programme (section 3.). The eradication strategy is applied mainly in two different situations (Tables 1 and 2):

- Eliminating an established pest population, e.g. the tsetse fly *Glossina austeni* in Unguja Island (Zanzibar) (Vreysen et al. 2000),

- Eliminating outbreaks of an invasive species before full establishment of the pest can occur, e.g. the painted apple moth in New Zealand (Suckling 2003) (additional examples in Table 3).

The second situation is likely to increase, with more pest introductions due to globalization, pest survival in previously inhospitable climates due to climate change, and the growing awareness by governments of the need for monitoring networks for early detection to facilitate eradication (hendrichs, enkerlin et al., this volume). Once the target pest has been eliminated from a given area, it is imperative to maintain this area pest free. This will require efficient, permanent, and stringent quarantine procedures to preclude reinvasion.

To declare eradication, two very important decisions (which have significant economic implications) have to be made: (1) the period of time in which releases of sterile insects should continue after the last wild insect has been detected (Vreysen, this volume), and (2) the duration of continued monitoring after releases have stopped, to be able to declare with sufficient confidence the status of eradication (Barclay et al., this volume). When creating a new pest free area, this period of no detections can last up to a whole year or longer for some insect pests such as tsetse flies (Vreysen et al. 2000). For the eradication of fruit fly pest outbreaks in free areas, ISPM 26 established a period of zero detections equivalent to a *minimum of three life cycles* after catching the last wild fly (FAO 2016c). This approach has been criticized as unscientific (Carey et al. 2017), but historically has proven effective (McInnis et al. 2017; Shelly et al. 2017). Moreover, in practice and for trade purposes, the actual period required is often established bilaterally between trading partners.

Various mathematical models have been developed that, given the biology of the specific pest species, and the efficiency and density of the deployment of monitoring tools, determine the time required to ascertain, within certain confidence limits, the probability that the target population has been eliminated. These models, which are important complementary decision-making tools, have confirmed the overall effectiveness of the three-life-cycle period (Manoukis and Hoffman 2014; Collier and Manoukis 2017). Agent Based Simulations are a very recent approach to model invading pest populations such as the MED-Fly Outbreak and Eradication Simulation (MED-FOES) that aims at modelling invading Mediterranean fruit fly populations to determine the effective duration of the quarantine and other eradication measures following the last detection of an incursion (Manoukis and Collier 2021).

The decision to establish a pest free area (and then maintain its free status) is sometimes questioned in view of the permanent threat of reinvasion, which would result in a loss of the investment. The likelihood of reinvasion of a pest insect is related to its biology, its geographic distribution, the volume of travel and trade into the free area (Liebhold et al. 2006), the efficiency of the quarantine infrastructure, and the location and size of the pest free area. Therefore, the selection of an eradication strategy will also be influenced by these parameters.

The reinvasion potential of a species in a given area is also inherently linked to the economics of the various strategic options, which will therefore significantly influence the decision to select a suppression or eradication strategy. “*Sequential eradication*” in a target area can still be economically beneficial, notwithstanding periodic reinvasion, if the average period between reinvasions is long enough so that the economic and

environmental benefits of each pest free period between reinvasions exceed the costs of having to “live with” the pest and the effects of the continuous control.

J. Mumford (personal communication) proposed the concept of “*serial eradication*”, which entails the elimination of a pest population in a certain target area without heavy investment to prove the “status of eradication”. If the area is reinvaded, the eradication effort is simply repeated. Not having to constantly “demonstrate the pest free status” could save considerable sums of money, although the trade benefits of a certified pest free status would be continuously in jeopardy and therefore not fully available, similar to situations of “near zero” or “low prevalence” populations (FAO 2016b).

Serial eradication could be applied in conjunction with the concept of “pest free place and site of production”, where the pest free status needs to be maintained only for a fixed period, for example the harvest season (FAO 2016a). To illustrate, melons from Honduras are being exported to Taiwan from registered and qualified places of production maintained pest free only during the harvest season (IAEA 2017). This concept is normally associated with a situation where the commodity is considered a poor or only “conditional host” of the regulated pest (FAO 2017d). However, when the commodity of interest is considered a “good host”, to obtain the trade advantages, the concept of serial eradication would require a “systems approach” (FAO 2017c), which includes a combination of low-cost monitoring, postharvest and other treatments, and occasional intensive area-wide suppression actions.

The decision to adopt a strategy of permanent suppression or periodic eradication is, however, based not only on economics and trade. The affordability of “living with” a disease vector population, even when suppressed, also needs to be considered. Eradication of major vectors of human or livestock diseases (or potentially even plant diseases) is often the preferred option, since a low density of the pest population does not necessarily lead to low levels of disease transmission (Otieno et al. 1990; Feldmann and Hendrichs 2001).

2.3. Containment

Containment is defined (FAO 2017b) as:

Application of phytosanitary measures in and around an infested area to prevent spread of a pest.

Containment programmes are adopted to avoid the spread of invading pests that have become established in part of an area, or to consolidate progress made in an ongoing eradication programme. Several examples are given in Table 3. Some of these programmes are largely stationary and thus become permanent containment efforts (e.g. the Mediterranean fruit fly programme on the border between Mexico and Guatemala, or the screwworm programme in eastern Panama), whereas others successfully advance or gradually retreat and eventually collapse. An example of the latter is the Queensland fruit fly Tri-State Fruit Fly programme. It was conducted since 1988 in eastern Australia to protect an area that contains much of the horticultural production areas of southern New South Wales, northern Victoria, and eastern South Australia (Jessup et al. 2007), but eventually had to be converted into an area-wide

suppression programme due to the expanding range of the Queensland fruit fly. On the other hand, the pink bollworm programme in California is an example of a containment programme that, after many decades of successfully protecting cotton production in the San Joaquin Valley, eventually advanced towards successful eradication of the pest from south-western USA and north-western Mexico once technological change (i.e. *Bt*-cotton), the political situation, and stakeholder commitment favoured it (Henneberry 1994; NCCA 2001; Staten and Walters 2021).

A typical containment situation is illustrated spatially or geographically in Fig. 1, showing a gradient in the density of the pest population from an infested area (NAPPO 2004) on the left to a pest free area on the right. In between there is a relatively steep wild population decline across the various operational areas where the pest is being contained.

KEY ELEMENTS	OPERATIONAL AREAS				
	INFESTED AREA	POPULATION REDUCTION	LOW PEST PREVALENCE	BUFFER AREA	PEST FREE AREA
DENSITY of WILD INSECT PEST POPULATION					
USE of CONTROL METHODS		Population Reduction Tools			
		Sterile Insects			
DENSITY of STERILE INSECT RELEASES	High				
	Low				
DENSITY of MONITORING	High				
	Low				

Figure 1. Schematic representation of containment (and also rolling-carpet approach to eradication in large blocks, section 7.1.), illustrating geographically the gradient in pest population density and degree of activities in the different operational areas, including some preventive sterile insect releases in the pest free area closest to the buffer area.

Various population reduction tools have to be integrated in areas and hotspots where pest levels are too high for sufficient numbers of sterile insects to be released, whereas the SIT is increasingly implemented over lower population levels, mainly low pest prevalence areas with some pest remnants or *incursions* (FAO 2017b)). Sterile insects are particularly effective in adjacent areas that already are largely pest free, but that are subject to regular pest *entries* (FAO 2017b). Ideally, sterile insects are also released as a safety measure in a buffer zone and over parts of the contiguous pest free areas, in view that the pest may occasionally be moved by the transport of infested host material. The degree of population reduction, sterile insect release, and monitoring efforts along this gradient are also indicated in Fig. 1, reflecting requirements to maximize their effectiveness. For example, to be able to detect as

early as possible any entry or incursion, monitoring activities have to be the highest in the buffer zones and adjacent pest free area.

2.4. *Prevention*

The prevention strategy is defined here as the “application of phytosanitary measures in and/or around a pest free area to avoid the introduction of a pest” (however, it applies also to the preventive application of sanitary measures against animal pests). Preventive sterile insect releases have been applied effectively where the invasion pressure is very high, and quarantine activities are not sufficient to maintain the area pest free (table 3). An example is the permanent release of sterile melon flies over the okinawa islands closest to taiwan (kuba et al. 1996). In situations where the invasion risk is not very high, sequential or serial eradication approaches are probably more viable economically (section 2.2.).

For agricultural trade, the strategic options of containment and prevention are designed to maintain market accessibility, although the prevention option is most desirable in terms of cost, as it is always cheaper to prevent a pest problem than to deal with it later (Knippling 1979). (Enkerlin (this volume) provides a more detailed explanation of the costs of containment and prevention.)

3. TEMPORAL PHASES OF AREA-WIDE IPM PROGRAMMES INTEGRATING THE SIT

Irrespective of the strategic option selected, AW-IPM campaigns that include the SIT will likely have similar basic elements and be implemented following distinct temporal phases, i.e. from research to feasibility assessments and pilot studies, all the way to operational field implementation (Hendrichs et al. 2007):

- *Pre-intervention Phase*
 - a. The collection of baseline data on the distribution, dispersal, and population dynamics of the target species in space and time (Itô et al., this volume; Vreysen, this volume),
 - b. Research and development, evaluation and validation of control methods to be integrated,
 - c. Technical feasibility and benefit-cost assessments (Mumford, this volume), and adequate programme planning, including obtaining external technical expert advice, and
 - d. Assuring political commitment and support from major stakeholders and community leaders, and mobilizing adequate financial resources (Dyck, Reyes Flores et al., this volume).
- *Preparatory Phase*
 - a. Staff training and human capacity building, including stakeholders that need to be involved in some activities,
 - b. Launching a public relations campaign (Dyck, Regidor Fernández et al., this volume),

- c. Establishment of funding mechanism, organizational structure and semi-autonomous institutional set-up under public-private operation and oversight,
- d. Development of physical infrastructure (including the mass-rearing and sterilization facility, emergence and release centres) or contractual arrangements made to procure sterile insects from established mass-rearing facilities and to outsource the release of sterile insects (Dowell et al., this volume; Parker, Mamai et al., this volume),
- e. Implementation of small pilot tests to validate the approach and train staff, and
- f. Review by independent external experts to confirm readiness to embark on the operational phase (can also provide periodic reviews during this phase).
- *Operational Phase*
 - a. Population reduction. Control measures are applied, with varying intensity depending on the strategy and seasonal variation in pest population levels, to reduce the density of the target population prior to the release of sterile insects. Various population reduction methods are available, depending on the target insect (Mangan and Bouyer, this volume). However, these are not always required, e.g. when the pest emerges in low numbers after a winter, or when the population undergoes a natural decline as a result of environmental conditions.
 - b. Release of sterile insects. The systematic release of sterile insects over the target area to reduce the target population to a pre-determined level (suppression strategy), to drive the target population to extinction (eradication strategy), or to avoid pest establishment (containment and prevention strategies). This second part of the operational phase can in some instances overlap with continued population reduction, e.g. combining larval suppression and the use of insecticide-impregnated bednets to kill biting mosquito females with the release of sterile males (Mangan and Bouyer, this volume); concurrent treatment of wounds in livestock with insecticides and the release of sterile insects in screwworm eradication campaigns; or the simultaneous application of the male annihilation technique and the SIT as part of a male replacement approach for *Bactrocera* fruit flies (Barclay et al. 2014).
 - c. Maintenance of control. To sustain the low prevalence status (suppression strategy) or the pest free status (containment and prevention strategies) through the permanent implementation of activities, or
 - d. Verification and preservation of pest free status. To confirm and maintain the pest free status (containment and eradication strategies) through permanent implementation of quarantine and early detection and response activities (Barclay et al., this volume).

Progressing from each of these major phases to the next should ideally follow a *phased conditional approach*, e.g. fulfilment of the activities and requirements of a phase as the basis and precondition for entering the subsequent one. It is particularly important when deciding to embark on the operational or programme implementation phase that all previous pre-intervention and preparatory activities have been completed successfully. Preferably this readiness is confirmed by an independent review by a team of external experts (Vreysen et al. 2021).

4. STRATEGIC CONSIDERATIONS IN RELATION TO PEST STATUS AND TARGET MARKETS

The selection of a control strategy is influenced significantly by whether the pest is a disease vector or an agricultural pest. For major vectors of plant, animal or human disease the relevant issue is whether a suppression strategy (releasing only sterile males) can largely maintain the population below a transmission threshold, or whether even low pest populations can result in considerable disease transmission, requiring the eradication option.

For agricultural pests two main factors are of relevance in decision-making: the status of the pest in the target area, and the target market for the produced crop or livestock commodities.

4.1. Target Area and Pest Status

Pest status depends not only on whether the insect is present or absent in the target area, but also on the specific situation and national plant and animal health legislation of the importing and exporting countries in relation to that pest; thus, a pest can be *non-regulated* or *regulated* (both *quarantine* and *regulated non-quarantine* pests (FAO 2017b)). The pest status in a given area, together with the specific situation of the pest (non-regulated or regulated) (Tables 1, 2 and 3), are the primary factors (Klassen's "decision-makers") that will influence the type of strategy(ies) that are economically viable and feasible to be developed and implemented:

- An area is considered as *infested* (NAPPO 2004) when the pest is naturally occurring or non-native pest *establishment* (perpetuation, for the foreseeable future, of a pest within an area after entry (FAO 2017b)) has taken place and the pest has *spread* (expansion of the geographical distribution of a pest within an area (FAO 2017b)). A suppression or eradication strategy can be applied under these circumstances depending largely on the economics as well as isolation and ease of establishing/maintaining quarantine regulations, e.g. a suppression programme against the Mediterranean fruit fly in Valencia, Spain (Primo 2003), and eradication of the same pest in temperate fruit-production areas in Mendoza and Patagonia, Argentina (De Longo 2000).
- Situations of multiple presence of major pest species in a target area necessarily complicate strategic considerations, although there are some suppression or eradication programmes where more than one species have been simultaneously addressed. Examples are the eradication of both the Mexican and the West Indian fruit flies from north-western Mexico (Reyes F. et al. 2000), or the eradication of three tsetse populations (*Glossina p. gambiensis*, *Glossina tachinoides* Westwood and *Glossina morsitans submorsitans* Newstead) from 3500 km² in Burkina Faso (Politzar and Cuisance 1984; Clair et al. 1990).
- An area is considered *pest free* when the insect pest is not present in that area (FAO 2017b). If there are frequent *entries* (FAO 2017b) of a major invasive pest, and the area is *endangered* (area where ecological factors favour the establishment of a pest whose presence in the area will cause economically important loss (FAO 2017b)), the most cost-effective strategy to protect the area from any potential

introductions will often be preventive releases of sterile insects, a successful example being the Preventive Release Programmes in California (Dowell et al. 2000; Enkerlin, this volume). About 150 million sterile male Mediterranean fruit flies are being released per week in the Los Angeles Basin, a “high-risk” area for introductions of this pest because of favourable ecological factors, the huge amount of international trade, the substantial volume of international postal shipments with infested fruit, high traffic in contraband fresh commodities, and the large number of fruits carried illegally by tourists (Liebhold et al. 2006).

- Simultaneous to strengthening quarantine measures, the threat of entry and introduction into a pest free area can be reduced by requesting postharvest treatments and pre-clearance actions, as well as proactively supporting *offshore pest risk-mitigation* activities in places where the pest originates (i.e. neighbouring countries or regions), e.g. Chile’s support to the release of sterile Mediterranean fruit flies north of and along the border between Chile and Peru to avoid reinvasion of this pest from Peru into Chile (Enkerlin et al. 2003). Another example is the USA’s support of the Moscamed programme along the Guatemala/Mexico border.
- A pest free area, contiguous to an infested area, can be protected by a containment strategy, e.g. the release of sterile pink bollworms over decades to prevent the spread of this pest from infested areas into the cotton production areas of the San Joaquin Valley in California, USA (Henneberry 1994); more recently this programme successfully shifted to an eradication strategy (Staten and Walters 2021).
- When establishment of an invasive insect pest has taken place recently, and the *outbreak* (a recently detected pest population, including an incursion, or a sudden significant increase of an established pest population in an area (FAO 2017b)) has not yet spread significantly out of the outbreak area, the recommended strategy is a rapid response to achieve eradication as soon as possible, e.g. elimination of the New World screwworm in Libya (Lindquist et al. 1992; Krafurs and Lindquist 1996; Vargas-Terán et al., this volume) or the Mediterranean fruit fly in the Dominican Republic (Zavala-López et al. 2021). Containment is the second-best strategic option for this situation, but only when immediate eradication is no longer feasible or has failed.

4.2. Requirements of Target Market

For agricultural pests, the type of market targeted for the commodity produced plays a major role in selecting a control strategy. There are four major potential markets that can be accessed (IAEA 1995) (Table 4):

- *Domestic markets* are normally the least demanding, but also the least lucrative, and a suppression strategy using sanitation and other conventional methods is normally sufficient. Only when there are important local markets having special requirements in terms of low pesticide residues is the use of more environment-friendly pest control methods warranted.
- *Non-discriminating export markets* also often have no special requirements, and thus may be similar to domestic markets. However, increasingly, as a result of globalization, these markets tend to decrease in importance, whereas export

markets demanding lower pesticide and/or pest presence in commodities are growing.

- *Low-residue export markets* are typically in developed countries that have demanding supermarket chains (in terms of maximum allowed residue levels) and a growing demand for such products. These markets either already have the pest or have climates in which the pest cannot become established. A suppression strategy involving application of more environment-friendly methods is suitable to gain access to these markets.

Table 4. Access to potential markets using available control strategies

Control Strategy	Potential Markets			
	Domestic markets	Non-discriminating export markets	Low-residue export markets	Pest free export markets
Suppression (infested area)				
Conventional control	Yes	Yes	No	No
Low pesticide including the SIT	Yes	Yes	Yes	No
Low pest prevalence and systems approach	Yes	Yes	Yes	Yes ¹
Eradication (pest free area developed)	Yes ²	Yes ²	Yes ²	Yes
Containment (pest free area protected)	Yes ²	Yes ²	Yes ²	Yes
Prevention (pest free area maintained)	Yes ²	Yes ²	Yes ²	Yes

¹ Only when combined with complementary measures, such as post-harvest treatments, except for marginal hosts of the pest

² Development, protection or maintenance of pest free areas, involving quarantines and intense monitoring, is usually not cost-effective for these markets unless they target mainly pest free export markets

- *Pest free export markets* are the most demanding, with zero tolerance for the presence of the pest in the export commodities. Accessing these markets requires an eradication strategy to establish certified pest free areas. Alternatively, a suppression strategy can be followed to establish a low prevalence area, but this strategy demands in addition a systems approach involving integration with complementary pest risk-mitigation measures such as, in some instances,

postharvest treatments to guarantee pest free commodities. In situations where the exporting areas are already partially or fully pest free, the logical approaches to protect or maintain these markets are containment or prevention strategies, respectively.

5. STRATEGIC CONSIDERATIONS IN RELATION TO PEST BIOLOGY AND ECOLOGY

There are several factors related to the biology and ecology of the pest that influence the selection of a control strategy, and affect both planning and implementation, e.g. Pest mobility, pest densities, average lifespan, potential for direct and indirect damage, and ecological aspects such as topography, vegetation, and climate, as well as the capacity to monitor pest presence, together with gene flow, to determine the degree of isolation of the target population.

5.1. *Pest Dispersal*

One of the most critical aspects is the degree of isolation of the target population and, associated with it, the dispersal ability of the target insect (Vreysen, this volume). Knowledge about dispersal ability is essential to assess the likelihood of invasion or reinvasion, which remains an important consideration in selecting and developing a strategy. Highly mobile insects can be advantageous for programmes that release sterile insects, as this trait will increase the probability of finding and mating with virgin wild female insects. However, at the same time, the greater the dispersal of the wild insect, and in particular wild females, the more difficult it will be to protect pest-cleared areas (Lance and McInnis, this volume).

Mark-release-recapture studies, using both wild and sterile insects, can also be used to study dispersal, but this approach, although valid, can be expensive and cumbersome (Itô et al., this volume).

An alternative is the analysis of the gene frequencies of target and neighbouring populations as an indirect approach to dispersal (Krafsur and Ouma, this volume; Vreysen, this volume). Pest dispersal ability is a decisive component in strategy selection, in assessing the minimum size of an intervention block where the SIT can be effectively applied (section 8.; Barclay et al. 2011; Klassen and Vreysen, this volume), and in determining the need for temporary and permanent buffer zones (section 9.).

5.2. *Release Density*

Itô et al. (this volume) provide detailed mathematical guidance on estimating absolute densities of insect populations and growth under different situations and for pests with different biology. An estimate of these parameters of the pest population in the target area is key to determining the need and extent of population reduction required before the application of the SIT, and to make accurate estimates of the required number of sterile insects. The latter will obviously influence the total cost of the programme, and

will represent a major consideration when selecting a strategy (Mumford, this volume).

The cost of the SIT component of AW-IPM programmes has traditionally been calculated using data from the production of sterile insects, and the cost associated with handling and release operations. Even though very large variations in the production and release costs of different insect pests exist, i.e. from only USD 0.25 to produce 1000 Mediterranean fruit flies to USD 85 to produce the same number of tsetse flies (Table 5), the ultimate cost of an SIT operation will also be determined by the number and frequency of sterile male insects per unit of surface that are needed to obtain adequate sterile to wild male overflooding ratios. A comparison of costs per surface and time unit for different pest species is presented in Table 5.

Table 5. Comparison of costs of AW-IPM programmes that release sterile insects (data for codling moth calculated from information provided by R. Fugger and L. Tomlin, Sterile Insect Release Program, Canada, and Bloem et al. 1998)

Pest species	Cost of producing sterile male insects (USD per 1000 insects)	Cost of handling and releasing sterile males (USD per 1000 insects)	Total cost (production and release) (USD per 1000 insects)	Release rate (number of sterile males per km ² per week)	Cost of sterile male production and release (USD per km ² per year)
Codling moth ^{1,2}	1.9	0.65	2.55	100 000	5167
Mediterranean fruit fly	0.25	0.15	0.4	200 000	4160
<i>Glossina austeni</i> (savannah tsetse species)	85.0	33.0	118.0	80	491
New World screwworm ²	1.0	0.4	1.4	2500	182
<i>Glossina p. gambiensis</i> (riverine tsetse species)	85.0	96.0	181.0	15	141

¹ Data for codling moth based on releases for only 20 weeks per year

² Both sterile males and females are released

For example, following application of population reduction measures, only 15 sterile male *Glossina p. gambiensis* (riverine species of tsetse) are required per km² per week, whereas for the Mediterranean fruit fly, ca. 200 000 sterile males per km² per week are needed. Consequently, although the production and release costs of Mediterranean fruit fly are very low and for tsetse very high, the costs per km² per week of the SIT operation are much higher for Mediterranean fruit flies (USD 80) than for riverine species of tsetse (USD 2.7). Therefore, considering the cost of the sterile

fly requirements per surface and time unit provides a much more accurate indicator of the economic implications of SIT operations.

5.3. *Pest Aggregation*

Aside from the absolute population density, the degree of population aggregation or dispersion is important. Sterile insects are usually released by air, and are thus distributed fairly homogeneously over the target area, irrespective of whether the target pest is distributed evenly or clumped. Pest insects with a clumped distribution require effective hotspot detection and suppression (Shiga 1991), as well as higher release rates as compared with those with a homogeneous distribution, to obtain the required sterile to wild male ratios (Barclay, this volume), and thus pest aggregation also affects strategy selection and its cost. Only if the released insects can find the same aggregation sites and aggregate in a similar manner as wild insects (Vreysen et al. 2011), so that adequate sterile to wild male overflooding ratios are obtained in those sites, is there no need to increase release rates to compensate for such clumping (Vreysen, this volume).

5.4. *Sterile Male Longevity*

The density of the sterile male population in the field, which fluctuates in relation to the release frequency and the sterile male mortality rate, should not decrease below that needed to maintain the critical ratio (Fig. 2, upper graph) (Kean et al. 2007; Barclay, this volume). Therefore, the frequency and number of sterile males released has to be carefully assessed in relation to the average longevity or survival of the sterile males, to effectively avoid periods when insufficient sterile males are present in the field (Fig. 2, lower graph).

As generations normally overlap in multivoltine species, releases have to be continuous, with survival determining whether they have to occur on a weekly (New World screwworm), twice a week (Mediterranean fruit fly, tsetse), or even daily basis (*Drosophila suzukii* (Matsumura) in greenhouses). The importance of assessing the survival of sterile male insects in the natural habitat must be emphasized here (Vreysen, this volume), as their actual survival in open field conditions is often drastically lower than in protected field-cage situations, where sterile males have easy access to food and are protected from predation (Hendrichs et al. 1993). In addition, mass-rearing conditions often inadvertently select for short-lived individuals (Cayol 2000). A shorter sterile male lifespan, although not directly representative of competitiveness, often requires higher release frequencies, and thus can significantly increase programme costs compared with longer-lived sterile insects.

5.5. *Topography and Other Conditions of Target Area*

The topography of the target area, combined with the density of roads, has major implications for programme implementation and the selection of an intervention strategy. A flat terrain and a well-developed road network will facilitate most field

activities (including ground release in some cases), whereas mountainous areas, dense vegetation, and the absence of roads will make implementation more challenging. In most of the larger programmes, releases and some of the population reduction activities use fixed-wing aircraft (Vreysen et al. 2000; Dowell et al. 2000), helicopters (Koyama et al. 2004), gyrocopters (Vreysen et al. 2021), or more recently even unmanned aerial vehicles (Benavente-Sánchez et al. 2021; Dowell et al., this volume), and the topography and presence/absence of a road network are less critical.

Figure 2. Effect of sterile insect longevity (assume daily mortality rate of sterile males is 0.1) on sterile to wild overflooding ratio. Upper: Due to only weekly releases, sterile insect population routinely decreases significantly below the critical overflooding ratio; Lower: twice-a-week releases overcome this problem.

Actually, the absence of a good road network is often advantageous for the establishment of efficient quarantine procedures in support of an eradication strategy. Monitoring, however, is mostly ground-based, and extreme terrain conditions make eradication campaigns (which have a more intensive monitoring component) much more complex and costly than programmes following a suppression strategy (which have less intensive monitoring activities). Likewise, topography influences the requirements of sterile insects or bait sprays, e.g. mountainous areas have a larger surface area per square kilometre as compared with flat, two-dimensional conditions,

demanding higher sterile insect release rates. Furthermore, helicopters, which are more expensive to operate than fixed-wing aircraft, are often needed in difficult terrain for safety reasons and to properly treat narrow valleys.

5.6. Capacity to Monitor and Delimit Pest Presence

The distribution of the target population has to be known accurately; direct and indirect monitoring methods are usually available to assess this for the different target species. Each monitoring tool, however, has its limitations, and none is perfect. Knowledge about the efficiency and limitations of the monitoring methods is essential to assess the accuracy of, and the ability to demarcate, the total distribution of the target population (Vreysen, this volume).

The different phases of programme implementation require specific adjustments to the monitoring system according to the pest density (Fig. 1). The intensity of deploying monitoring tools, or of indirect surveys, gradually changes from the initial relatively low monitoring effort during the baseline data collection to increased activity during the initial population reduction, low-prevalence, and eradication activities (highest need for detection capability), and will decrease again during maintenance/verification (FAO/IAEA 2018). Therefore, along the gradient in pest population density, the density of monitoring tools will also vary according to their efficiency in the different operational areas. For an eradication strategy, very efficient monitoring tools are particularly important once populations have decreased to very low densities; the same is true for population remnants or entries and incipient incursions (Fig. 1). In pest free areas, monitoring efficiency is important also for early detection of, and delimiting, the population of a new introduction. Inefficient monitoring tools to assess the status of eradication, or for delimiting purposes, will increase the cost of programmes — high deployment densities are required to compensate for the lower efficiency, and longer deployment times to obtain the required confidence limits (McInnis et al. 2017).

6. STRATEGIC CONSIDERATIONS IN RELATION TO PEST DISTRIBUTION

The characteristics of the spatial distribution pattern of the target population will be a crucial factor when selecting a strategy and developing an implementation plan. An insect population can be confined to an island, or have a fragmented or continuous distribution on a continent.

6.1. Island Distribution

Targeting a pest population confined to an island is the ideal and simplest situation for which to develop an AW-IPM programme, e.g. New World screwworm on various islands in the Caribbean, cactus moth on islands off the Yucatán Peninsula in Mexico (Bello-Rivera et al. 2021), and melon flies or sweetpotato weevils on islands of the Okinawa archipelago (Kohama et al. 2003; Koyama et al. 2004), etc. Islands can be relatively small, making area-wide intervention easier, and, if the size is not too large,

the insect population can be tackled at one time. Typically, insect populations on islands are isolated, with the ocean being an ideal natural barrier. Sustaining such areas pest free after eradication is only a minor concern for species such as the tsetse fly *G. austeni* which was eliminated from Unguja Island of Zanzibar, whereas for other species the establishment of quarantine procedures is facilitated by the island situation. However, migration over considerable distances has also been reported for species such as the melon fly (Koyama et al. 2004), where movement between Taiwan and islands in southern Japan has been recorded routinely (Kuba et al. 1996).

6.2. *Fragmented Distribution*

Insect populations on continents are fortunately not always distributed continuously, but often appear to be fragmented and confined to “ecological or population islands”. Examples are the carob moth in date palm oases in the Mediterranean Basin and the Near East, the mosquito *Anopheles arabiensis* Patton confined to isolated mosquito habitat along the Nile River in Sudan (Malcolm et al. 2009), and various tsetse species confined to valley systems in south-western Ethiopia, fragmented habitat in the Niayes of Senegal (Bouyer et al. 2010), and in river basins in West Africa (Bouyer et al. 2015).

Although the distribution of insect populations is sometimes perceived as vast and continuous, topographical features (e.g. mountains, lakes, deserts), and factors such as host availability, climate, and vegetation, often result in the division of populations into smaller population units. This subdivision occurs more easily at the edge of the distribution, where the insects are confined to those areas with favourable conditions. Field surveys assisted by a GIS-based analysis, supported by satellite imagery and population genetics studies (Feldmann and Ready 2014; Bouyer et al., this volume; Krafur and Ouma, this volume), are needed to determine the degree of reproductive isolation between such smaller population units.

Since detailed data on the distribution of the target population are often not available when needed, satellite-derived parameters are used increasingly to develop models to predict the probability of presence or even abundance of a certain pest in a given target area (Bouyer et al., this volume). These prediction models can greatly facilitate the demarcation of the pest’s distribution, and provide the foundation for developing an adequate intervention strategy, as was done for *G. austeni* and *Glossina brevipalpis* Newstead in KwaZulu Natal, South Africa, and Matutue Province, Mozambique (Kappmeier Green et al. 2007) (Fig. 3). However, the fragmented nature of the distributions of the two species predicted by the distribution prediction model (AVIA-GIS 2002) was later refuted through more extensive surveys that sampled both species where they had not been found before (de Beer et al. 2016).

Insect populations are rarely stable in space and time, and temporal changes in their dispersal potential can significantly affect the isolated nature of seemingly distant population pockets. Seasonal changes in vegetation cover can be particularly dramatic in subtropical and tropical environments, with important consequences for insect dispersal, e.g. populations can be confined to “vegetation islands” during the dry season, when conditions for survival are harsh, but during the rainy season dispersal potential increases, spatial distribution expands, and larger distribution areas are

created. Likewise, some moths and other pest populations are confined to limited overwintering areas in the subtropics from where they migrate each spring covering vast temperate areas (Wu 2007).

Figure 3. Distribution of *Glossina austeni* (left) and *Glossina brevipalpis* (right) in KwaZulu-Natal in South Africa, derived from trapping data from the 1993–1999 and 2005–2009 surveys. (Maps reproduced with permission from C. de Beer.)

6.3. *Continuous Distribution*

The most complex scenario is when insects are distributed continuously over very large areas. For both suppression and eradication strategies, a vast distribution of the pest will make it technically, logistically and economically impossible to tackle the entire infested area at one time. Consequently, the AW-IPM programme has to be developed and implemented in different stages, and thus the target area has to be subdivided into “intervention blocks”. The appropriate block size will depend on the sterile insect production capacity and the biology of the particular species (section 8.), but has to be large enough to preclude migration of mated fertile females into the core area of each block.

Determining the exact size and precise demarcation of the blocks is a very challenging task, as it could determine success or failure (Barclay et al. 2011). Topographical and ecological features (e.g. major cities, mountain ranges, rivers, non-host areas, and arid or open areas of unsuitable habitat), which constitute natural barriers for the target insect, should separate to the maximum possible extent adjacent intervention blocks. In principle, to reduce the probability of migration among blocks, the size and number of temporary buffer zones between the blocks should be limited.

7. STRATEGIES FOR CONTINUOUS DISTRIBUTION

For large target populations that are distributed continuously, the “rolling-carpet principle” or the “wave principle” can be used to plan and implement AW-IPM programmes. Intervention according to the rolling-carpet principle entails advancing along a unidirectional front (Figs. 1 and 4), whereas for a bidirectional or multidirectional front the intervention follows the wave principle (Fig. 5). The different blocks have to be demarcated and selected in such a way as to minimize the invasion pressure from various directions. Multiple fronts complicate a programme, and necessitate the establishment of temporary buffers, which obviously can reduce the probability of success. In both approaches, it is of prime importance that the starting point of operations be selected carefully. Once the programme has started, it must be continued in view of the continuous pest distribution, and cannot be interrupted until a pest free area (eradication strategy), or a low pest prevalence area (suppression strategy), has been obtained in all blocks. Ultimately, in most cases, a permanent containment barrier will need to be established in a block at a more easily defensible location, e.g. Darien Gap for the New World screwworm programme (Klassen et al., this volume; Vargas-Terán et al., this volume).

7.1. *Rolling-Carpet Principle*

The rolling-carpet principle is dynamic. The basic activities described in section 3. (baseline data collection as part of the pre-intervention phase, and population reduction, releases of sterile insects, and maintenance/verification of low prevalence/pest free areas as part of the operational phase) are carried out simultaneously in a progressive manner along the adjacent blocks (upper part of Fig. 4). Obviously, this approach with overlap of releases in adjacent blocks is more time

and cost-efficient than without an overlap, in which each of these interventions would be implemented only in a given block before proceeding to the next block.

The diagram in the lower part of Fig. 4 shows the implementation of the rolling-carpet principle in space, i.e. the programme is initiated with the collection of baseline data and capacity building in block 1 (stage 1), and these activities are progressively shifted to adjacent blocks. Simultaneously, reduction of the population, release of sterile insects, and maintenance/verification of low prevalence/pest free areas will be carried out in those blocks where the previous activities have been completed. The approach in stages will entail a gradual increase in operational activities (and operational complexity) during the first four stages, with expanding needs for funding, personnel, and logistics.

Since the duration of each new operational stage can be different, the different stages of the rolling-carpet principle should be considered not only in space, but also in time (upper part of Fig. 4), i.e. baseline data collection (stage 1) usually has to take into account temporal changes in the density, distribution, and structure of insect populations, and often takes at least one full year to complete, whereas reduction (stage 2) of the target population is often implemented in shorter periods.

To achieve the desired population reduction, sterile insects must be released for a period of several generations (Knipling 1979). The duration of sterile insect releases to obtain a pest free area (eradication strategy), or to establish an area of low pest prevalence (suppression strategy), will depend on the reproductive rate and the generation time of the target species. For species such as tsetse flies, which have a long lifespan and long generation times, the release stage can take up to 18 months. Theoretically, this will be less for insects that have shorter generation times, like mosquitoes or fruit flies, but their high rates of reproduction can be a complicating factor.

The exact timing and initiation of each activity will be crucial for efficient implementation of the programme, e.g. a too-early start of the population reduction stage could result in a reduction of the target population before sterile insects are available for release. Therefore, the availability of sufficient sterile males should be taken as the "baseline", and all other activities should be scheduled in relation to the releases. These, in turn, depend largely on the production capacity of the mass-rearing facility. The overlap of releases in certain blocks (upper part of Fig. 4) has important implications for the cost of the programme, the time to reach programme goals, and the need to establish protective buffer zones (section 9.).

For example, in the hypothetical case with an overlap of releases for 12 months in two adjacent blocks (and even an overlap of 6 months in three blocks), the maintenance/verification period in the last low prevalence or pest free block can be initiated in the third quarter of year 5, whereas if there is no overlap of releases in adjacent blocks, this is delayed until the third quarter of year 8. In addition to the more advantageous implementation time, the first example offers a much more effective operation when compared with the second example, since the insect population in the block adjacent to the release area is always under active population reduction that minimizes the dispersal of gravid females into the release area (Fig. 1).

Overlap of releases in adjacent blocks

No overlap of releases in adjacent blocks

On the other hand, in the second example the population reduction activities in block 2 are only initiated 12 months after the initiation of releases in block 1, requiring the establishment of temporary buffer zones to prevent the migration of females from the still “untreated” block 2. It is equally important that the contiguous part of the area that is already pest free be treated preventively with sterile insects as a biological buffer zone (Fig. 1), an ultimate insurance that individual entries or incipient incursions cannot become permanently established in the freed area.

7.2. Wave Principle

The wave principle entails an expanding operational block size with each new operational stage (Fig. 5), and this must be considered when designing a production facility. For example, if an intervention were initiated in a 10 x 10 km (100 km²) area, and in each stage expanded by 10 km to the east, west, and south, the total intervention zone would expand from 100 km² in stage 1 to 6600 km² in stage 6 (Fig. 6).

In an eradication strategy, the release area (shaded area in Fig. 6) would expand from 100 km² in stage 1 to 500 and 2100 km² in stages 2 and 6, respectively. If the release density of sterile males were 200 000 per km², the sterile male requirements in each stage would increase linearly by 80 million insects, i.e. from 20 million sterile insects in stage 1 to 420 million in stage 6.

In a suppression strategy, however, the sterile insect requirements would be different. If sterile males were released at a density of 200 000 per km² during the release stage (shaded area), and at a density of 50 000 per km² during the maintenance stage of low prevalence areas (white area), the sterile insect requirements would increase more dramatically with each stage when compared with an eradication strategy, and are best described by the following equation:

$$y = 2E + 0.7x^{1.9119} \text{ (Fig. 6).}$$

The number of sterile males needed for each stage is also very different in a strategy using the wave principle compared with that using the rolling-carpet principle. In the rolling-carpet principle, subsequent intervention blocks are often approximately the same size (Fig. 4). In the wave principle approach, the requirements of sterile males and other resources will increase with each stage; therefore, there will be a limit beyond which the operations cannot be sustained. At a given point, the programme will need to advance in one direction (for example south), and temporary or permanent buffer zones have to be established in the west and east to protect the low prevalence or pest free zones achieved (Fig. 5).

A mobile, modular insectary approach, e.g. containers as production modules, would in some situations have the advantage that, if the target area were expanding, modules could be added relatively easily (Tween 2004). Furthermore, the entire insectary could be moved with the expanding eradication or low pest prevalence front. This would reduce the transport time and cost between a stationary factory and the release area (in the case of an eradication strategy, the distance between the target zone and the factory increases with each new operational stage).

Figure 5. Diagram of different activities and stages of an AW-IPM programme using the SIT according to the “wave principle” against a pest population with a continuous distribution. In this theoretical example, the intervention starts at the edge of the pest distribution and develops along a multidirectional front in the first 6 stages, until full production capacity of sterile males is reached. Beginning in stage 7, the intervention continues along a one-directional front, having either reached natural barriers or requiring the establishment of temporary buffer zones that includes suppression and quarantine activities as well as the release of sterile flies.

Figure 6. Diagram of the wave principle (upper drawing) and sterile male requirements (lower graph), with an expanding intervention front of 10 km south, east, and west, and each stage using eradication and suppression. Numbers indicate: (A) total surface area in km² / (B) area in km² where sterile males are released / (C) pest free area in km² (eradication) or low pest prevalence area (suppression). (More details in the text.)

A mobile insectary could be relocated occasionally to areas where the pest is still present, and, in the case of eradication, expensive insect-proofing systems would not be needed. However, the relative merits and economics of insect-proof systems and increasing transport time versus relocation costs of the modules need to be considered. An example was the New World screwworm mass-rearing facility in Tuxtla Gutiérrez, Chiapas, Mexico. As the programme succeeded and then advanced southward into Central America, the factory remained in an area now free of screwworms, requiring expensive and cumbersome biosecurity measures. These included the continuing release around the facility of several million sterile insects per week to deal with any fertile flies that might have escaped accidentally from the facility. Eventually, a new facility was established in Panama and the Tuxtla Gutiérrez facility closed (Vargas-Terán et al., this volume).

8. SIZE OF INTERVENTION BLOCKS FOR AW-IPM PROGRAMMES

At what spatial scale is an area-wide approach no longer technically and economically feasible? Is there a minimum size of the target area below which effective implementation of AW-IPM programmes using the SIT becomes technically impossible and economically unjustifiable (Barclay et al. 2011)? These questions are of major importance since the SIT, similar to mating disruption (Cardé 2021), does not kill the pest and hence is particularly susceptible to immigrating gravid female insects, which are largely unaffected by the sterile males, although in some target pest species females do remate (Von Borstel 1960).

Intervention blocks are composed basically of two distinct areas, i.e. the core and the edge areas. The core area contains the commodity that is being protected (e.g. crop, cattle, humans in urban area, etc.), whereas the edge area, although included in the treatment zone, is defined by the edge effect: a certain level of infiltration by gravid wild females from the surroundings into the area under treatment (Fig. 7). In some situations the edge area completely surrounds the core area, often requiring the establishment of a protective buffer zone (section 9.) to minimize this edge effect.

The size of both core and edge areas is determined mainly by the combined effects of the dispersal potential of the pest species and the degree of protection required for the target area, which depends on the strategic objective of the programme: higher for eradication, lower for suppression. Other biotic and abiotic factors, such as presence of natural barriers, ecological and topographic characteristics of the area, tolerable nuisance or damage level, acceptable economic threshold, and managerial-logistic capacity, are likewise of relevance.

If the selected target area were completely isolated, e.g. an island, there is no need to establish protective buffer zones unless the pest can reach the island from other areas (Kuba et al. 1996). However, when a continuous pest population surrounds or is adjacent to the selected core area, the size of each block must be much larger to absorb the edge effect without affecting progress in the core (Fig. 7). For pests having a high dispersal rate, individual blocks will have to be larger (Barclay et al. 2011).

The size of the blocks will also affect the strategic approach and the economics of each approach. If the goal is to eradicate the pest and to maintain an area pest free, larger blocks will most likely be required to reduce the relationship of edge to core

area (Fig. 7). However, if pest suppression is the strategic goal, a certain damage threshold is usually acceptable, thus relatively smaller blocks and smaller protective buffers are acceptable (Larcher-Carvalho and Mumford 2004; Barclay et al. 2011). This confirms earlier observations that, by nature, eradication is a more extensive and intensive strategy when compared with suppression (sections 2.1. and 2.2.).

Figure 7. Relationship of core area to edge area at three different scales of block size. An edge effect based on pest dispersal of 8 km is assumed, and square core areas for either pest free (containment and eradication) or low pest prevalence (suppression) area.

The ratio between the size of the core and edge areas is related to this, i.e. the larger the core area, the smaller the edge area in relation to the whole block surface. Also, the relative effort needed to maintain protective buffer zones becomes proportionally smaller with larger block areas. The following example illustrates this point. Assuming that the core areas are squares, and that dispersal can occur into an edge with a width of up to 8 km (Fig. 7), the percentage of the total surface area represented by the edge area decreases from 64 to 29 to 12% for a core area of 1600, 10 000, and 62 500 km², respectively. For the small block of 1600 km², the effort going into the edge area is relatively larger than the one going into the core area. Such a situation could only be justified if the value of the commodity being protected outweighs the costs incurred to maintain protective activities in the relatively large edge area.

The scale of application will also influence programme economics, especially when it includes the initial capital investment of a mass-rearing and sterilization facility, as well as emergence and release facilities. Particularly in those cases, the programme needs to be applied on a scale large enough to become economically

viable and competitive with alternative control options (which operate at real economies of scale, i.e. production of insecticides). Therefore, larger blocks incur a lower cost per surface unit or per unit of the commodity that is being protected. This relates directly to the size of the mass-rearing facility; experience has shown that the cost of a unit of produced sterile insects is inversely related to the level of mass production (Enkerlin 2003). Higher fixed costs are associated with factories designed to produce relatively small numbers of insects.

The size of blocks has ranged from tens of square kilometres, as was the case of the oriental fruit fly pilot suppression programme in Thailand (Sutantawong et al. 2004), to thousands of square kilometres in the case of large programmes such as the New World screwworm eradication campaign, where each treatment block encompassed at least one and a half of the Central American countries (Vargas-Terán et al., this volume).

A conceptual model was developed for assessing the minimum size area for AW-IPM programmes (Barclay et al. 2011). It is primarily based on a diffusion coefficient that uses the dispersal rate of the target insect, and considers other main variables such as the fertility rate and mortality involved to produce estimates of minimum-size intervention blocks for different pests and programme objectives. It can be used as a guideline to recommend quantitatively the minimum intervention size for the range of different conditions where sterile insects can be released.

9. BUFFER ZONES

To address the edge effect as described above, there is often a need to establish buffer zones (FAO 1999, 2005) to protect containment or eradication efforts, or to maintain low prevalence commercial production areas. This may necessitate the application of conventional control methods or the release of sterile insects or both in the buffer zone, and may be either temporary or more permanent.

9.1. Temporary Buffer Zones

Eradication programmes that proceed in stages or blocks, irrespective if a rolling-carpet or wave principle is adopted, might require buffer zones between the intervention blocks to temporarily protect achievements made in each new operational stage of the advancing programme. These temporary buffer zones have two main objectives:

- To prevent a massive influx of the pest from areas where it is still uncontrolled to blocks where sterile insects are being released. Population reduction activities, normally implemented in blocks adjacent to the release blocks, often serve as temporary buffer zones (Figs. 4 and 5).
- To consolidate progress in areas where the pest has already been eliminated. Preventive sterile insect releases and other control activities are implemented in these areas adjacent to the population reduction and low prevalence areas (Fig. 1). Hence, these buffer zones attempt to ensure that any migrating gravid females, or

those that are transported across a permeable quarantine, cannot re-establish new populations.

Temporary buffer zones were established during the progressive eradication campaign of the New World screwworm in Mexico and Central America (Vargas-Terán et al., this volume). The programme was implemented according to the rolling-carpet principle, and always included (at the back end of the moving eradication front) a large screwworm-free buffer area in which sterile insects were released as an insurance in case screwworm-infected cattle was moved into the pest free area.

Such buffer zones are only established temporarily in the dynamic rolling-carpet or wave-principle approaches, and are progressively moved from block to block with the advancement of the eradication campaign (Fig. 4). Occasionally, special buffers are needed when the increasing size of the intervention front of an expanding programme exceeds the available resources, e.g. at a given stage, the multidirectional moving front of a wave-principle strategy will be shifted to a front that proceeds temporarily in only one or two directions (Fig. 5). The areas where such buffer zones have to be established should be identified during the collection of baseline data and programme planning activities of the pre-intervention phase.

9.2. Permanent Buffer Zones

Permanent buffer zones are often established for containment (Fig. 1). These buffers should have a width sufficient to intercept any immigrating insect and the capacity to deal with progeny of any gravid female that enters the area. In tsetse flies, for example, which are relatively poor fliers and have no free-living immature stage, the dispersal potential is much lower (Feldmann and Jannin 2001) than that of new world screwworms (Lance and McInnis, this volume). However, the potential for reinvasion of screwworm flies is much lower than that of polyphagous fruit flies, which are present in innumerable small hosts that can contain larvae, and are easily transported by travellers or postal shipments. Therefore, in addition to buffer zones, rigorous quarantine measures/procedures have to be established to intercept any insect that is transported passively with animal or plant commodities, e.g. fruit fly larvae in fruit, screwworm larvae in livestock, pets, and humans, codling moth pupae in packing boxes, and tsetse flies resting on vehicles.

A good example of a permanent buffer zone is the one that has been established permanently in eastern Panama as part of the New World screwworm programme to prevent this pest from dispersing from Colombia to the screwworm-free areas of Central and North America (Fig. 8). Aircraft release ca. 15–20 million sterile insects per week over a 30 000-km² area bordering with Columbia (APHIS/USDA 2001), and adjusting release densities based on risk areas within the barrier (3000 sterile flies per nautical mile² in low-risk areas and 6000 in high-risk areas). The large size of the Darien buffer zone is required because of the high mobility of screwworms; individual flies can cover distances up to 290 km (Hightower et al. 1964).

Another example is the sterile Mediterranean fruit fly buffer zone that has been maintained for approximately 40 years between Mexico and Guatemala as part of the Moscamed containment programme (Villaseñor et al. 2000; Enkerlin et al. 2015, 2017). The requirements and optimal dimensions for efficient buffers are often

underestimated and, when combined with insufficient resources, frequently result in the establishment of localized inefficient buffers that “leak”.

Permanent buffer zones are also needed around low pest prevalence commercial production areas where suppression, rather than containment or eradication, is the strategic goal. The objective is to reduce the impact of gravid females moving into such areas by applying conventional methods of pest control or extending the sterile insect releases beyond the core commercial production areas. Once low pest prevalence has been achieved, releases could be decreased in the core area, while the buffer would continue with higher release rates and other population reduction activities (Larcher-Carvalho and Mumford 2004). In cases where the core area is well managed so that it does not contribute to the pest population (i.e. growers routinely remove all infestation sources of fruit flies such as fallen fruit, or citizens eliminate all *Aedes albopictus* (Skuse) mosquito breeding sites in an urban area), area-wide releases can focus mainly on the sources of the pest in the surrounding natural vegetation areas from where the pest reaching the core area originates (Kovaleski and Mastrangelo 2021; Liedo et al. 2021).

Since suppression is the strategic objective in these situations, these permanent buffer zones do not require the establishment of rigorous quarantine procedures, and can be much more modest than those required for containment or eradication programmes. Nevertheless, the width of these buffers also needs to be determined, taking into account pest mobility, host density, tolerable damage threshold, and population pressure from the surrounding areas (Barclay et al. 2011).

Figure 8. The permanent buffer zone in the Darien Gap in Panama, consisting of the weekly release of sterile *New World* screwworm flies. (Map from R. B. Matlock, adapted.)

10. CONCLUSIONS

Insect pest control using an AW-IPM approach with an SIT component is more complex and management-intensive than applying simpler control methods, and hence requires more initial baseline data collection, feasibility assessments, careful planning, and stakeholder involvement to ensure effective implementation. The SIT is a very powerful technique; for more than a half century it has been applied successfully for the eradication, suppression, containment or prevention of major insect pests. Unfortunately, too often it has been promoted as a “silver bullet”, resulting in unrealistic expectations that then often cannot be fulfilled.

Programmes that attempt to eradicate a target insect population are particularly ambitious and challenging, but in reality are often poorly prepared, frequently underfunded, and lacking in public and in regulatory support to achieve their objective. In some cases, such programmes are operating without even the indispensable establishment of quarantine measures to protect a pest free area. In some of these situations, changing the strategy from eradication to containment or suppression is a more realistic option, but changes during ongoing implementation are politically costly, even if eventually successful. More modest initial goals, starting with a suppression objective to reduce insecticide use, or a containment effort to stop the spread of a pest, are often more realistic. If successful, such strategies can, under more favourable political, financial or technical situations, eventually be upgraded to an eradication strategy (Staten and Walters 2021).

Before embarking on an AW-IPM programme with an SIT component, the choice of strategy must be carefully assessed and prepared during pre-intervention and preparatory phases, ideally following a phased conditional approach, so that the programme is based on a thorough understanding of the target pest population as well as on adequate planning and implementation of the operational phase.

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