CHAPTER 3.6.

SUPPLY, EMERGENCE, AND RELEASE OF STERILE INSECTS

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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 mass-production and sterilization of insects, as well as subsequent shipment, adult emergence, holding, feeding, collection, and field-release activities based at production or emergence and release facilities (ERFs), are vital components of applying the sterile insect technique (SIT). Mass-rearing, and these post-factory SIT activities, have evolved into a well-established modular/industrial process that has adapted and adopted manufacturing principles such as the development of standard operational procedures (SOPs) and quality control (QC) standards, allowing a common understanding/agreement between producers and users of sterile insects at satellite ERFs. Shipment practices for short- and long-distance transport are well documented, and it is likely that they will continue to be developed and improved for current and new insect species according to their biological needs. Procedures for insect emergence, feeding, and holding for sexual maturation of sterile insects (including the designs of new holding containers) have gradually evolved because of a better understanding of their biological requirements. ERFs specialize in insect emergence, holding, providing food and water to the adults, maturation, and collection for release. For some target pests, such as moths, adults can be collected after emergence for direct transport and release, without previous holding and feeding of adults. Release of sterile insects varies depending on the species and the nature of the area-wide integrated pest management programme (AW-IPM). This chapter also reviews the methods of release – static, ground, and aerial (using aircraft with fixed-wing or rotary-wing, and unmanned aerial vehicles (UAVs)). Recently, developed technology has allowed prototyping of release equipment designed for UAVs. New release boxes and machines for a wide range of insect species have been developed, aiming to optimize equipment that enables variation in release densities, and takes into account other operational considerations according to the needs of action programmes. New ground- and aerial-release equipment has been tested and put into operation -- increasing the quality of the released insects. Through the use of combined GPS/GIS, dedicated software, and devices plugged into computers and the internet, additional progress has been made in implementing electronic/navigating equipment that enables knowing the precise location of insect releases and recording the conditions of their aerial broadcast. These developments enable the delivery, monitoring, and supervision of releasing sterile insects, with the results available in real time. The private sector has actively participated and demonstrated continued interest in the provision and processing of sterile insects, as well as aerial GPS/GIS guided release.

1. INTRODUCTION

During the past decades the mass-rearing of insects has been developed further, with major improvements in the industrialization of the production process for the application of the sterile insect technique (SIT). By documenting their procedures

and practices, some mass-rearing facilities (MRFs) have established/received ISO 9001–2015 certifications for insect rearing, thereby bringing about greater consistency in production numbers and insect quality (ISO 2019; E. M. Ramírez-Santos, personal communication). All these mass-rearing activities are the focus of the chapter by Parker, Mamai et al. (this volume). In addition to these improvements in the production of sterile insects, there have been significant advances in the quality-control processes (covered in detail in the chapter by Parker, Vreysen et al., this volume) that have increased the availability and supply of sterile insects for their use in area-wide integrated pest management programmes (AW-IPM) worldwide.

This chapter focuses on the receiver/end-user of SIT implementation, i.e. the post-factory activities after sterile-insect production, marking and sterilization activities at MRFs. They take place mostly at emergence and release facilities (ERFs) located either at or near production sites, or near distant target release sites to which the sterile insects are usually shipped in bulk as pupae. Activities carried out at ERFs and during preparation for release are discussed, including the adoption of improved processes related to the chilled adult release technique (Tween and Rendón 2007), through which sterile insects are emerged, maintained, and fed for several days, and then chilled and released as robust and competitive sterile insects via novel technologies.

After leaving a MRF, nutritional, semiochemical, and other treatments applied to adult sterile insects (to improve their field performance) are the focus of the chapter by Pereira et al. (this volume).

2. SUPPLY OF STERILE INSECTS

2.1. Availability from Established Mass-Rearing Facilities

The most rapid and cost-effective way (at least in the short-term) to obtain a continuous supply of sterile insects is by their purchase/importation from an established MRF that rears the required target species (Dowell et al. 2000; Blomefield et al. 2011; Bjeliš et al. 2016; Horner et al. 2016; section 4.6.). In the case of long-distance transport, of course cost-effectiveness depends on the shipment; for long distances the shipping cost can be considerable, and the shipping duration can affect sterile-insect quality. However, especially when containment or eradication programme activities are urgent, outsourcing sterile insects enables operational programmes to avoid spending time and economic resources on the training of personnel, planning, and construction required to establish an MRF. Establishing and maintaining an operational MRF is a demanding economic endeavor that is time-consuming and requires major investment. Instead, by procuring sterile insects, emergency programmes can rapidly integrate the SIT, e.g. eradicating a pest outbreak such as the 2015–2017 eradication of the Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) in the Dominican Republic (Zavala-López et al. 2021). The tsetse eradication programme in Senegal decided not to build an MRF but to outsource the sterile flies from Burkina Faso (Vreysen et al. 2021) -- a wise decision for programmes that will no longer require the MRF after achieving eradication.

Also, there are examples of programmes that routinely purchase sterile flies because the target areas are relatively small, e.g. the *C. capitata* fruit fly programmes in Croatia (Bjeliš et al. 2016) or Patagonia (De Longo et al. 2000), or where no MRF can be established for regulatory reasons in pest-free areas, such as the preventive release programme (PRP) in California (Dowell et al. 2000). Other programmes begin by buying sterile flies (for some years) so as to establish and gain experience with SIT operations, while planning and eventually establishing their own mass-rearing facilities -- examples are the *C. capitata* programmes in Israel, Morocco, and Spain (Primo 2003; Cayol et al. 2004; Qadda 2017).

There is a limited number of insect species for which MRFs are well established: Mediterranean fruit fly, Mexican fruit fly *Anastrepha ludens* (Loew), West Indian fruit fly *Anastrepha obliqua* (Macquart), melon fly *Zeugodacus cucurbitae* (Coquillett), Queensland fruit fly *Bactrocera tryoni* (Froggatt), codling moth *Cydia pomonella* (L.), false codling moth *Thaumatotibia leucotreta* (Meyrick), and pink bollworm *Pectinophora gossypiella* (Saunders). Additionally, mass-rearing facilities for some veterinary and medical pests have been successful: New World screwworm *Cochliomyia hominivorax* (Coquerel), tsetse flies *Glossina austeni* Newstead, *Glossina fuscipes fuscipes* Newstead, *Glossina palpalis gambiensis* Vanderplank, and *Glossina pallidipes* Austen, and Asian tiger mosquito *Aedes albopictus* (Skuse).

In general, MRFs are built to produce sterile insects for their own programme requirements, and therefore only a few of them have the capacity or interest to produce sterile insects for customers in addition to those needed for their own use. Despite the perceived shortage of sterile-insect supply, there has been much collaboration between programmes to supplement sterile insects when the need arises. The Joint FAO/IAEA Programme maintains a database of rearing facilities, capacities, and contact information (IDIDAS 2019; Bakri et al., this volume).

Due to their role in national plant protection or animal/human health, most of the sterile insect release programmes have some form of government involvement (Dyck, Reyes Flores et al., this volume). They operate with limited budgets, and are driven by an urgent need to manage serious pests to limit pest damage, confine the pest to the smallest area possible to reduce operational costs, and maintain or open markets for locally-produced commodities. Therefore, as a complement to other control activities that the programmes may implement, a reliable source of good-quality sterile insects at an affordable cost is always in demand. The provision of insects by government-operated institutions is usually conducted through bilateral agreements and on a full cost-recovery basis, including the depreciation of facilities and equipment. Often the "excess" capacity of an MRF, where output exceeds direct programme needs, may not always be available as it is dedicated to others through contractual agreements to prioritize such partners in case of emergency needs.

The production cost per million insects (eggs, pupae, adults) can be greatly reduced with economies-of-scale (Parker, Mamai et al., this volume). As a rule, due to their cost of construction, most MRFs were built undersized rather than basing the production output on a per-insect unit cost. In small rearing facilities, the fixed costs are relatively high, therefore increasing the production cost per million sterile insects.

One major improvement in the rearing and release of some insect species is the feasibility of deploying only sterile males, through the use of genetic sexing strains (GSSs) (Franz et al., this volume) or other approaches (Papathanos et al. 2018). In general, this option reduces by half the costs of insect dyeing/marking, irradiation, shipping, and aerial release, while increasing SIT effectiveness when compared with standard/both sex releases (Hendrichs et al. 1995; Rendón et al. 2004). The introduction of GSSs that remove females before their shipment, coupled with rearing efficiencies and economies-of-scale, greatly reduce product and shipping costs in addition to reducing the cost of processing insects at ERFs.

2.2. *Processing Insects for Release*

There are three common approaches to managing sterile insect production and release:

- Operate a centralized facility that combines an MRF with an ERF that prepares sterile insects for release (Schwarz et al. 1985; Ortiz et al. 1987; Nakamori et al. 1992; Liedo et al. 1993; Msangi et al. 1999; Bloem and Bloem 2000; Koyama et al. 2004).
- Operate an MRF for rearing and sterilization, and one or more satellite ERFs to which sterile insects are shipped and where they are processed for the releases (IAEA 2008).
- Receive eggs from another MRF for local rearing, sterilization, and release (section 4.6.2.).

2.2.1. *Centralized Facilities Combining Production with Emergence and Release*

The decision to establish a combined production-release facility versus separate ERFs is normally linked to convenience (directly at the MRF or located nearby close to or at the local airport used for aerial releases), as well as the size and distance from the target release areas. When these can be serviced from the local MRF/ERF without excessive ferry times, there is no need to establish satellite ERFs.

One of the advantages of locating an ERF next or close to an MRF is that preparing insects for release at the place where they are reared eliminates the extra operations of packing the sterilized insects for shipment and sending them to a satellite ERF; it also has the added advantage that, due to the lower hypoxia time during pupal shipment, the quality and quantity of sterile insects available for releases increases (Arredondo et al. 2018). Due to the progress in control activities within the Moscamed action programme in Guatemala, an ERF has been established directly at the El Pino mass-rearing facility; this unit is experiencing an increase of insect quality due to reduced hypoxia and handling (E. M. Ramírez-Santos, personal communication).

For the eradication of *Glossina austeni* in Zanzibar, sterilized tsetse fly adults, produced and emerged in Tanga, Tanzania, were released aerielly in degradable cardboard boxes over Unguja Island, resulting in the elimination of the trypanosomosis disease in cattle (Msangi et al. 2000; Vreysen et al. 2000). In the pink bollworm programme in the USA, moths were reared, sterilized, and emerged

in Arizona, but then flown to and directly released in California (USDA 1995; Walters et al. 2000; Staten and Walters 2021). A single centralized facility produces and releases sterile codling moths in British Columbia, Canada (Bloem and Bloem 2000; Nelson et al. 2021), and also ships them successfully to South Africa and New Zealand (Blomefield et al. 2011; Horner et al. 2016; Dyck, Reyes Flores et al., this volume). In the 2016–2017 eradication of the New World screwworm outbreak in Florida, sterilized pupae from the MRF in Panama were shipped to the USA, where the pupae were directly placed into ground-release chambers in the field from which adults emerged (USDA/APHIS 2017; Skoda et al. 2018).

Regardless of whether there is a single centralized production-release facility, or additional satellite ERFs, it is an advantage to have a single management structure for a programme, allowing efficient decision-making and the rapid exchange of information among the components of the mass-rearing and release processes (FFEPO 1999; Dyck, Reyes Flores et al., this volume).

2.2.2. Satellite Facilities for Emergence and Release Only

Flying emerged sterile adults to distant target areas for release can result in long and costly ferry times that may be detrimental to insect quality; the establishment of ERFs strategically located near the release sites to minimize ferry times is the more viable alternative in these cases.

The operation of satellite ERFs has several additional advantages: (1) sterile insect programmes can work in areas that, for regulatory reasons, cannot have MRFs, (2) one large MRF, operating at increased economies-of-scale, can provide insects to several satellite facilities, often in different countries, and (3) several insect species can be simultaneously prepared for release.

The shipment of sterile insects to satellite ERFs enables them to be placed in areas generally free of the target insect without the risk of fertile pest insects escaping from a local MRF (Dogan et al. 2016). This is important if the goal of the programme is the eradication of isolated invasions of the target pest, or its exclusion from an area free of it through preventive releases. Thus, sterile pupae, for example of the Mediterranean fruit fly, Mexican fruit fly, and New World screwworm, can be shipped from MRFs located in areas where these pests occur to ERFs in areas free of permanent infestations (USDA 1995; CDFA 2002).

The use of satellite ERFs gives maximum flexibility to the release of sterile insects. One large MRF can provide sterile pupae to several satellite facilities scattered throughout a region. For example, producing sterile fruit flies in large MRFs in Guatemala and southern Mexico, and shipping them as pupae to a chain of ERFs in northern Mexico, as well as California and Florida, has been more cost-effective from an operational standpoint (USDA/APHIS 2009; Enkerlin, this volume).

Satellite ERFs are less complex in their design than centralized MRFs, and often do not require permanent construction. As programme needs change, satellite ERFs can be relocated. The satellite ERFs, used to prepare sterile New World screwworms for release, moved steadily southwards from Mexico to Panama, as the screwworm eradication programme progressed through Central America, but the MRF continued to operate in Mexico (Wyss 2000) until a new MRF became operational at Pacora,

Panama (Scott et al. 2017; Vargas-Terán et al., this volume). This approach should be followed when several countries/regions have a common pest problem, avoiding duplication of efforts in the construction and operation of rearing facilities, while reducing costs due to economies-of-scale and servicing several countries with the large production of sterile insects.

Several species of sterile insects from different MRFs can be handled in a single ERF facility. In California, the same staff processes Mediterranean and Mexican fruit flies at the same satellite ERF located at Los Alamitos. Recently, the states of Florida (Fig. 1) and California produced floor plans to renew their existing ERFs after the successful establishment of the concept of preventive release programmes (PRPs) (which have greatly reduced the cost of eradicating invasive populations while avoiding the establishment of Mediterranean and Mexican fruit flies) (Hendrichs, Enkerlin et al., this volume). These new ERFs already included additional space to allow for the emergence and release of other pest species.

Figure 1. United States Department of Agriculture (USDA) sterile insect emergence and release facility, Sarasota, FL, USA (USDA 2019). (Photo from Halfacre Construction Co., Aerial Innovations of Florida, and J. Renshaw, 2018, reproduced with permission.)

The different goals and physical separation of MRFs and ERFs can result in more attention and focus on field operations, and in the case of independent customers provide a more objective assessment of sterile insect quality. Conducting product quality control tests in accordance with agreed procedures, and exchanging these results between MRFs and ERFs, provide a better way to monitor quality and address end user/client concerns.

There are rearing issues where real cause/effect needs to be documented to avoid supply or quality reductions. In some instances, the problems observed in the rearing or transportation processes are only brought to light after the satellite ERFs note a decrease in the quality of the resulting insects being prepared for release, while sometimes the problem might also be the result of mishandling at the ERFs. Currently, with the improved availability of electronic means of communication and electronic data storage, shared boxes or drives (with access by sterile insect producers and receivers/users) can be dedicated to report results on quality by independent testing at MRFs and ERFs for feedback and comparisons. Statistical analysis of the data has also enabled the preparation of quality-control charts that

gradually raise, or at a minimum monitor and maintain, insect quality over time (FAO/IAEA 2018a).

2.3. *Commercial Production and Release of Sterile Insects*

There are advantages and disadvantages to both governmental and private suppliers of sterile insects (Dyck, Reyes Flores et al., this volume). Government suppliers, unlike private suppliers, may be willing to develop insect MRFs for which there is a potential need, but not necessarily a continuous demand, as in the case of eradication programmes (Quinlan and Enkerlin 2003). They fund programmes to develop the SIT against new pests such as the sweetpotato weevil *Cylas formicarius* (F.) (Kohama et al. 2003; Kumano et al. 2011) or the cactus moth *Cactoblastis cactorum* (Berg), or programmes that demonstrate the feasibility of funding and implementing the SIT in new ways, such as taxing the local community for codling moth suppression, or applying public-private partnerships for false codling moth AW-IPM programmes. Governments can also establish programmes that cross several political entities, such as the pink bollworm programme on both sides of the Mexico-USA border (Simmons et al., this volume), the Mexican fruit fly preventive release programme along the California-Mexico border (Enkerlin, this volume), or the release of New World screwworms along the Panama-Colombia border (Skoda et al. 2018; Vargas-Terán et al., this volume). Governments are more likely to invest in research designed to develop potential new technologies for use in mass-rearing and release programmes if the pest is considered to be a potential animal/human health or phytosanitary threat.

However, government-funded facilities have several drawbacks, one being the tendency to change policies and/or funding priorities, e.g. after elections. Thus, a programme that had the strong support of one administration may find its budget reduced or eliminated by another (Dyck, Reyes Flores et al., this volume). This can make programme managers feel insecure, postpone needed changes in programme procedures or facility upgrades, and make growers, ranchers, and other stakeholders reticent to support the programme. Another major drawback of government funding is the tendency to ask the programme to do more and more with a static budget. This leads to decisions that tend to lower the quality of sterile insects produced while keeping the numbers of insects produced and released high (Liedo et al. 1993). This can have a negative impact on programme success, which consequently will often lead to further funding cuts that continue the cycle of problems and often cause reinfestations to occur, making the suppression or eradication efforts appear not to be technically feasible because of the budgetary inconsistencies.

The affected agricultural industries can play a major role in creating awareness of the importance of sterile insect programmes among their members, government leaders, and the public (Dyck, Regidor Fernández et al., this volume). They can help develop confidence in the use of sterile insects for eradication or pest suppression. This will generate a demand for the sterile insects that, in turn, will attract private companies to invest in production plants necessary to meet this demand.

In the Mediterranean region, bait sprays have traditionally been used to suppress major pests such as the Mediterranean fruit fly and the olive fruit fly *Bactrocera*

oleae (Rossi). Encroachment on traditional production areas by “urban sprawl”, and the expansion of tourist resorts, makes the future of aerial-bait applications increasingly untenable. In 2009 the European Union prohibited aerial spraying of pesticides (EU 2009), thereby effectively ending most aerial application in all member states and overseas territories. Nowadays, aerial spraying in the EU requires special authorization by local governments (but only when justified by emergency conditions).

As a consequence, the integrated use of sterile insects, with the objective of routine area-wide pest suppression, has great potential for commercialization (Hendrichs et al. 1995; Hendrichs, Vreysen et al., this volume). The agricultural industry itself is searching for, and promoting the development of, more environmentally acceptable measures to substitute less acceptable technologies developed more than 50 years ago. Private companies are increasingly participating in the production and provision of sterile insects, e.g. de Groene Vlieg in the Netherlands (De Groene Vlieg 2019), BioBee in Israel (Bassi et al. 2007; BioBee 2019), and in South Africa FruitFly Africa Ltd. (Venter et al. 2021) and Xsit (Boersma 2021), although most of these private-sector services are providing sterile insects to customers in their own countries.

Most programmes contract with private firms to provide the aerial services for sterile insect release. Some also contract for part or the whole of sterile insect emergence and release processes. For example, the Mexican National Fruit Fly Campaign has outsourced the operation of five Mexican fruit fly and West Indian fruit fly ERFs in Mexico (Leal Mubarqui 2005; Bassi et al. 2007). Private companies are paid per flight hour, from take-off to landing, or in some instances for actual engine-time utilized (based on the Hobbs meter); both are valid practices. An exception is the Mexican fruit fly programme in Texas, where the aircraft is owned by the United States Department of Agriculture (USDA), and the pilot is an employee of the US government. The Animal and Plant Health Inspection Service (APHIS) of the USDA uses this aircraft to design and develop new technologies for releasing sterile insects.

Experience in the USA and elsewhere indicates that usually it is cheaper to contract with a private company (to provide aircraft and pilots) than to purchase aircraft and pay for maintenance, full-time pilots, and mechanics. However, this may not be true in all countries (due to limitations in the offer of such services), and a detailed economic analysis needs to be conducted for each programme. Due to the continuous search for operational efficiencies, action programmes are actively looking for alternatives to conduct aerial releases through the use of unmanned aerial vehicles (UAVs); this initiative has already developed some alternatives for some pest species, for example mosquitoes, where releases are often concentrated over villages or towns (section 5.3.3.).

3. SHIPPING STERILE INSECTS

There is a major advantage to producing, marking, and sterilizing insects in an MRF, and then shipping them to an ERF that is dedicated to emerging, holding, and releasing the sterile insects. Shipping procedures are well known and tested. Sterile

insects, e.g. codling moth, Mediterranean fruit fly, New World screwworm, and tsetse flies are shipped routinely to near and distant places (Enkerlin and Quinlan 2004; Blomefield et al. 2011; Rull et al. 2012; FAO/IAEA 2014, 2016b, 2017a, b, 2018b; Horner et al. 2016; Dyck, Reyes Flores et al., this volume).

3.1. *Shipping Time, Distance, and Insect Quality*

At present there is still a limit on how far sterile insects can be shipped. Adult emergence and flight ability decrease with increasing shipment time, even when shipping pupae in a low-oxygen atmosphere (hypoxia) – an effect that seems to be reduced in some species such as *Bactrocera tryoni*, where a decline in adult emergence of 0.1%/h (inside sealed plastic bags for periods up to 192 h at 17°C) has been reported (Dominiak et al. 2011a). For example, sterile Mediterranean fruit fly pupae have been shipped successfully from Guatemala and Mexico to Argentina, Austria, Chile, the Dominican Republic, Israel, South Africa, and the continental USA (Dyck, Reyes Flores et al., this volume). They have also been shipped from Argentina to Spain, from Israel and Spain to Croatia, and from Portugal and Spain to Morocco, etc. Since 2010, sterile Mexican fruit flies have also been shipped from Guatemala to South Texas, and Reynosa and Tijuana in northern Mexico, with high-quality parameters reported after shipment. In general, the hours of pupal hypoxia have been in the range of 43–45 h (departure to arrival) (M. López, personal communication).

Enkerlin and Quinlan (2004) developed an international standard to facilitate the transboundary shipment of sterile insects. A summary of worldwide transboundary sterile insect shipments during the last 50 years can be found under FAO/IAEA (2018b).

Shipments of sterile insects are often conducted by renting space in the cargo compartment of commercial airlines (fitting in the containers/boxes that will deliver an agreed number of sterile insects). Usually a broker company is contracted to arrange documentation for customs and the airlines. Optimized flight routing is mandatory to reduce time in transit, the number of airports used, and detours made. Delays in shipments do occur -- some of them are due to security measures, mistakes in paperwork, changes in routing or the airlines shifting their priorities to baggage (cargo is then not loaded, generating delays in the arrival time at the final destination). If pupae are kept under hypoxia for longer than the documented/expected periods of time, the quality of the resulting adult insects decreases (FAO/IAEA 2017a, b; Arredondo et al. 2018).

When shipping to exceedingly distant destinations, the packing configuration is modified so as to contain coolers and ice packs in sufficient number to ensure that temperature and relative humidity conditions are maintained (Pagabeleguem et al. 2015). Although not under hypoxia, the quality of tsetse adults suffers if the pupae are kept chilled too long (Mutika et al. 2002, 2014). Before starting routine shipments, trial shipments between interested rearing and release facilities should be sent so as to document shipping routes, costs, and final product quality before assuming viability or non-viability of the supply.

3.2. *Shipping Eggs*

An additional form of insect supply is to ship the early development stages of insects, which will then be reared at the recipient MRF. Mediterranean fruit fly thermally-treated eggs (to kill female eggs for the production of only males), and the black-pupae strain (BPS) of the Mexican fruit fly, are routinely shipped with little or no loss in yield or quality of the resulting sterile adults (IAEA 2002; H. Conway, personal communication). This procedure avoids the problems associated with maintaining pupae under hypoxia for long periods of time. As the volume and weight of eggs are far less than those of pupae, shipping costs are substantially reduced. For example, one litre of eggs is equivalent to almost 5 million pupae. Of course, egg shipment still requires MRFs for producing males and sterilizing them at the receiver end. Currently, 9 litres of Mediterranean fruit fly eggs of a *tsl*-genetic sexing strain are shipped daily from the El Pino production facility in Guatemala to the production facility in Metapa, Mexico. Purchasing eggs is a very reliable process, enabling the receiving programme to avoid maintaining a viable colony of fertile adult insects for egg production (since escapes are always a security concern in areas declared or about to be declared free of the pest). One additional advantage is that it also avoids the costs and the intricacies of the maintenance of filter-reared colonies of GSSs (Fisher and Caceres 2000; Franz et al., this volume; Parker, Mamai et al., this volume).

3.3. *Shipping Adult Lepidoptera*

In general, lepidopteran species are shipped as chilled sterile adults. One reason is that larval or pupal separation from diets is complicated; another is that sterilizing adults instead of pupae results in more competitive insects (Stewart 1984; Dyck 2010; Boersma 2021; Bakri et al., this volume). Lepidopteran species (such as codling moths) shipped as adults can tolerate more than 60-h shipments (Blomefield et al. 2011). Shipments of codling moth pupae and adults from Canada to New Zealand and South Africa provided support to the suggestion that the SIT for codling moth (in pome-fruit production areas) might be implemented by the importation of irradiated chilled moths from rearing facilities in a different country or hemisphere (Blomefield et al. 2011; Horner et al. 2016). The success in these shipments points out the need to explore new methods or conditions for transporting pupae and/or emerged sterile adults from the MRF to where they are to be released (Dyck, Reyes Flores et al., this volume).

3.4. *Shipping Costs*

One important consideration related to the establishment of satellite ERFs is the cost of shipping sterilized insects (Wyss 2000). For example, the shipping cost alone to send New World screwworm pupae to Libya (packed in cardboard boxes for adult emergence and direct release) was four times the purchase price, and four times the dispersal cost. Shipping cost is reduced by 50% if using GSSs (where females are removed, enabling the shipment of only males).

The shipping cost of sterile Mediterranean fruit flies from El Pino in Guatemala to California and Florida PRPs is about 16–18% of the total cost of one million pupae plus shipment (E. M. Ramírez-Santos, personal communication), while for the Mexican fruit flies shipping from Guatemala to the continental United States is about 11% (M. López, personal communication); both facilities produce and ship males-only of their respective rearing species. As in the case of mass-rearing costs, the unit shipping costs depend largely on the volume of pupae that are shipped. Shipments of low sterile fly numbers (less than 5 million per shipment) to pilot projects usually result in high unit costs due to the fixed costs of the customs broker company.

In addition to issues related to insect quality, increasing shipping distance results in increasing shipping costs and delays that are also a concern for the supply of sterile insects to EFRs and action programmes. The New World screwworm production facility in Tuxtla Gutierrez, Mexico, provided the sterile flies for the Central American eradication programme. However, with increasing shipping distance, both the shipping costs, and the potential for problems, including delays in the shipping process, increased (FAO 1992; Wyss 2000). By 2006, a new mass-production plant for the New World screwworm was inaugurated in Panama, and now supplies the sterile fly barrier in the Darien region along the border between Panama and Colombia (Hendrichs, Vreysen et al., this volume; Klassen et al., this volume; Vargas-Terán et al., this volume).

4. EMERGENCE AND RELEASE FACILITIES

4.1. Location, Design, Building Materials, and Construction

Strategic placement of the ERFs, and therefore their sterile insect release activity, is relevant to operational efficiency and costs. ERFs that are located close to the areas where control activities are conducted by the action programme will see their operating costs reduced. Having ERFs equidistant from all the areas where releases are conducted reduces costs in expensive ferry times to conduct releases and return to airport landing strips. For the selection of sites to establish an ERF, action programme decision-makers need also to consider all the adverse conditions that will prevent aircraft from conducting their insect release activity and avoid/minimize them while selecting the location. Among the various factors to consider are rain patterns, prevailing winds, and the presence of commercial airports in close proximity that could limit the operation, etc. When choosing a site for the establishment of an ERF, there are other requirements (which facilitate the stability of the operations) that need to be considered, e.g. having an adequate site not too far from all the facilities of a medium-sized metropolitan city (for the convenience of the workers and obtaining equipment-repair services) but still a distance from it so as to avoid disruption of daily operations (FAO/IAEA 2004, 2012; Parker, Mamai et al., this volume).

It is relevant that ERFs have a dependable supply of electricity; nevertheless, the facility should also budget for the provision of an emergency plant generator. The provision of potable water is essential for the ERF; however, the provision of

municipal water and/or the drilling of its own well and water purification system will avoid any shortages in the amounts of water that are required for this type of operation. A water-treatment plant may also be needed because the sewage in ERFs is often contaminated with fluorescent powder arising from the washing of holding boxes or trays and racks; this can be a big problem unless properly addressed.

An ERF also needs to be close to a good ground-transportation system. This reduces the cost of transporting sterile pupae or adults, and also reduces the time that pupae or adults are in transit, thereby increasing the quality of the resulting adult insects. When eradication programmes are progressing in their control activity, it may be necessary to change the ERF's location to increase operational efficiencies and insect quality, as well as to reduce operational costs. Therefore, in long-term eradication campaigns, the ERFs may be designed to be movable or permanent, and their layout will be influenced by these needs.

Some emergency programmes use trailers or refrigerated trailers and basic insect containers (such as buckets or Plastic Adult Rearing Containers (PARC) used for the PARC system) and paper bags (in which to emerge and release adults either aially or by ground) (Fig. 2), thereby rapidly solving the problems that appear in an emergency programme in which the goal is to eradicate the pest as soon as possible with minimal investment in equipment and infrastructure. On the other hand, in other pest control situations, such as the PRPs or long-term exclusion/eradication programmes, in which continuity of operations is foreseen, the design and selection of building materials for the establishment of ERFs shifts to more permanent constructions, choosing in this case materials such as metal structures combined with block and concrete.

In general, ERFs are designed with a modular layout. Each of the modules/rooms is implemented to maintain sterile insects for several days with adequate environmental conditions (temperature and relative humidity) that will enable insects to emerge and mature sexually – for subsequent release using the release method of choice. The size of rooms is designed to emerge and hold the number of insects that are released each operational day; this usually coincides with the number of sterile insects that is received daily from one or sometimes two MRFs. Some ERFs process and release sterile insects every day, others only during weekdays; the capacity of the ERF is based on the operating and release requirements.

4.2. Environmental Control Equipment

The environmental conditions under which sterile insects are maintained prior to their release play an important role in their adult emergence time, sexual maturity, feeding status and survival in the field. ERFs need to consider the relationship time/temperature accumulation, e.g. degree days, to set adult emergence room temperature to ensure adequate time (in hours) for emergence and associated age/sexual maturity reached at the time of insect release (Parker, Mamai et al., this volume).

Also, relative humidity plays an important role. If it is too low, it may be difficult for an adult to emerge, and thus it uses up critical energy reserves prior to release. Regarding the feeding status of the insects, low humidity dehydrates sterile

insects, as can some food sources, reducing vitality and numbers. On the other hand, in a high-humidity environment, insects stick to one another or to the screen surfaces and food; excess humidity also promotes the presence of unwanted fungal development on top of the food provided. Therefore, adequate humidity levels, along with appropriate regular cleaning of emergence rooms and equipment, are relevant to avoid contamination of surfaces (Abd-Alla et al., this volume).

Since the ERFs operate 24 h/day year-round, even if releases are only conducted in some instances during weekdays, the environmental conditions need to be monitored constantly because deviations from the required conditions can have great impact on the release numbers and insect quality.

Figure 2. Mediterranean fruit fly emergence and release facility in Retalhuleu, Guatemala, showing clockwise: A: Worker placing sterilized dyed pupae into a PARC emergence box; B: Stapling paper bags in the centre to permit flies to leave the bag; C: Placing one modified agar-block diet; D: Stacks of six PARC boxes inside an adult emergence room. At the Neretva Valley, Croatia, Mediterranean fruit fly programme: E: Machine for loading pupae into paper bags; F: Adult emergence room containing bags for fly emergence. Water is provided/sprayed through the surface of the bag.

4.3. Facility Operation

In general, the ERFs that receive shipments of sterile pupae operate with a building layout as follows:

- *Reception area* – workers assigned to this area are responsible for receiving and preparing the pupae when they arrive from the MRF. In this area, the conditions

of the biological material are documented on arrival, e.g. temperature, the irradiation dosimeters are visually verified, and the weights of the biological material received are checked to calculate the total number obtained in the shipment. Additionally, an observation of the external dust-dye is conducted to determine if there are problems with water condensation, lack of fluorescent-dust marking, or others (nowadays MRFs document the percentage marked pupae prior to shipment departure) (section 4.3.). The pupae are then moved to the next step in the process.

- *Pupae distribution* – this area is used to place, manually or by automated systems (Fig. 2E), the biological material inside containers (PARC boxes or adult emergence towers) that will enable adult emergence and feeding for a predetermined number of days. In parallel to this process, the adult food is applied or placed prior to insect emergence (food is usually prepared ahead of time in diet-cooking rooms) (section 4.4.).
- *Diet-cooking room* – a kitchen that usually has several boilers or kettles to prepare agar-based food. As alternatives to this type of diet, there are currently two additional options, a liquid diet and a diet that is a combination of both in which solid and liquid diets are combined inside the Mubarqui tower (Fig. 4).
- *Adult emergence and holding rooms* – usually as many as the number of days per week of programmed releases.
- *Aromatherapy room* – for the species that have this option to enhance mating activity (Pereira et al., this volume), the size of this room allows for at least one-day-release capacity; alternatively, this type of “sexual pre-conditioning” treatment can be conducted within the last adult emergence room a day prior to insect release using existing adult emergence rooms.
- *Chilling room* – for insect species where chilled adults are transported and released in aerial or ground releases (Tanahara et al. 1994); some programmes supplement aerial releases with ground releases of chilled adults.
- *Washing area* – for cleaning and drying materials and equipment used in the adult emergence and release process; in this area industrial washing machines are employed to clean PARC boxes or tower trays.
- *Quality control (assurance) area* – the biological characteristics of the sterile insects received, as well as those that are released in the field, are measured and documented (Parker, Vreysen et al., this volume). Early efforts at judging the quality of sterile insects focused mainly on the adult insect (Calkins 1989; Calkins et al. 1996; Dominiak et al. 2014; Fanson et al. 2014; FAO/IAEA/USDA 2019), and only pre-/post-irradiation on arrival at an ERF. These insects are subjected to measurement of various parameters: emergence, survival, flight, and mating competitiveness (Ortiz et al. 1987; FFEPO 1999; Koyama et al. 2004). The current approach is also to include in the measurements all those parameters that will describe the quality characteristics of sterile insects before and after their field delivery (FAO/IAEA/USDA 2019).
- *Administration* – area to provide administrative support to all technical activities of the ERF operations, processing bills, personnel technical assistance, and other logistic needs.
- *Methods development* – area designed to evaluate and validate rearing and

quality-control practices prior to or during their implementation at the ERF operations.

- *Maintenance* – for personnel dedicated to resolve operational and maintenance problems with equipment and buildings, as well as prototyping equipment and other needs.
- *Warehouse* – space must be provided for storing high-quality diet materials. Delivery times, rates of consumption and others (local vs. imported diet materials) should be calculated to allow sufficient areas for process/human safe storage of products. For the operation of ERFs, the number of ingredients to prepare adult diets is reduced when compared with those in an MRF. For most insects, this means access to locally produced products (IAEA 2008). It is very important that these diet materials are free of insecticide residues.

5. EMERGENCE AND COLLECTION OF STERILE INSECTS

5.1. *Holding, Marking, Feeding, and Collecting Adults*

In some target species, such as fruit flies, tsetse flies, and mosquitoes, adults need to be held after emergence for various periods in different types of containers for feeding and maturation; then they are collected for release by moving the holding containers to cold rooms (where the low temperature makes them quiescent).

5.1.1. *PARC System*

In many AW-IPM programmes that integrate the SIT, sterile pupae are shipped to ERFs where they are placed into containers in which adults emerge. Systems for the emergence, holding and feeding of fruit flies prior to their field release have changed over time. An early system was the “bucket method” used for roving ground release (FAO/IAEA 2017a, b). This was followed by the paper bag system for aerial release (Nadel et al. 1967). Later, the PARC system was developed for the aerial release of chilled flies (shown in Fig. 2, where preparations are being made for Mediterranean fruit fly emergence using PARC boxes). This system was developed by the USDA (Mabry 1986) to replace the earlier paperboard Tanaka box, developed by the California Department of Food and Agriculture (CDFA). The PARC system, an improvement over the Tanaka box, permitted the containers to be sanitized after each use, and reduced the number of escaped flies within an ERF.

The use of these systems requires that the sterile pupae be dispensed into paper bags at a predefined amount; six bags are placed into each PARC box. Once filled with pupae, the bags are then loosely stapled at the top to allow emerging sterile flies to escape and live and feed inside the container until they are ready for field release. Screen panels on the sides of the container provide ventilation, and a screen panel in the lid permits the flies to feed on a gelatinous slab consisting of agar, sucrose, water, and a food preservative -- usually sodium benzoate or methylparaben. This stackable PARC system (Fig. 2D) requires much controlled-environment space to hold a large number of these bulky containers during the emergence and fly maturation period. It is also labour-intensive, although recently

automated systems have been designed for both loading the pupae (Figs. 2, 3) and cleaning the boxes using industrial washing machines. Paper bags are costly, both in direct and waste-disposal/littering cost. Also, some flies are lost when the bags are destroyed. This PARC system is still used today in some release programmes (although there is a gradual trend to implement newer technologies) or in emergency situations e.g. the 2015–2017 eradication of *C. capitata* in the Dominican Republic (Fig. 2).

5.1.2. Tower System

In a gradual progress towards an ideal system, a sterile insect “emergence or Worley tower” was developed by the USDA in Mission, TX (Salvato et al. 2004) to improve upon the PARC boxes. This new “tower technology” also facilitates the concept of chilling insects and loading them into release containers for aerial dispersal using the chilled adult release technique (Tween and Rendón 2007). This tower system is currently used for emerging, feeding, and chilling/immobilizing Mediterranean fruit flies in Florida and California, and Mexican fruit flies in Texas (Fig. 3).

Each tower consists of interlocking screen-panelled aluminium frames (trays) stacked on a portable/movable base. Pupae are placed into a channel around the inside perimeter of each aluminium tray. One or two slabs of gelatinous food are put on each screen panel. Up to 80 trays can be stacked in one tower, producing a solid tridimensional aluminium block. To provide air circulation, a small direct-current axial exhaust fan is placed on the top of each tower (stack of trays) to provide forced upward ventilation within the tower. When flies emerge they move from the perimeter channel to the screen of a tray, while the empty puparia are left in the channel. The flies remain on the screen and feed for 4–6 days, the period required for maximum adult emergence. On the day of field release, the towers are moved into a cold room where higher-volume exhaust fans suck cold air ($\sim 4^{\circ}\text{C}$) into each tower to accelerate fly immobilization. After a period of exposure to the cold, the puparia are vacuumed from the channels, and the screened trays are manually turned upside down over a hopper (and pan beneath) to collect the chilled flies (Fig. 3). After the collected chilled flies are weighed, they are transferred to the aerial release box and transported to, and loaded into, a release aircraft (Figs. 10, 11).

Two additional tower systems (Hernández et al. 2010) are currently being used at the Moscamed programme in Mexico (Fig. 4) and Guatemala (Fig. 5). The Mubarqui tower system in Mexico has a larger surface area and volume for the flies to expand their wings, feed, and mature. The system uses a predesigned “Mubarqui diet” for feeding adults of Mediterranean and Mexican fruit flies (Fig. 4).

The two systems shown in Figs. 4 and 5 use the environmental room conditions (temperature and relative humidity) without the need for exhaust fans on top of the towers; this was the reason for not using the previously described “Worley tower system”. Electricity fluctuations generated too many inconsistencies in the operation of the many fans, thus their use was discontinued in favour of a new tower design.

Figure 3. Tower system for Mediterranean fruit fly -- stages in the emergence and collection of fruit flies using the tower system (Worley Tower). Upper left: Screen tray loader, showing an upper rotating-revolver mechanism (transparent containers) to load each tray with pupae. Upper right: Aluminium frame/tray, showing a slab of agar-based food diet and dyed pupae in a channel around the edge. Lower left: Stacks of trays forming towers, each connected (yellow cables) to a power outlet to operate a fan that draws air upwards. Lower right: Tower system for Mexican fruit fly -- screen trays in cold room with puparia removed from channels by suction, and chilled flies on screen being collected in a hopper. USDA/APHIS, Sarasota, FL, USA.

The other difference of the tower system used in Guatemala compared with the previous system is that it uses a “liquid diet”, replacing the expensive and cumbersome preparation, handling, and discarding of agar diets, and enabling the liquid diet to be replenished externally. This permits flies to be kept with no refill until they are released, or with a refill for longer periods when overcast climatic conditions prevent aerial release on the scheduled date (or for some different insect species that have longer maturation periods). These two additional tower systems use the same chilling process as the one described above for the “Worley tower”. Automated washing of the screens is also available for the liquid-diet tower.

Compared with the PARC system, the tower system improves considerably the quality of the flies to be released. Also, it reduces fly escapes as well as the required controlled-environment space, with a consequent reduction of fixed costs, although

there are obvious variations in the space requirements of the different systems described above. However, the optimal holding density of sterile insects in the tower system must be carefully determined because higher densities result in decreased sterile-insect quality (Hernández et al. 2010).

Figure 4. Left photo: Self-stackable 16-tray Mubarqui tower system for Mediterranean and Mexican fruit flies. Right photo: Inner components of an emergence tray -- left upper corner, agar slab for water provision; centre, green panels for increased fly-resting space; right, black tray for pupae placement and white tray for placing the "Mubarqui diet". Medfly Programme, Neretva Valley, Croatia, and Mexican Fruit Fly Programme, Mexico.

Figure 5: Left: Fly emergence and maturation room inside the new ERF at El Pino, Guatemala, using liquid-diet towers, with air-conditioning units for room conditioning. Right: Liquid-diet tray showing (through the screen) two white plastic trays holding pupae (pupae marked with orange-coloured dye). A cotton cloth (white) and a sponge (blue) draw the liquid diet by capillary action from the PVC-pipe system placed on the side of the trays (as shown in the left photo).

The only waste materials produced in the tower system are puparia, food residues, and water from the mechanical tray washer. Overall, labour requirements are also reduced, primarily because of the automated pupae loading, puparia separation and disposal, and tray-washing processes. On the other hand, since there are fewer flies in each tower tray than in a PARC box, collecting chilled flies from tower trays is slower; thus, during the critical time in which chilled flies must be collected from tower trays, more manual labour (than from PARC boxes) is required. Hence, on balance, even though the tower system requires more hand-labour in the final step of the process, i.e. collecting chilled flies, its overall cost is lower than that of the PARC system because of the optimization of space and savings in hand-labour costs in the other steps of the process (as well as saving the cost of buying and disposing of paper bags, and the agar-diet preparation process which includes the cost of agar, electricity, and hand-labour), while adding the main advantage that tower-reared flies are better fed and less “stressed” than those reared using the PARC system.

5.1.3. Marking Emerging Adults

To enable identification after capture in the field, many species are normally marked at the MRF prior to shipment, emergence, and release (Hendrichs and Robinson, this volume; Parker, Mamai et al., this volume; Vreysen, this volume). Calco and tinopal dyes have been used successfully to mark lepidopteran larvae (Stewart 1984; Dyck 2010; Boersma 2021). Fluorescent dyes, used on fly pupae (Fig. 6), are transferred to the ptilinum of the adult as it emerges at an ERF (Steiner 1965; Schroeder et al. 1972; Vreysen et al. 1999; Dominiak et al. 2010; FAO/IAEA 2016b). The transferred dye becomes incorporated into the head capsule as the ptilinum is withdrawn into the insect’s head (Fig. 7). Upon capture, as adults are viewed under a long-wave ultraviolet (blacklight) lamp; the dye fluoresces, enabling wild unmarked and reared marked flies to be distinguished from each other. Currently, there are several insect species for which there is technology available to supersede the described marking process (Niyazi et al. 2005). This new technology is based on the insertion of genes that allow fluorescence of body parts and sometimes other insect tissues, e.g. testis – sperm. Some of these species/strains have already been tested for their rearing characteristics (Ramírez-Santos et al. 2017), but at this time this technology is not approved for use in the field by most government regulations.

5.1.4. Provision of Food and Water Prior to Release

For most adult insects, it is important that they are provided with a source of food and water shortly after emergence. Most SIT target species are anautogenous, and the food reserve accumulated during larval development is only sufficient to sustain the adult for 1 or 2 days under ideal environmental conditions. Intake of protein (Papanastasiou et al. 2019) and other essential resources is required by emerged sterile males and females to permit reaching sexual maturation after a time-delay following feeding (Hendrichs and Prokopy 1994). Studies have shown that providing food and water to newly emerged adults results in much higher recapture rates following release (FAO 1992; Hernández et al. 2010; Bellini et al. 2014; Maïga

et al. 2014; FAO/IAEA 2016b, 2017a, b; Parker, Mamai et al., this volume) (sections 3.3., 4.1., 4.2.; Figs. 2, 3, 4, 5). Increasing the food surface available for emerging sterile insects is important; all adults need access to the food within the crowded conditions of PARC boxes or tower trays (USDA/APHIS 2009).

Figure 6. Left: Bags containing DayGloTM-dusted pupae -- showing also an irradiation dosimeter that has become black (Bakri et al., this volume), proving that the dose administered reached the required level. Centre: Pupae showing DayGlo dye on the surface of the puparia (a high percentage of marked adult flies is desirable for field traceability). Right: Mediterranean fruit fly males emerging from pupae, marking their body parts during the process. (Photos from E. M. Ramírez-Santos, reproduced with permission.)

Figure 7. Upper photos: Unmarked flies. Lower photos: Marked flies showing sterile flies that have emerged from DayGloTM-dyed pupae (from left to right: ptilinum mark, dorsal body marks including wings, and ventral position marks mainly on the legs). Observations conducted using an epifluorescent microscope, El Pino MRF. (Photos from E. M. Ramírez-Santos, reproduced with permission.)

The addition of specific food supplements to the adult diet, including proteins, for emerging male fruit flies to enhance their post-factory field performance and competitiveness, are discussed in detail by Pereira et al. (2013) and Pereira et al.

(this volume); these papers also discuss the interaction between nutritional and hormonal treatments to advance sterile male sexual maturation, as well as semiochemical treatments to improve sterile male competitiveness.

Sterile insects are often released soon after emergence to minimize space requirements in an ERF, or a few days later, but well before full sexual maturation is reached (avoiding mating between sterile males and sterile females in the case of bisexual strains). However, the use of GSSs (Franz et al., this volume), emerging only sterile males at ERFs (and processing half the volume of a bisexual strain), enables holding them closer to sexual maturation when they are better able to compete for wild females (this also reduces the often high losses that sterile males suffer in the field, due to predation and other causes, between the time of their release and reaching maturity).

McInnis et al. (2013) found (for the Mediterranean fruit fly in large field cages) that holding sterile males longer at the ERFs and releasing them closer to maturity (and also providing food and water during the maturation period) increased adult survival and thus the number of sexually mature males active in the field.

5.2. Collecting Emerged Adults by Positive Phototaxis for Direct Release

In some insect species, adults are directly collected after emergence, without previous holding and feeding of adults. Often, they are positively phototropic, and thus show a strong positive phototaxis to a light source. This behavior has been used to attract newly emerged adults into cold rooms at ERFs directly for release, e.g. New World screwworm flies (Wyss 2002). Also, adults of pink bollworm moths, codling moths, and false codling moths (Fig. 8) are collected after emergence, often directly at MRFs, using fluorescent, ultraviolet or incandescent lights (Hutt et al. 1972; Stewart 1984; Dyck et al. 1993; Wyss 2002; Dyck 2010; Boersma 2021). Cold temperatures are used to temporarily immobilize the adults following collection (Dyck 2010; Hofmeyr and Pretorius 2010; FAO/IAEA 2016b; Boersma 2021), as well as while they are being transported to an aircraft or ground-release vehicle, and then during release operations.

Figure 8. Cabinets for emergence and collection of false codling moths (Xsit, Citrusdal, South Africa). (Photo from Boersma 2021, reproduced with permission.)

The importance of having adequate control of relative humidity during chilling, holding, and release of adult insects cannot be overemphasized (Tween and Rendón 2007). If the relative humidity is too high, it can affect insect quality. This is particularly problematic when chilling adults (covered externally with a dust-dye) at high humidities and loading them into metal release boxes. Condensation on the inside of the release box can lead to excessive moisture that completely saturates the insects, causing them to become tangled in a large ball at the bottom of the box, resulting in fly damage during release. Commercial dehumidification systems can be used to reduce the humidity during chilling, transporting, and releasing insects.

6. RELEASE OF STERILE INSECTS

There are three approaches of releasing sterile insects -- static ground-based receptacles (static release), mobile ground-based vehicles (ground release), and releases using aircraft (aerial release). Each approach has advantages and disadvantages. Usually field action programmes use a combination of them for their operations, according to the conditions, needs, and strategic objectives.

The aforementioned chilled adult release technique is complementary to the release methods. It is used just before releases and aims to produce easy-to-handle quiescent sterile insects that can then be loaded into different-sized release containers, usually metal boxes or bags. The chilling process takes place inside a wall-insulated cold room, where emergence/feeding containers are rolled in. Cold rooms are pre-chilled at the appropriate temperature, usually at ca. 4°C. The actual chilling process requires 40–60 min. Chilled insects are then collected and loaded into an additional container for field release.

6.1. *Static Release*

Typically static release receptacles are containers deployed in the field into which sterile pupae or adult insects are regularly placed (Liu and Yeh 1982; Williamson et al. 1983; Cuisance et al. 1984; Oladunmade et al. 1990; FFEPO 1999; Msangi et al. 2000; Yamagishi and Kakinohana 2000; Koyama et al. 2004; Sutantawong et al. 2004; Dominiak et al. 2011b). When pupae are placed into them, adults are able to emerge in synchrony with local diurnal and temperature cycles, leave the receptacle, and disperse from the site during the day as the temperature rises. Static releases require a uniform distribution of release sites throughout the target area, and the pinpointing of areas to receive increased numbers of sterile insects. This approach is possible only for relatively small-sized areas that are accessible.

This method was used in the 2016–2017 outbreak of the New World screwworm in Florida, where ground release sites covering several islands were used. These static sterile-insect releases, combined with other quarantine, treatment, and inspection procedures, achieved eradication of the pest a few months after its detection (USDA/APHIS 2017; Skoda et al. 2018; Vargas-Terán et al., this volume).

Placing pupae in release receptacles eliminates the need to establish ERFs, reducing labour and infrastructure costs. Pupae are easily handled; they can be poured into the release receptacle or included in a pre-prepared insert placed into the

release receptacle. Simple volumetric measurements provide a way of estimating the number of pupae in each receptacle.

Static releases have major disadvantages: deployment is limited by ground access to release sites, distribution of sterile insects is clumped (with foci separated by areas of low insect density), provisioning release receptacles is labour-intensive, and emerged insects are very susceptible to bad weather and predators that learn to visit the release sites. However, for some species and conditions, this release method is still considered (Dominiak et al. 2011b; Reynolds et al. 2012). Most programmes that have used static releases have changed to either ground or aerial releases (Liu and Yeh 1982; Koyama et al. 2004).

6.2. Ground Release

In a mobile ground-release system, adult sterile insects are dispensed from slow-moving trucks (CMFFEPP 2019), all-terrain vehicles (ATVs) (OKSIR 2019; Boersma 2021; Nelson et al. 2021), or mountain bicycles (Horner et al. 2016). The insects are released by hand or machine, directly into the environment, or in open bags from which they escape after release (Holler and Harris 1993; Fisher 1996; FFEPO 1999; Bloem and Bloem 2000; Covacha et al. 2000; Loosjes 2000; Koyama et al. 2004; Bjeliš et al. 2013, 2016). To maximize their dispersal away from the release vehicle or bag, the insects may be kept at ambient temperatures during the release procedure. The Carnarvon Western Australia eradication project uses a “Medfly blower” consisting of a refrigerated cooler that keeps the flies immobile at about 5°C, and incorporates an auger, heater, and blower fan. The unit is mounted on the back of a truck (Fig. 9) which, combined with a remote dispersal release interface, enables the insect releases (B. Woods, personal communication).

Ground releases can treat a larger area more quickly and uniformly than static releases. The vehicle routes can easily be changed to meet changing demands of the programme, and additional release trips can be made in areas that need higher numbers of sterile insects. Fewer workers are needed to make ground than static releases. The negative impact of predators on the sterile insects is minimized when the adults are released directly into the environment (Fig. 9). Since pupae are kept indoors at relatively constant temperatures, the adults emerge at a predictable rate, making long-range scheduling possible. Adult insects can be held at lower temperatures during periods of inclement weather, and then released when acceptable weather conditions return. Ground releases are used regularly in fruit fly programmes to supplement aerial releases in areas with difficult access. In the *C. capitata* eradication programme in the Dominican Republic (Fig. 9) (Zavala-López et al. 2021), ground bag releases were conducted to supplement aerial releases along the coastal areas, which were affected by wind drift. Ground releases may not be as uniform as aerial releases, and greater sterile insect densities will occur close to areas bordering the path of the release vehicles. There are also safety issues associated with having slow-moving vehicles travelling on normal roads, and inaccessible areas of dense vegetation pose problems for ground-release systems. In the case of bag releases, bird and vespid predators will learn to exploit the insects contained in them, and bags themselves may constitute a litter problem.

ERFs are still needed to prepare/feed insects prior to their release. Since adults will emerge even during periods of inclement weather, when releases are not possible or advisable, the accumulation of insects may necessitate their destruction. However, in the Lower Rio Grande Valley at the Mexican fruit fly programme in Texas, when aerial releases cannot occur due to weather conditions, ground releases are a practical solution (Fig. 9). They are also used to increase sterile insect densities in pest hotspot areas where it is required, as well as sensitive areas such as bird sanctuaries and butterfly gardens where other means of control cannot be used (H. Conway, personal communication). If long periods of overcast conditions, e.g. rainy season, are expected, one might need to choose an alternative emergence and release system to prevent/reduce foreseen losses.

Figure 9. Upper photos (left and centre): Ground release of sterile insects along coastal areas during the recent eradication of the Mediterranean fruit fly in the Dominican Republic. Flies emerged in paper bags housed in PARC boxes, and were taken to field locations where the bags were opened (ripped), enabling the males to fly. (Photos from R. Nina, reproduced with permission.) Upper right: Sterile male Mediterranean fruit flies being ejected from a ground-release machine in Croatia. (Photo from FAO/IAEA, L. Popović and Z. Marinović, Neretva SIT Programme Croatia, Center for Plant Protection, HAPIH, reproduced with permission.) Lower left: Testing of ground-release equipment in Texas for the Mexican fruit fly. The equipment uses vehicle speed and a potentiometer to deliver a known number of flies/ha. (Photo from H. Conway, reproduced with permission.) Lower right: “Medfly blower” releasing flies in Carnarvon, Western Australia. (Photo from B. Woods, reproduced with permission.)

6.3. *Aerial Release*

Aerial releases from aircraft directly discharge chilled sterile adults (chilled adult release technique) or eject bags or boxes containing the adults (Howell et al. 1975; Nakamori and Kuba 1990; FAO 1992; USDA 1995; Vreysen et al. 1999; Msangi et al. 2000; Pereira et al. 2000; Villaseñor et al. 2000; Vreysen et al. 2000; Walters et al. 2000; Wyss 2000; Yamagishi and Kakinohana 2000; Kohama et al. 2003; Rendón et al. 2004; Staten and Walters 2021).

The direct release of sterile adults requires that they be taken from adult emergence containers or rooms, chilled (or first chilled in the containers), and put into large refrigerated boxes that are then loaded onto a specially equipped aircraft (FFEPO 1999; Dowell et al. 2000; Villaseñor et al. 2000; Walters et al. 2000; Wyss 2002; Koyama et al. 2004; Staten and Walters 2021) (Figs. 10, 11, 12). The insects are dispensed from the aircraft using a motor-driven conveyor or screw auger that delivers the insects from the release box to the release tube. The release rate is controlled by varying the speed of the auger and the aircraft. Since screw conveyors cause some damage to flies, an improved release machine design uses instead flat vibrating conveyor belts that reduce sterile-insect damage prior to their release (Leal Mubarqui et al. 2014).

In some programmes, the aerial release of sterile insects has been done with paper bags or boxes (Hentze and Mata 1987; FAO 1992; Vreysen et al. 1999; Covacha et al. 2000; De Longo et al. 2000; Msangi et al. 2000; Opiyo et al. 2000; Villaseñor et al. 2000; FAO/IAEA 2006a). Usually pupae are placed in bags/boxes, held in the release containers until adult emergence, and then the release bags or boxes are loaded into larger holding containers and placed into the aircraft. The release bags or boxes are held at ambient temperatures and dispensed from the aircraft by hand or conveyor belt. Releasing sterile insects in their emergence bags or boxes reduces preparation time, compared with the chilled-insect procedure, but there can be some damage due to bag compaction if too many are transported to the aircraft or too many placed within it, and the sterile-insect dispersal achieved is more limited compared with the chilled adult release technique.

Aerial releases enable the covering of large areas quickly, regardless of the difficulty of the terrain, lack of roads, or high density of vegetation. They distribute the sterile insects over the treated area as required, especially if the aircraft flight paths are controlled by a Global Positioning System (GPS) guidance programme (Villaseñor et al. 2000; USDA 2019) (section 6.4.). The mechanized release system can be linked to a computer to provide flexibility in the release rate during a flight. This allows more sterile insects to be delivered to those areas needing them, without having to make multiple flights over any given area. If boxes or bags are used, the release rate is increased by ejecting more of them in a given time period (section 6.4.).

On the other hand, aerial releases are more weather-sensitive than ground releases, and an ERF is required. The aerial release of sterile insects in bags or boxes is problematic if litter is a concern (but a biodegradable container mitigates this problem). Bags and boxes are expensive, and for some insects (such as tsetse flies that are extremely sensitive to insecticides) the cardboard boxes must be free of any chemical residue (this increases the price of the boxes). They also take up

considerable space in an aircraft that could instead be devoted to holding many more chilled insects. Aerial releases of the Mediterranean fruit fly in Argentina, using bagged adults, averaged only 1.2–1.3 million flies per flight (De Longo et al. 2000), whereas aerial releases by directly releasing chilled flies can release 10 million per flight (in Spain with a Cessna 206) and up to 40 million flies per flight (in Mexico with a Cessna Caravan). The number of sterile insects that can be released by an aircraft is also a function of the type of insect, the release rate, and the aircraft size. Flight duration is usually determined by the amount of time that sterile adult insects can tolerate chilling without a reduction in quality (usually about 4 h), but this depends on the temperature and size of the insects. Pereira et al. (2000) found that aerial releases are less expensive than ground releases.

Both fixed-wing (Figs. 10, 11) and rotary-wing (Fig. 12) aircraft can be used to deliver sterile insects aurally to the target area. The choice of aircraft type will depend on programme needs and local environmental conditions, as well as the availability of aerial services or the cost of the aircraft. Releasing with rotary-wing aircraft is usually more expensive, although gyrocopters are less expensive than fixed-wing aircraft. Rotary-wing aircraft are used usually for the spot-treatment of restricted host areas, or canyons, where fixed-wing aircraft cannot operate easily.

Figure 10. Fixed-wing aircraft used to release sterile pink bollworm moths in 2007. Placement of the release machine into the aircraft is shown. Locations of the moth-holding and moth-release equipment, flight recording/guidance unit (Wag-Aero (Brand name) = GPS navigation unit that tracks the flight path), and SIT controls are labelled. (Photo from the California Department of Food and Agriculture, reproduced with permission.)

Figure 11. Releases from fixed-wing aircraft. Upper photos: Preparing aerial bag releases in Mendoza, Argentina. Lower photos: Loading refrigerated boxes with chilled sterile Mediterranean fruit flies in Retalhuleu, Guatemala. RT: Refrigerated Truck; RB: Refrigerated Box; SA: Screw Auger; RS: Release Shut. (Photos from G. Iriarte, reproduced with permission.)

Figure 12. Aerial release of sterile male tsetse flies in the Niayes region of Senegal using a gyrocopter (Dixit 2015). (Photo from J. Bouyer, reproduced with permission.)

Due to recent technological developments in aerial technology and guidance systems, programme managers look for improved and alternate ways of releasing sterile insects, so that the process is more efficient in its coverage and more cost-effective. There are different release devices being considered for this exploratory new wave of technology; the initial step is to acknowledge that there are very dissimilar requirements in terms of the release rates/unit area needed to achieve pest control. For fruit flies and mosquitoes, usually thousands of insects per ha are required, in lepidopteran species hundreds of insects per ha, in screwworms tens of insects per ha, and in tsetse only individual flies per ha (Table 5 in Hendrichs, Vreysen et al., this volume). This variation in release rate changes the aircraft requirements. For pest species that require an extensive coverage at a very low release rate, such as tsetse flies, fuel-tank capacity in fixed-wing aircraft is a more limiting factor than the capacity to hold sterile insects. On the other hand, for fruit flies, in view of the relatively large volumes to be released per area, larger fixed-wing aircraft are required to maximize the release per flight. However, because of the difference in millions of insects to be released in the diverse programmes, there is also a gradient in fixed-wing aircraft size/capacity. For lepidopteran species, fixed-wing aircraft have been used for pink bollworm moths (Simmons et al., this volume) (Fig. 10); in other operations such as releases of the false codling moth in South Africa, ATV squads and gyrocopters have been used. However, both practices were discontinued due to worker issues in the former and security concerns in the latter (Boersma 2021; S. Groenewald, personal communication). In the Niayes region of Senegal, the programme to eradicate tsetse flies (which required very low rates of sterile males per ha) used a gyrocopter for the aerial releases (Dixit 2015) (Fig. 12).

New ways of releasing sterile insects from the air are being explored and adopted – type of aircraft as well as new technologies for release. For the capacity of aerial release machines, there is now an adaptable or “universal” delivery system; it was developed so as to meet the needs of very different operations, sizes and release rates, i.e. size of the aircraft needed, as well as the number of sterile insects being released in the field. This “smart delivery system” is capable of releasing at varying densities, ranging from 10 flies per km² for tsetse flies at one extreme up to more than half a million per km² for fruit flies on the other (Leal Mubarquí et al. 2014) (sections 6.3.3., 6.4.).

6.3.1. *Fixed-Wing Aircraft*

In the early years of sterile insect release, degradable bags or boxes were released from aircraft, e.g. New World screwworm flies, Mediterranean fruit flies (Fig. 11), and tsetse flies. For a long time, fixed-wing aircraft were the standard vehicle for releasing sterile insects, e.g. New World screwworm flies, pink bollworm moths (Fig. 10), Mediterranean fruit flies (Fig. 11), Mexican fruit flies, and tsetse flies. Today, in many cases, chilled insects are released from special machines with augers or conveyor belts that eject the insects automatically according to a predetermined rate, enabling the planned density of sterile insects to be achieved on the ground, e.g. false codling moths in South Africa (Xsit 2019a; Boersma 2021).

6.3.2. Rotary-Wing Aircraft

Compared with fixed-wing aircraft, rotary-wing aircraft are appropriate for making release flights over mountainous terrain or small target areas (Vargas et al. 1995). Melon flies were released with helicopters in Okinawa, Japan (Nakamori and Kuba 1990; FAO/IAEA 2016c; Enkerlin, this volume), and a gyrocopter was used to release sterile tsetse flies in Senegal (Fig. 12) (Dixit 2015; Vreysen et al. 2021; Feldmann et al., this volume). For a period of time, false codling moths were released in South Africa with gyrocopters, but currently these moths are being released with small helicopters (Boersma 2021).

6.3.3. Unmanned Aerial Vehicle (UAV) (Drone)

Unmanned aerial vehicles (UAVs), remotely piloted aircraft systems (RPASs) or drones are the latest development in aerial release technology; their main components are shown in Fig. 13. Using these systems is attractive to operational programmes because of the potential cost reduction in some sterile-insect release activities (Tan and Tan 2013). Also, the adoption of this technology can avoid the loss of human lives that sometimes results from aircraft accidents (Dyck, Reyes Flores et al., this volume).

The advantages of the RPAS technology (accuracy, increased safety, and cost-efficiency for small- and medium-scale operations) are counterbalanced by limitations at the technical level (reduced payload and flight duration) as well as at the regulatory level (mandatory special operational permits from regulatory agencies for operations beyond the visual line of sight) (Benavente-Sánchez et al. 2021). Compared with ground releases, sterile insect dispersal and survival should be improved when using UAVs.

Figure 13. Main components of a Remotely Piloted Aircraft System (RPAS). Modified after Maxorazon, Wikipedia CC BY-SA 4.0. (Wikipedia Commons 2018). (Drawing from Benavente-Sánchez et al. 2021, reproduced with permission.)

Following the development of commercially available UAVs, they are increasingly being tested for releasing insects in several SIT projects (Table 1): *Aedes* mosquitoes (Fig. 14), chilled tsetse flies (Benavente-Sánchez et al. 2021) (Fig. 15), codling moths (Figs. 14, 16) (Horner et al. 2016; M3 2018; PFR 2018a, b; Proskiw 2018; Seymour 2018; FGN 2019), false codling moths (Xsit 2019b; Boersma 2021), and pink bollworm moths (USDA/APHIS 2018).

Table 1. Technical parameters of Remotely Piloted Aircraft System (RPAS) applications releasing sterile insects (data adapted from Benavente-Sánchez et al. 2021, reproduced with permission)

Parameter		Release of sterile insects		
		Male <i>Aedes</i> mosquitoes ¹	Male <i>Glossina</i> tsetse flies ²	Codling moths (♂+♀) ³
Adult weight (mg)	Min	0.9	14	23
	Max	1.1	18	25
Release density (nr/ha)	Min	1000	0.5	200
	Max	3000	1.0	1000
Insect biomass (g/km ²)	Min	90	0.7	690
	Max	330	1.8	2500
Area covered per flight (ha)	Min	40	4000	40
	Max	60	8400	100
Swath width (m)	Min	75	500	120
	Max	100	700	180
Flight distance (without ferry) (km)	Min	5.3	80	3.3
	Max	6.0	120	5.6
Flight time (without ferry) (min)	Min	11	67	6
	Max	13	100	9
Speed during operation (m/s)		8	20	10
Payload (g)		300	800	7000
Type of aircraft		Rotary; micro/small	Fixed-wing, rotary; medium	Fixed-wing, rotary; medium
Type of operation		VLOS ⁴ ; urban area	BVLOS ⁵ ; rural area	BVLOS ⁵ ; rural area
Special flight authorization		Mandatory	Mandatory	Exempted

¹ Trial release of *Aedes aegypti* in Juazeiro, Brazil, 2018 (Benavente-Sánchez et al. 2021; J. Bouyer, personal communication)

² Planned release of *Glossina* spp. in Chad and Ethiopia (Benavente-Sánchez et al. 2021)

³ Routine release of *Cydia pomonella* in a pilot area of 391 ha in Central Hawke's Bay, New Zealand (PFR 2018a, b; Benavente-Sánchez et al. 2021; R. M. Horner, personal communication)

⁴ VLOS = Visual Line Of Sight

⁵ BVLOS = Beyond Visual Line of Sight

UAVs are particularly appropriate for situations requiring the release of relatively small sterile-insect quantities, and on small areas (including residential areas), e.g. releasing mosquitoes over urban areas (an emerging need due to the recent explosion of mosquito-borne diseases) (Lees et al., this volume). UAVs have been tested to release sterile *Aedes aegypti* (L.) in Brazil (Fig. 14) and Mexico. A prototype (Remotely Operated Mosquito Emission Operation -- ROMEO) has been developed (HEIGHT TECH 2019) that can carry half a million mosquitoes per load, and has flight independence up to 30 min, enough to cover an area of 1 km² (FAO/IAEA 2016a; Garnier et al. 2018; UN 2018; Bouyer et al. 2020) (Fig. 14).

Benavente-Sánchez et al. (2021) reviewed the progress and prospects for using RPASs in SIT projects. They present a table with data on tests releasing sterile insects (mosquitoes, tsetse flies, and codling moths) – comparing the weight of adults, payload, release density, area covered per flight, and flight distance, speed, and time, etc. (Table 1) (see Table 5 in Hendrichs, Vreysen et al., this volume, for another cross-species comparison). Details of appropriate equipment and procedures are provided. They also reviewed the progress made in different countries in regulating and harmonizing internationally the use of different-sized RPASs for various agricultural applications. Legislation, regulation, certification, and authorization are essential for any routine use of RPASs in support of SIT projects.

Figure 14. Left: Drone ROMEO (Remotely Operated Mosquito Emission Operation) (From FAO/IAEA 2016a; UN 2018; Bouyer et al. 2020). Centre: RPAS and mechanism to release sterile male mosquitoes *Aedes aegypti* in Brazil in 2018 (From J. Bouyer, reproduced with permission). Right: Drone releasing sterile codling moths in Canada (From M3 Consulting Group -- hd-mediaitemid51688-3698 (M3 2018); Proskiw 2018; Seymour 2018).

Figure 15. Prototype Unmanned Aerial Vehicle (UAV) (drone) for releasing sterile tsetse flies. The pods under the wings carry the chilled adult males in biodegradable boxes that are dropped according to a pre-planned flight programme. (Photo from Benavente-Sánchez et al. 2021, reproduced with permission.)

Figure 16. Remotely piloted fixed-wing drone, operated in visual line-of-sight, releasing sterile codling moths in New Zealand (PFR 2018a, b). (Photo from R. M. Horner and Plant and Food Research Institute, New Zealand (PFR 2018a), reproduced with permission.)

6.4. Global Positioning System (GPS) for Guiding and Monitoring Insect Release

Guidance of aircraft used to release sterile insects has evolved from a system based on compass headings, landmarks, and flight times to one that now uses the Global Positioning System (GPS) (Slagell 2000; Bouyer et al., this volume) (Figs. 10, 17, 18). Using the GPS, programme managers can lay out the exact flight paths for the aircraft. This technology allows the distribution of sterile insects precisely where desired. It has also reduced flight times and pilot error, eliminating duplication of flight paths and the unintentional omission of some of them. Today, most programmes making aerial releases use the GPS to guide the aircraft. The GPS is especially useful in areas that lack the visual landmarks that pilots may use to determine where they are and where they need to fly.

A computer with its software enables recording of pre-programmed flight lanes, release elevation, and airplane speed, information that can be classified and displayed using Geographic Information Systems (GIS) (Bouyer et al., this volume). Programme managers greatly benefit from the combination of these tools to supervise the work and guide the release and other control activities (Figs. 17, 18). GPS and GIS location of the sterile and fertile insect captures is also used to map out presence and distribution of the flies as well as the sterile to wild ratios relevant for the success of the SIT (FAO/IAEA 2006b).

In the Mediterranean fruit fly programme in Valencia, Spain, differential release rates of sterile males are applied according to pest density as the aircraft flies over release blocks with non-regular shapes, so curvilinear release paths are adapted to them. The flow of sterile males is adjusted automatically by the release machine during the flight to fit the target release map that was previously created using the most recent trapping information on apparent densities of wild flies in the field (Fig. 18) (section 6.3.).

The MACX system is a sterile-insect release monitoring option that was designed to track the quality of chilled-adult releases. The data are recognized, analysed, translated, and re-transmitted to a website where it is available to supervisors and programme managers; the system can follow the releases in real time (Leal Mubarqui 2005; Leal Mubarqui et al. 2014).

Figure 17. Aircraft flight lanes (thin red lines) for sterile insect releases in the Mexican Fruit Fly Programme in Baja California, Mexico. (Illustration from L. Charles, USDA/APHIS/IS Mexico, and E. Lira, USDA/APHIS/IS Guatemala, reproduced with permission.)

Figure 18. Left: Release block with non-regular shape and curvilinear flight path adapted to it, showing the target release intensities (red colour means high densities of sterile males are needed). Right: Map showing the differential release actually conducted (the red colour of the release flight line confirms higher release flows of sterile males).

To release boxed tsetse flies, an electronic counter is used; this device has an optic sensor and a GPS antenna. It counts the biodegradable boxes as they are released from a fixed-wing UAV (Fig. 15), and saves a digital file recording the position at which each box has been dropped. The file can be imported into GIS software for later analysis of the quality of the flight (FAO/IAEA 2016b; Benavente-Sánchez et al. 2021).

7. CONCLUSIONS

Most of the large operational programmes that integrate the SIT have established emergence and release facilities (ERFs) in the vicinity of the release areas, usually separated from the mass-rearing facilities (MRFs) that supply them with the sterile insects, commonly in the form of pupae. This operational scheme results in lower costs for the programme and better quality insects in the field, provided the duration of shipments and temperature of the shipped insects are kept at acceptable levels. However, in some insect species, adults can be collected after emergence (Fig. 8) (without the need for holding and feeding) for direct transport and release.

MRFs can also supply sterile insects to independent field programmes, thereby avoiding large initial investments in the mass-production of sterile insects. Shipping sterile insects across national borders has become a major activity, with improved shipping procedures resulting in higher-quality sterile insects.

More efficient methods for emerging, holding, and feeding high-quality insects, such as the tower system for fruit flies, have been developed, optimizing the space needed in the ERFs and reducing the workload for the daily operations. However, earlier methods are still useful depending on the particular action programme, e.g. emergency response vs. permanent activity.

The incorporation of GPS technologies into surveillance systems has enabled the determination of the precise location of pests in the field and at which sterile-insect releases should be directed. Navigation technologies, using GPS, GIS, and electronic communication systems have greatly improved the accuracy, reliability, efficiency, and recording of sterile-insect releases.

Similarly, insect ground- and aerial-release methodologies have evolved, using available industrial technologies. Although still in the development and validation phase, in some situations unmanned aerial vehicles (UAVs) or drones appear to be a realistic and cost-effective possibility for releasing sterile insects within their technical limitations of payload and endurance. However, the regulation and international harmonization for using different-sized remotely piloted aircraft systems (RPASs) are still in progress.

Quality-control manuals have been updated (FAO/IAEA/USDA 2019; FAO/IAEA 2017a, b) to include assessments of sterile insects prior to, and even after, their field release, ensuring their viability for the expected introduction of sterility into feral populations. A spreadsheet on sterile-insect release density calculations and its manual, recently published (FAO/IAEA 2019), has enabled release densities (as well as the corresponding ratios of sterile to wild insects based on actual field trapping data) to be determined; its programmatic use has already contributed to achieving an improved use of the SIT. All of these improvements add

up to a more cost-effective implementation of the SIT as part of an area-wide integrated pest management approach to pest control.

8. ACKNOWLEDGEMENT

We gratefully acknowledge permission from P. Rendón to reproduce photos shown in Figures 2, 3, 4, 5, 6, and 11.

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