Chapter 14
Insect Eradication and Containment of Invasive Alien Species

Ken Bloem, Eckehard G. Brockerhoff, Vic Mastro, Gregory S. Simmons, John Sivinski, and David M. Suckling

14.1 Introduction to Insect Eradication

This chapter provides a brief introduction into the tactics and strategies necessary to achieve eradication of invasive pest insect populations and the requirements needed to mount an effective eradication programme. This chapter also considers pest containment as a component of eradication and as an explicit goal. These response programmes are used mainly against specific organisms that warrant an attempt to mitigate the high management, environmental, or direct impact costs if those pest organisms were allowed to establish and spread. Eradication differs from other management tactics in that the goal is finite. For some pest introductions, the goal from the initiation of any management action has been eradication. In other programmes, where the goal was initially to contain damage or limit pest spread, improvements in management tactics have made it possible to change to an

K. Bloem (✉)
USDA-APHIS-PPQ-Center for Plant Health Science and Technology (CPHST), Raleigh, NC, USA
e-mail: Kenneth.Bloem@aphis.usda.gov

E.G. Brockerhoff
Scion (New Zealand Forest Research Institute), Christchurch, New Zealand

V. Mastro
USDA-APHIS-PPQ-CPHST, Buzzards Bay, MA, USA

G.S. Simmons
USDA-APHIS-PPQ-CPHST, Salinas, CA, USA

J. Sivinski
USDA-ARS-Center for Medical, Agricultural and Veterinary Entomology, Gainesville, FL, USA

D.M. Suckling
New Zealand Institute for Plant & Food Research Ltd, Lincoln, New Zealand

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eradication goal. The question then becomes, "Why proceed with eradication or official control?" The main reasons are to maintain or gain market access, or lower the costs of production; other reasons include human health and welfare or environmental impacts.

Eradication programmes have been organized against pest insects (Walters et al. 2008), plant pathogens (Sosnowski et al. 2009), weeds (Panetta and Lawes 2005) and mollusks (Kean et al. 2009; Barker 2002). This chapter's scope is limited to insect pests. The insect Orders that have been successfully targeted by eradication programmes are Diptera > Lepidoptera > Coleoptera > Hymenoptera. Much less frequently, successful eradications have targeted Hemiptera and Isoptera (Kean et al. 2009). Here, the context is not pest management, although many tactics developed during an eradication programme could be suitable for pest management. More than 800 eradication programmes have been initiated to date (Kean et al. 2009), and the frequency of initiation is increasing exponentially over time. This increase in eradication programmes can be attributed to the increased movement and establishment of organisms in new places due to increased trade and travel (Sect. 1.2).

The global philosophy behind "biosecurity at the speed of commerce", or without disadvantage to trade, represents one of the reasons the number of new organism introductions is increasing (Knight 2008). This situation must be viewed from the perspective of a dynamic system. New invasive pest arrivals do not replace or displace existing pests from the system. Rather, the system accumulates them. The enlarged pest complex may disrupt or neutralize current management practices and increase long-term pest management costs. Successful eradication offers the possibility of mitigating these long-term costs and impacts. In a similar way, containment of a pest is a tactic to avoid these impacts for as long as possible in areas where the pest is not yet present. These containment programmes are not undertaken lightly. Unfortunately, the outcome of a programme cannot be predicted and the scientific literature is not well developed for recording the progress or execution of these typically government-led programmes. This lack of scientific documentation to guide managers in formulating and executing new programmes highlights the importance of such documentation (reports and publications).

A sequence of decisions and steps are followed when considering whether to eradicate during the early stages of infestation/establishment, after an organism is reported or discovered. The sequence involves: (1) Investigation and data gathering; (2) accumulation of evidence of plausible scenarios that might warrant an intervention from all aspects and perspectives; (3) consideration of options and their likelihood of success and impacts; (4) decision making based on target-setting and available resources; and finally (5) communication and implementation of an operational response (Brockerhoff et al. 2010). Economic considerations are paramount because eradication programmes are complex and expensive (Mumford 2005).

Typically, government appropriations are involved. Cost-benefit analyses are normally developed as quickly as possible, allowing for various scenarios, since it is often difficult to accurately predict the impact of a pest or the exact inputs and the outcome of a programme. As a consequence, cost ranges are normally used in these

Table 14.1 Costs and averted economic impacts from eradications of forest insect pests in New Zealand, amounting to a combined net value of averted losses of $70–700 Million USD (Adapted from Brockerhoff et al. 2010)

Organism	Estimated eradication cost (USD$ million)	Estimated economic impact over 20 years (USD$ million)	Estimated averted costs (economic impact less cost of eradication)
White-spotted Tussock Moth (1996–1998)	9	19–133	$10–124
Gum Leaf Skeletonizer 1 (1997–1998)	3	76–107	$73–104
Painted Apple Moth (1999–2006)	49	44–267	−$5–218
Fall Webworm (2003–2006)	5	14–62	$9–57
Gum Leaf Skeletonizer 2 (2003)	90[a]	76–107	−$14–17[a]
Gypsy Moth (2003–2005)	5	2–218[b]	−$2–214

[a]Eradication not attempted due to an unfavorable cost–benefit analysis; eradication cost estimate (see Brockerhoff et al. 2010 for details)
[b]The value shown for impact over 20 years was calculated according to Harris Consulting (2003)

cases (see Table 14.1 for a comparison of costs and benefits of recent forestry-pest eradication programmes in New Zealand). Nevertheless, the economic, environmental and human impacts likely to be caused by an invader typically exclude various parameters that are difficult to quantify (Holmes et al. 2009), suggesting that the actual benefits (i.e., averted damages) that can be gained from successful eradications are likely to be greater than initial estimates. However, Myers et al. (1998) argue that there is a lack of detailed information on programme operations and outcomes to support this claim and that the benefits of most eradication programmes are overestimated and the costs underestimated.

All eradication programmes include some form of containment as part of the strategy. In some cases, containment may be the only target that can be realistically achieved. Containing or slowing the spread and preserving areas free of an invasive pest will prevent management costs from being incurred, may also permit unrestricted trade and will reduce environmental, health and social impacts.

The human dimension of an eradication programme cannot be ignored. Most eradication programmes encompass private and public areas because of the distribution of hosts and the often polyphagous nature of the targeted pests. If the public is to understand and support these programmes, then there is a strong need for a robust educational effort beyond simple communication of the critical cost-benefit information. This is particularly true early in a programme when the full impact of the pest has not been realized and the operational responses may include inconvenient actions or cause potential non-target impacts (e.g., aerial spraying over urban areas, removal of host plants or establishment of quarantine zones). Failure to work with the people involved can lead to complications or program failure. Examples include attempts to eradicate Citrus Canker in Florida (Kean et al. 2009) (Sect. 18.3) and the

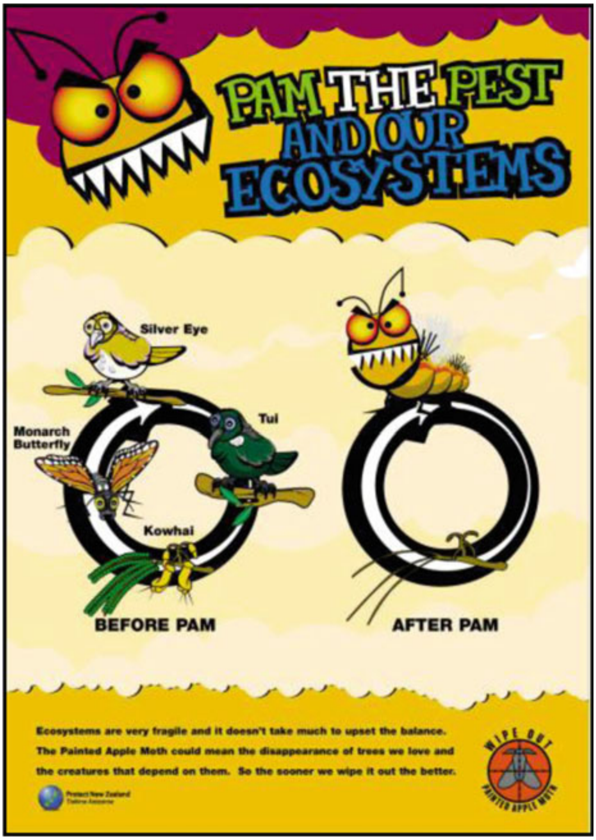

Fig. 14.1 Educational materials highlighting the negative impacts of "PAM the Pest" were used by the New Zealand Ministry of Agriculture and Forestry (MAF) during the Painted Apple Moth (PAM) eradication programme to help focus public sentiment on the moth as the enemy, not the eradication activities or MAF itself (Materials courtesy MAF, Wellington, NZ)

Light Brown Apple Moth, *Epiphyas postvittana* (Walker), in California (Suckling and Brockerhoff 2010). Both programmes were hindered by public resistance largely based on mistrust and misinformation. In the successful eradication of Painted Apple Moth, *Teia anartoides* Walker, in Auckland, New Zealand (Suckling et al. 2007), about 30 % of the budget was spent on research and operations, with the remainder spent on communication and health monitoring to ensure that the health and well-being of 180,000 people were not affected by aerial spray of a bacterial insecticide formulation (Fig. 14.1). Similarly, large investments were made in monitoring human health and non-target impacts in Asian Gypsy Moth, *Lymantria dispar* (Linnaeus), eradication programmes in Washington, Oregon and North Carolina during the early 1990s (Kean et al. 2009). In other cases, host destruction has been the most controversial area (Smith et al. 2009). Above all, outreach and education efforts must utilize the newest social media devices as well as traditional forms of communication (Chap. 8).

We see renewed interest in population ecology to better understand the role of population effects that occur at low density (such as the interaction between density-independent and density-dependent factors), including deliberate intervention tactics and their life-stage targets. Tactics that change the Allee threshold, at which the growth of small founder populations becomes positive, can be very useful, because they help to drive invader populations to extinction (Liebhold and Tobin 2008). Use of combinations of tactics such as the release of pheromones for mating disruption and the Sterile Insect Technique (SIT) can lead to super-additive outcomes through their positive interactions at low pest densities (Suckling et al. 2012). This deployment of combined tactics has helped foster the development of concepts such as "Integrated Pest Eradication" (see Sect. 14.6). Any eradication is must be area-wide and consider the total pest population. Of course, the population must be contained while the programme is conducted. Often this is accomplished by regulatory restrictions to slow the artificial spread and population suppression measures along the spreading/leading edge of the infested area.

14.2 Chemical Controls

Insecticides of one form or another have been used in all insect eradication programmes since the 1800s (Metcalf and Metcalf 1993). Early eradication programmes used inorganic arsenical or other environmentally hazardous and/or persistent materials that are no longer acceptable (Fig. 14.2), including nicotine and organochlorines such as DDT. Today, governments consider the hazardous properties of different options and weigh them against efficacy in a Cost Benefit Analysis. A combination of different insecticides with different properties may be used depending on the target pest and the circumstances of where the infested area is located. For example, less ecotoxic materials (such as insect growth regulators) may be applied near waterways, or biopesticides and pheromones may be acceptable when applied over human populations. Pheromones and other attractants, which are not insecticidal, represent a minimally hazardous class of chemical tools for managing certain insect groups such as moths and beetles (El-Sayed 2011). These are considered elsewhere in this chapter (see Sect. 14.3).

Fig. 14.2 Early Gypsy Moth eradication efforts in the 1920s included burning vegetation and widespread spraying with chemicals such as lead arsenate (Photo courtesy USDA-APHIS-PPQ-CPHST, Buzzards Bay, MA)

14.2.1 Classes of Insecticides

Insecticides operate by different modes of action, including poisoning the insect nervous system or disrupting endocrine processes with man-made analogues of natural products (Metcalf and Luckmann 1994; Metcalf and Metcalf 1993). Some insecticides operate through direct contact (e.g. aerosols) or require ingestion while feeding (*Bacillus thuringiensis* var. *kurstaki* or *Btk*), and a few may be acquired systemically through the plant (neonicotinoids). Some insecticides are very short-lived (e.g. biological insecticides) and could require repeated applications as a compromise for greater environmental safety. These properties determine the types of application tactics that must be considered to achieve eradication and manage environmental risks (Dubey and Patyal 2007; Plapp 1991). Table 14.2 shows examples of different types of insecticides, some of which were recommended for use in California against recent incursions there.

Organophosphates are the oldest class of insecticides still in general use (Metcalf and Metcalf 1993). They disrupt the insect's nervous system by binding to enzymes involved in signal transport (e.g. acetylcholinesterase), usually causing rapid death. Organophosphates are highly effective against insects, but unfortunately also affect a relatively wide range of other organisms, including vertebrates (Metcalf and Metcalf 1993). Similar to organophosphates, carbamates also affect the insect's nervous system, but they generally are less persistent and somewhat less toxic (Metcalf and Luckmann 1994).

Pyrethroids form a major class of insecticides and are based on analogues to natural pyrethrin insecticides extracted from plants (Krieger 2010; Metcalf and Metcalf 1993). The analogues vary enormously in persistence and toxicity depending on their structure, and typically act very quickly to cause "knock-down", although recovery can eventuate. Pyrethroids are more selective towards insects than the insecticide classes listed above, although fish and amphibians are highly sensitive to them.

Insect Growth Regulators (IGRs) *and Ecdysone agonists* represent another major class of insecticides (Krieger 2010; Yu 2008; Metcalf and Metcalf 1993). IGRs tend to be very selective, although some persist in the environment (Krieger 2010; Yu 2008; Metcalf and Metcalf 1993). These compounds target insect endocrine systems, and typically disrupt development, rendering them slower acting than other insecticides. Their selectivity and generally low environmental hazard make them attractive for use in sensitive ecosystems.

Neonicotinoids, recent synthetic analogues of nicotine sulfate insecticides, have a much lower acute mammalian toxicity, greater persistence, and many have systemic properties (Krieger 2010; Yu 2008). This can mean that application to soil, directly as a cover spray, or through injection into the plant leads to uptake and transport throughout the plant's living tissues, which can give excellent foliar coverage and reach cryptic insects.

Other insecticides could be considered on a case-by-case basis, although for eradication programmes only those with excellent efficacy should be considered. Anti-feedants, certain biological insecticides, and other products may not have

Table 14.2 Products representing most insecticide classes available for insect eradication. Suitability and formulations may differ depending on target

Class	Examples of active ingredients	Target life stage	Comment
Avermectin	Emmamectin benzoate	Larvae	Selective to insects
Biological insecticide	*Bacillus thuringiensis*	Larvae	Weakly active for 72 h, very selective
Biological insecticide	*Cydia pomonella* granulovirus	Larvae	Ultra-selective, short-lived
Biological insecticide	Gypsy Moth Nucleopolyhedrosis Virus	Larvae	Ultra-selective, short-lived
Carbamate	Carbaryl	Larvae and adults Very effective	Broad-spectrum, short-lived
Ecdysone agonist	Methoxyfenozide, Tebufenozide	Larvae only Highly effective 28+ days	Moderately persistent
Insect Growth Regulator	Diflubenzuron	Eggs Unknown efficacy	Moderately persistent
Insect Growth Regulator	S-methoprene, Pyriproxyfen	Larvae	Narrow-spectrum
Juvenile Hormone Analogue	Fenoxycarb	Eggs and larvae	Moderately persistent
Neonicotinoid	Acetamiprid, Thiacloprid, Imidacloprid	Larvae Unknown efficacy	Narrow-spectrum
Organophosphate	Chlorpyrifos, Phosmet, Diazinon, Dichlorvos, Malathion, Dimethoate, Trichlorfon	Eggs, larvae, adults Excellent control	Broad-spectrum
Pyrethroid	Deltamethrin, Cypermethrin, Lambda-cyhalothrin	Larvae and adults Highly effective	Broad-spectrum
Phenyl Pyrazole	Fipronil	Larvae	Narrow-spectrum
Spinosyn	Spinosad, Spirotetramat	Larvae + adults Very effective 10–14 days	Low-persistence, selective to insects

sufficient efficacy to contribute to insect eradication and are more appropriate for pest management. However, *Bt* and Spinosad have both been used effectively in Gypsy Moth and fruit fly eradication programmes, respectively (Hajek and Tobin 2009; Burns et al. 2001). Emmamectin benzoate when applied through injection shows excellent efficacy against the Emerald Ash Borer, *Agrilus planipennis* (Fairmaire).

14.2.2 Use of Insecticides

The target organism, the size and density of its population(s), characteristics of its host, and the physical and environmental circumstances will all contribute to the selection of insecticides and the application techniques. Aerial application of insecticides may be necessary when the area to be covered is large or the terrain is inaccessible. For instance, Red Imported Fire Ant (*Solonopsis invicta* Buren) baits were aerially applied over a steep and dangerously unstable hillside in New Zealand, in the interest of worker safety (Kean et al. 2009). Aerial applications of formulations containing *Bacillus thuringienis* (Foray 48B) were used in three recent campaigns in urban New Zealand, against Tussock Moth (Gypsy Moth group). The largest programme covered more than 12,000 ha, with up to 40 aerial applications of Foray 48B (Suckling et al. 2007), supported by spray deposition modeling (Richardson et al. 2005). Individual applications gave 85 % mortality of larvae on sprayed foliage (Charles et al. 2005), and this information was used in a model to predict the impact of multiple applications, and ultimately to declare successful eradication (Kean and Suckling 2005).

In a large successful containment programme for European Gypsy Moth (*Lymantria dispar* L.) ("Slow the Spread") in the USA, *Bt* and mating disruption formulations have been applied to hundreds of thousands of acres annually (Sharov et al. 2002). Aerial application of S-methoprene on salt marsh was critical to the successful eradication of the Southern Salt Marsh Mosquito, *Aedes camptorhynchus* (Thomson), in New Zealand (Yard 2008). Mosquito larvae arriving in used-car tires with water was the likely pathway that led to the need for the eradication of this pest and represents an example of commerce (in used tires) presenting a potentially greater risk than the economic benefit. Aerial application of insecticide bait sprays, such as malathion and NuLure or Spinosad and GF-120, which utilize hydrolyzed proteins as food-based attractants, have traditionally been used to lower fruit fly populations prior to the initiation of aerial releases of sterile insects when combating Mediterranean or other fruit fly incursions in the USA (Kean et al. 2009).

More recently, the use of bait sprays has come under public criticism because of perceived environmental and health-related problems, and lawsuits have been filed to stop application (Dyck et al. 2005; Burns et al. 2001). Indeed, aerial application of any pesticide, pheromone or other pest management materials over residential areas is controversial and the benefits must be explained to the people being affected. As stated earlier, resources focused on public outreach and education and health monitoring may eclipse those expended on direct pest management aspects of the programme.

Ground application is often preferred for small areas, although coverage can be problematic. Ground applications of pesticides seem to be more easily accepted by the public even though in some cases more material is applied per unit area. However, in some cases the insecticide used is the point of contention. The ground application of chlorpyrifos and deltamethrin against Painted Apple Moth in New Zealand was discontinued in response to community pressure, and while undoubtedly more effective, the compounds were replaced by multiple applications of *Btk* (Suckling et al. 2005). Although aerial applications of bait sprays now seldom are used in the USA for fruit fly eradication programmes, key states at risk for exotic fruit fly introductions still regularly use ground applications under Special Local Needs (SLN) permits to treat host plant material (e.g., oviposition, mating and resting sites) immediately around fly finds. In addition, insecticides have been applied as soil drenches under host trees at infested sites to kill larvae or pupae that may have left or fallen from infested fruit. Currently, the only effective chemicals available for this purpose are organophosphates such as diazinon and their use is now greatly restricted and requires emergency crisis exemptions.

Tree injection has been used against a range of recent pest incursions in the USA, where amenity values of urban forests can be high (Kean et al. 2009). Tree injection, with various formulations of imidacloprid, is used regularly in the Asian Longhorn Beetle Programme (*Anoplophora glabripennis* (Motschulsky)) to treat trees near known infested trees. Known infested trees are removed and destroyed, but newly attacked trees are difficult to detect even when examined by experienced tree climbers. Treatment of surrounding trees acts to eliminate any residual population, either by killing the larvae still feeding in the cambium or by killing emerging adults feeding on the leaves of treated trees.

14.3 Pheromones and Other Semiochemicals

Pheromones and other odorants have important roles in intra-specific and inter-specific communication (Howse et al. 1998; El-Sayed 2011). Well-known examples are the use of plant volatiles for host location by plant-feeding insects and the attraction of male moths to female sex pheromones. Because these and other ‘semiochemicals’ are often highly species-specific, they can be very valuable tools for invasive species eradications and associated activities. Such potent attractants are commonly used for detection (i.e., discovering the presence of an invader), delimitation (i.e., determining the geographic distribution), and population monitoring (i.e., assessing the relative abundance), which are all critical elements of eradication programmes. Semiochemicals can also be used directly for population control in techniques such as mass trapping, lure-and-kill, and mating disruption. Although these last-named techniques are not yet mainstream components of eradication programmes, we see considerable potential for their application as ‘greener’ alternatives to conventional control techniques that rely on pesticides (Brockerhoff et al. 2010).

14.3.1 Trapping for Detection, Delimitation, Monitoring

Early detection is an essential prerequisite for successful eradication (Myers and Hosking 2002), while the distribution of an invader is still limited and amenable to area-wide control. Traps baited with pheromones and other attractants can be highly effective for the detection of incipient populations, potentially well before any pest damage becomes apparent. Although some traps rely on other mechanisms (such as attraction to specific colours/wavelengths or flight intercept traps), they are usually less powerful than attractant-baited traps (Howse et al. 1998). Pheromones and other attractants are known for many species (El-Sayed 2011), and they may be available for purchase as synthetic compounds. However, for many other species such attractants remain to be discovered, and suitable long-range attractants for some taxa may not exist. Some of the most extensive detection programmes target the Asian Gypsy Moth, a highly invasive defoliator mainly of oaks and other broadleaved trees. In the USA, in a large, comprehensive, multi-agency containment and exclusion programme (Gypsy Moth Programme Manual – http://www.aphis.usda.gov/plant_health/plant_pest_info/gypsy_moth/index.shtml), approximately 90,000 traps were placed in the Slow-the-Spread area to monitor the expansion of the European strain in 2010. During 2010, an additional 248,500 traps were deployed to survey areas not infested by the European strain, and in ports for detection of introductions of the Asian strain (respectively, pers. comm., Leonard, USDA-FS STS National Programme Manager, and Spaulding, USDA-APHIS-PPQ Gypsy Moth Programme Manager). This large effort to detect new isolated infestations of the European Gypsy Moth in western and southern states has been ongoing since the late 1970s.

APHIS began to monitor ports and other high-risk sites for introductions of the Asian Gypsy Moth in the early 1990s (Mastro pers. comm.). Similar programmes aimed at Gypsy Moth are carried out in Canada and New Zealand (Ross 2005; Régnière et al. 2009). Detection trapping programmes using pheromones and host attractants have also been implemented for wood borers and bark beetles in several countries (Brockerhoff et al. 2006; Rabaglia et al. 2008). Recognizing the importance of early detection, the USDA established a nationwide system to track more than 400 pests of concern. The list of pests is reviewed and reprioritized annually. This Cooperative Agricultural Pest Survey (CAPS) Program is managed cooperatively by USDA-APHIS and state departments of agriculture, with universities, industry groups, and natural resource protection organizations as partners (http://www.aphis.usda.gov/plant_health/plant_pest_info/pest_detection/pestlist.shtml).

When an invasive species has been detected, traps are often used to delimit the affected area and to monitor population trends. For these goals, the number and density of traps are likely to be much greater than for detection trapping. If no known long-range attractant exists, then caged live insects (e.g., female moths) may be used for this purpose. This procedure was employed during eradication of the Painted Apple Moth in NZ (Suckling et al. 2005) and initially in the Slow-the-Spread program for Cactus Moth, *Cactoblastis cactorum* Berg, in the USA until a pheromone-based attractant was identified (Bloem et al. 2003) (Fig. 14.3).

An interesting variation of detection and delimitation trapping programmes was implemented during the eradication campaign against Dutch Elm Disease in Auckland, NZ (Gadgil et al. 2000). Over 200 traps baited with the pheromone of the Elm Bark Beetle, *Scolytus multistriatus* (Marsham), were used to determine the

Fig. 14.3 Wing-type traps with sticky bottom panels initially baited with live females to survey for the invasive Cactus Moth, *C. cactorum*, until a pheromone-based lure was developed. Live females were changed every 3–5 days; the current lure is replaced every 4–6 weeks (Images courtesy of USDA-ARS-CMAVE, Tallahassee, FL)

presence of the fungus (*Ophiostoma ulmi* (Buisman) Nannf.) causing Dutch Elm Disease by isolating fungal spores from this beetle, which is the obligate vector of this fungus. Sometimes, when a long-range attractant is not available, traps are used that depend on host plant odours and/or other behavioural cues. Such is the case in the Emerald Ash Borer programme in the USA, which depends on visually attractive traps baited with host plant volatiles. Even though the trap is not as effective as some pheromone-baited traps, it has allowed the programme to conduct effective detection and delimitation surveys (Crook et al. 2008).

14.3.2 Mass Trapping

The use of mass trapping for pest control is an intriguing concept, and it has received some attention in relation to eradication (El-Sayed et al. 2006). However, important limitations to using mass trapping for population control are founded in the population ecology of species (Howse et al. 1998; Yamanaka 2007). In order to be effective in reducing the population size of an invader, it is likely that 90 % or more of the population should be removed. Because attractants are often only available for males (e.g., male moths responding to female sex pheromones), effects on the ability of females to reproduce are less pronounced, particularly in species where males can mate many times. Consequently, mass trapping may only be effective if the number of traps approaches the number of individuals. Therefore, mass trapping may require the deployment of an unrealistically large number of traps. In unpublished studies with Gypsy Moth, a minimum of 25 traps/ha were required to eliminate mating with simulated low density populations (Schwalbe et al. 1984). However, smaller incipient populations may be controlled by mass trapping, especially in conjunction with other tactics (El-Sayed et al. 2006).

14.3.3 Lure and Kill

The attract- or lure-and-kill tactic involves combining a pheromone or other attractant with a contact insecticide and a viscous carrier material (typically a paste, gel or wax). Here, the goal is to control the target species by attracting it to large droplets of the formulation that are applied to a suitable substrate in the treatment area, causing mortality shortly after contact (Brockerhoff and Suckling 1999; El-Sayed et al. 2009). This tactic resembles mass trapping, but because droplets can easily be applied in large numbers, lure-and-kill is much more suitable for large-scale area-wide control and more cost-effective than mass trapping. Lure-and-kill is now well established for pest control (e.g., in orchards – Suckling and Brockerhoff 1999), but it has not been used often for eradication (El-Sayed et al. 2009). However, its use for eradications of fruit flies (mainly *Bactrocera* spp.) and Boll Weevil (*Anthonomus grandis* Boheman) were considered successful (El-Sayed et al. 2009). Although this tactic involves application of an insecticide, it is more acceptable than many other tactics because few species (other than the target) are likely to come into contact with the formulation, and it is applied at considerably lower rates than other insecticide applications (such as sprays).

Several other related approaches involving insecticides or other treatments have been considered. For example, bark beetles can be attracted to pheromone-baited trap trees that are subsequently treated with an insecticide, debarked or destroyed by burning or chipping, to prevent the emergence of beetle brood. Similarly, bait sprays have been used extensively in fruit fly eradication programmes. However, all lure-and-kill approaches are generally less feasible as eradication treatments when invader populations are large and widespread.

14.3.4 Mating Disruption

Mating disruption is usually considered a tactic for use on low-density populations and is ideal for use after a pest introduction but before populations have increased. Disruption also can be used after a conventional insecticide treatment has reduced the pest insect's density. Synthetic pheromone formulations can be applied to the environment to achieve the effect that male insects are no longer able to locate 'calling' females, thereby preventing fertilization of eggs (Howse et al. 1998). This method requires the release of pheromones such that their aerial concentration makes orientation impossible, because of habituation of pheromone receptors and the central nervous system (Cardé 2007).

An alternative mechanism, often referred to as 'false trails', may also occur under certain circumstance where males follow plumes or trails of pheromone from synthetic sources rather than those emitted by 'calling' females. If the number of pheromone release points (relative to the number of females) is much greater, then the likelihood of a male encountering a female is reduced. Mating disruption involves comparatively small quantities of pheromone (typically non-toxic and highly target-specific) and is considered one of the most environmentally friendly pest control methods. Mating disruption is well established as the method of choice for the control of numerous pests, primarily moths (Cardé and Minks 1995; Cardé 2007).

In recent years the use of insecticides has become increasingly controversial (especially when applied by aircraft), and mating disruption has been increasingly considered an effective alternative. Mating disruption is amenable to large-scale, area-wide application, and is used over very large areas in the eastern and central USA to achieve the localized eradication of European Gypsy Moth along the expanding edge of the infested area. In this 'Slow-the-Spread' programme, aerial application of the Gypsy Moth pheromone 'disparlure' has become the primary tool since 2000 (Sharov et al. 2002) and by 2010 over 1.4 million hectares will have been treated (USFS 2009). Mating disruption, in combination with other tactics, recently has been used for area-wide eradication of Pink Bollworm, *Pectinophora gossypiella* (Saunders), populations (Walters et al. 2000; Tabashnik et al. 2010).

Recent efforts to eradicate the Light Brown Apple Moth (*Epiphyas postvittana* (Walker) in California explored the use of mating disruption as the primary treatment (Suckling and Brockerhoff 2010). Because of the large area involved, and difficulties with access to some places, aerial pheromone application was the only viable option (Suckling and Brockerhoff 2010). A disadvantage of mating disruption is that for some time after a pheromone application, pheromone traps for monitoring are ineffective. However, traps in Gypsy Moth mating disruption areas provide an indirect measure of mating success. Areas where the treatment has not been totally effective can be defined, even though most male capture is shut down. This is actually an indicator of efficacy, but it worries programme managers accustom to trapping information.

14.4 Sterile Insect Technique (SIT)

SIT plays a significant role in containment and eradication programmes for numerous pests around the world (Klassen and Curtis 2005). SIT is defined by the International Plant Protection Convention (IPPC) as: "... a method of pest control using area-wide inundative releases of sterile insects to reduce the fertility of a field population of the same species" (FAO 2005). For SIT to be used as an operational method of pest control, several requirements must be met. These include the application of economic and effective methods of mass production for the target pest, an effective sterilization method and dose, and efficient handling and release methods for sterile insects (Dowell et al. 2005; Hendrichs et al. 2005).

To achieve control of a field population an effective over-flooding ratio of sterile to wild insects must be achieved that reduces the probability of a fertile mating so that with repeated releases over time, no offspring are produced and the local pest population is eliminated (Hendrichs et al. 2005). To achieve this goal, the released sterile insects must compete and mate successfully with their wild counterparts, and pest populations must be low such that effective over-flooding ratios can be achieved with reasonable economic release rates. Because sterile insects must perform well against the wild target pest, a sterile insect quality management system is a critical element of for programme management (Calkins and Parker 2005; Simmons et al. 2010). As with mating disruption, treated areas must be sufficiently large and/or isolated to minimize the effect of immigration from surrounding areas (Barclay et al. 2011).

SIT is not a stand-alone eradication tool. However, the use of SIT as a control tactic has many advantages, including species specificity and compatibility with the use of most other control tactics such as mating disruption, biological control, cultural/mechanical control and the use of pesticides (Klassen 2005; Carpenter 2000). When these methods are used together on an area-wide basis, SIT can form the foundation for a very powerful approach that has been and continues to be used successfully for eradication and long-term suppression (Hendrichs et al. 2007; Pimentel 2007).

14.4.1 Strategies

Four strategies are used in SIT to create a plant protection tool. These strategies are prevention, containment, suppression, and eradication (Hendrichs et al. 2005). All these strategies have been used together with other Integrated Pest Management (IPM) tactics compatible with use of the SIT in an area-wide control programme approach with varying degrees of success (Hendrichs et al. 2005).

Prevention: A Preventative Release Strategy or Programme (PRP) can be employed in a pest-free area at high risk of invasion. For example, consider an agricultural area or environment with suitable conditions for pest establishment and development (Hendrichs et al. 2005). The Los Angeles basin in California is at high risk of invasion by tephritid fruit flies (Barinaga 1991). The climate is warm, many potential host plants are grown in the basin, and it has a very busy port (Long Beach) with a very high volume of international air travelers (LAX) bringing in fruits that may be infested. The cooperative Mediterranean Fruit Fly, *Ceratitis capitata* (Wiedemann), exclusion programme has been operating in this region since 1996, releasing over 250,000,000 flies per week year round over a 2,155 mile^2 area (CDFA http://www.cdfa.ca.gov/phpps/pdep/prpinfo/index.html, Enkerlin 2005). The benefits of this programme have an estimated annual savings of $1.3–1.9 billion USD in costs that would be required for control, regulatory and quarantine compliance and loss of markets (Enkerlin 2005).

Containment: Containment programmes use release of sterile insects to prevent the spread of an established pest into an uninfested area by providing a barrier or buffer of sterile insects between an infested and an uninfested area (Hendrichs et al. 2005). This tactic may consolidate gains made in an eradication programme (Hendrichs et al. 2005), or prevent a pest coming into an area at risk to invasion. The barrier zone in Panama in the Darien Gap serves as an example. Sterile New World Screwworm Flies are released to prevent reinvasion into the eradicated zone in Panama. This operational eradication programme has now entered a maintenance phase (Hendrichs et al. 2005; Vargas-Teran et al. 2005).

One of the longer running containment programmes has been the release of sterile Pink Bollworm in large cotton production areas in the Central Valley of California for more than 40 years, to stop the spread of Pink Bollworm from the infested cotton production areas in southern California (Hendrichs et al. 2005; Bloem et al. 2005). During the programme's operation, regular interceptions of wild Pink Bollworm on monitoring traps at the southern end of this containment area have demonstrated the effectiveness of using SIT to block the invasion and establishment of this pest (Tabashnik et al. 2010). With the current success of the Pink Bollworm eradication programme, the need for this containment may diminish.

Suppression: For suppression, SIT is used as a control tactic to maintain the pest below an economic threshold. The first SIT efforts were viewed as primarily eradication tactics and were not considered cost effective as regular control tactics. However, improvements in rearing technology, market forces, consumer demand for pesticide-free fruit, and restrictions on the use of certain pesticides, have made the routine use of SIT for pest control a viable economic option (Hendrichs et al. 2005). Many programmes now use SIT in this manner, including: Several programmes for Mediterranean Fruit Fly in the Middle East, South Africa and Spain (Cayol et al. 2004; Hendrichs et al. 2005; Enkerlin 2005); Oriental Fruit Fly, *Bactrocera dorsalis* (Hendel), in Thailand (Orankanok et al. 2007); as well as several programmes for moths such as Codling Moth, *Cydia pomonella* (L.), on apples in British Columbia, Canada (Bloem et al. 2007b); False Codling Moth, *Cryptophlebia leucotreta* (Meyrick), on citrus in South Africa (Carpenter et al. 2007); and Pink Bollworm on cotton in desert valleys of southeastern California (Walters et al. 2000; Bloem et al. 2005). A highly developed rearing and release system has helped to facilitate expansion of the Pink Bollworm programme and a shift of the goal to eradication of this pest from North America (see below).

Eradication: Successful eradication efforts using SIT require the operation of a coordinated area-wide control programme where several compatible technologies are applied, reducing the pest population so that sterile insect rearing and release costs are not prohibitive. Several successful eradication campaigns against plant pests have used SIT as one of the primary tactics (Hendrichs et al. 2005). The New World Screwworm, *Cochliomyia hominivorax* (Coquerel), was eliminated from North America using SIT in combination with careful inspection and treatment of cattle (Vargas-Teran et al. 2005). Several tephritid fruit fly species in diverse agricultural regions in California, Mexico, Florida, and Japan and several moth species also have been successfully eradicated (Kean et al. 2009; Suckling et al. 2007; Hendrichs et al. 2005; Enkerlin 2005; Bloem et al. 2005). A large, 10 year, area-wide campaign against the Pink Bollworm has driven this pest to undetectable levels across the south-western cotton belt in four states and northern Mexico (Fig. 14.4). This programme uses a combination of tactics, including regional widespread planting

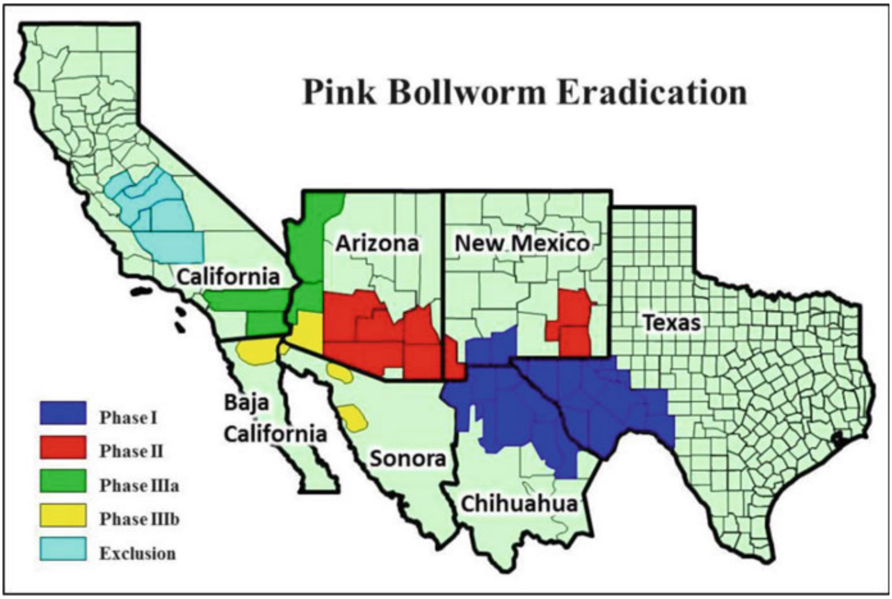

Fig. 14.4 Incremental phases of the international Pink Bollworm eradication programme. This programme uses a combination of tactics, including *Bt*-cotton, sterile insect technique (SIT), mating disruption and cultural control. The SIT component is considered particularly important as a final control measure to achieve eradication. Exclusion activities to prevent establishment of PBW in the San Joaquin Valley of California have been ongoing since 1968. *Phase I* of the eradication programme began in 2001 in the El Paso and Trans Pecos regions of western Texas. Operations in south-central New Mexico and the state of Chihuahua, Mexico, began in 2002. *Phase II* began in 2006 with the addition of cotton growing areas in southern Arizona, as well as southwestern and southeastern New Mexico. *Phase IIIa* began in 2007 with the addition of cotton acreage in western Arizona and southern California. *Phase IIIb* began in 2008 with the addition of Yuma County, AZ, Sonora, Mexico, and San Luis and Mexicali, BC, Mexico. As of December 2011, *Phases I* and *II* were 99% complete (i.e., PBW populations had been reduced by 99 % relative to preprogram levels) and being monitored for eradication, with sterile moth releases continuing throughout much of the area to prevent reestablishment. *Phase III* was approximately 98 % complete, with on-going monitoring and treatments using *Bt*-cotton, mating disruption and SIT where trap captures indicated breeding populations (Map and information updated by Walters 2011, APHIS-PPQ-CPHST, Phoenix, AZ, from El-Lissy 2009, APHIS-PPQ, Riverdale, MD)

of genetically modified cotton expressing the *Bt* toxin, SIT, mating disruption, and cultural control methods (Tabashnik et al. 2010). A similar application of SIT combined with integrated area-wide tactics against a much smaller infestation of the Painted Apple Moth in New Zealand resulted in the eradication of this species after 2 years of programme operation (Suckling et al. 2007).

Eradication campaigns using SIT must be well organized and operated in a coordinated fashion to ensure compatible technologies are used appropriately and the sterile insect resource is used effectively (Hendrichs et al. 2005). As in any operational programme, comprehensive monitoring and data management are critical to ensure that timely information is delivered to programme managers for "decision making" (Brockerhoff et al. 2010).

14.4.2 Choice of Strategy

The direct and indirect benefits of using SIT in control programmes are summarized in Enkerlin (2005) and Hendrichs et al. (2005). These include direct benefits such as increases in fruit or commodity quality and yield by decreased damage, reduction of pesticide use, reduction in production costs, and increased market access with the maintenance of Pest-free Export Zones. The selection of which strategy to use may depend on economics and other factors such as size of the established population, proximity to infested areas, and pest biology (Hendrichs et al. 2005). The most cost-effective option is prevention, compared with the costs of control or eradication of a pest after it becomes established (Hendrichs et al. 2005; Enkerlin 2005). If the pest is already established, then the option of eradication, while expensive, will return the most benefits relative to long-term options of suppression or containment (Enkerlin 2005). Factors such as the costs of operating permanent quarantine and monitoring activities, coupled with the lost opportunity costs of exporting agricultural commodities, must also be considered when choosing a strategy (Enkerlin 2005).

14.5 Biological Control

Two forms of biological control (classical and augmentative/inundative) have potential roles in eradication programmes. *Classical Biological Control* is the deliberate attempt to introduce exotic natural enemies to help reduce the densities of a target pest, usually an invasive species (Hoddle and Syrett 2002). Classical Biological Control programmes represent a process that can take 3–5 years or longer before biological control organisms are released. Therefore, they are not usually considered eradication tools. In fact, for many years biological control was not investigated as a management option for a new exotic pest by regulatory agencies until after eradication efforts were deemed no longer feasible. Conventional wisdom held that an early interest in biological control would send the wrong message to trading partners that regulators were not serious about eradication and that growers were already planning to live with the pest.

14.5.1 Classical Biological Control

Classical Biological Control for eradication attempts has also been dismissed because of the conventional assumption that success would result only in a stable, self-sustaining balance between the new natural enemy and their now less numerous, but not eliminated, target pest. However, introduced arthropod natural enemies sometimes appear to cause local insect and plant extinctions (Murdoch et al. 1985). In these cases the pest persists area-wide because of reintroductions from outside the area of eradication. For instance, two parasitoids were introduced into Nova

Scotia to control the invasive European Winter Moth, *Operophtera brumata* (L.), a defoliator of hardwood trees. Within years of the last introduction, the moth essentially disappeared from hardwood forests but was still present in apple orchards and shade trees. In another case, extensive sampling of the Larch Sawfly, *Pristophora erichsonii* (Hartig), in Manitoba following parasitoid introductions suggested a pattern of local extinction and reinvasion. Perhaps local extinctions effectively could be monitored and expanded as part of an Integrated Pest Eradication Programme. Certainly the inadvertent decimation of species such as the American Chestnut (*Castanea dentata* (Marsh.) Borkh.) By invasive organisms illustrates the potential impact of freely reproducing natural enemies.

Perhaps a more likely role for Classical Biological Control in eradication efforts is simply the suppression of pest populations to the point that other techniques become more practical. For example, the argument has been made repeatedly that lowering tephritid fruit fly populations through the establishment of parasitoids would make future SIT eradication programmes more effective and affordable (Hendrichs et al. 2005). In the most spectacular instance, Hawaiian populations of the Oriental Fruit Fly (*Bactrocera dorsalis* (Hendel) plummeted by ~90% with the introduction of the egg-prepupal braconid parasitoid *Fopius arisanus* (Sonan) (Haramoto and Bess 1970; Newell and Haramoto 1968). Confirmation that the cause of the decrease was indeed the natural enemy was obtained when the pest and parasitoid were recently reunited in Tahiti. Again, fly numbers dropped precipitously (Vargas et al. 2007).

Natural enemy establishment could also help maintain barriers erected with other techniques. For example, there is a multi-national attempt to create an SIT/host-removal barrier to prevent the spread of the invading cactus moth along the southeastern USA coastline into the western cactus-rich states and ultimately into Mexico (Bloem et al. 2007a). If this barrier can be erected, then it would probably be more effective and more cheaply sustained if pest population pressures were lower on its infested borders. Similarly, since 1996, APHIS, State and City cooperators in New York, Illinois, and New Jersey, and the US Forest Service have undertaken eradication activities against the Asian Longhorn Beetle by imposing regulated boundaries, conducting survey and control activities around confirmed sites, removing infested trees, and planting trees to restore areas where trees were removed (USDA APHIS ALB Cooperative Eradication Programme Strategic Plan http://www.aphis.usda.gov/plant_health/plant_pest_info/asian_lhb/index.shtml). Although the programme has deregulated some areas, program activities are expected to continue at least until 2020. Biological control, if available for this insect, might be useful to help minimize spread and possibly reduce the number of trees removed, during a long eradication process.

14.5.2 Augmentative/Inundative Biological Control

Augmentative/Inundative Biological Control (artificially increasing the numbers of a host-specific parasitoid or predator) has been frequently proposed as a viable eradication or area-wide pest-management tool (Knipling 1992), particularly as a method of dealing with pests of high value crops. Augmentation has been used extensively in greenhouses where growers of such crops as cut flowers prefer very low to nonexistent pest numbers. Various models predict the possibility of target eradication and some rely on the idea that since the seasonal growth of natural enemy populations tends to lag behind that of their target, an early-season mass release will inflict higher percentage mortalities than might occur in nature. In this way, low initial pest numbers can be driven even lower, perhaps to the point of extinction (Liebhold and Tobin 2008).

For practical purposes, any attempt at eradication through Augmentative Biological Control should first address several important concerns. First is the vulnerability of the target. If "refugia" habitats exist where the pest is safe from attack, then eradication becomes less likely. For example, tephritid fruit fly larval parasitoids (even those with the longest ovipositors) have difficulty reaching hosts that feed deep in the pulp of large fruits. Releases of parasitoids when and where large fruits are numerous would be less effective than releases into habitats where fruits are small. Fortunately some pest fruit flies are attacked by parasitoids that oviposit into eggs, (e.g., the highly successful *F. arisanus* previously mentioned) and host eggs are generally much closer than larvae to a fruit's surface.

The second concern is to determine natural enemy release rates (Parrella et al. 1992). This is often not easy to accomplish experimentally, particularly under ecologically realistic conditions in the field. Pests and natural enemies housed in large field cages may provide more opportunities to replicate different treatment levels, but these comparisons present difficulties of their own, such as preventing natural enemy dispersal.

A third concern is the expense of rearing, transporting and releasing natural enemies. The cost of mass-reared natural enemies can be high but must be compared with the alternatives. For example, Augmentative Biological Control of the Two-Spotted Spider Mite (*Tetranychus urticae* Koch) in strawberries through releases of *Phytoseilius persimilis* Athias-Henriot was shown to be possible many years before pesticide resistance, as well as the loss of some chemical controls and the rising costs of others, led to its widespread use (Parrella et al. 1992). Augmented releases of tephritid parasitoids such as *Diachasmimorpha longicaudata* (Ashmead) have suppressed Caribbean Fruit Fly, *Anastrepha suspensa* (Loew), by as much as 95 %. However, to be economically practical a parasitoid must be superior to its alternative, a sterile fly, such that the additional rearing costs are justified (Sivinski et al. 1996). In this case, effective release rates for parasitoids may be lower than those used for sterile males. Also, methods can be developed to reduce rearing costs by exploiting sexually dimorphic developmental rates to harvest mass-reared female fly larvae for exposure to parasitoids, simplifying release procedures by irradiating hosts to prevent adult fly eclosion, and perhaps manipulating parasitoid sex ratios with the endosymbiotic bacteria *Wolbachia* so that only female parasitoids are produced.

Augmentative Biological Control can be easily used in conjunction with SIT (Gurr and Kvedaras 2010). For example, the Australian Painted Apple Moth

(*Orgyia anartoides* (Walker) was eradicated from New Zealand through combined applications of the entomopathogen *Bt* and sterile males (Suckling et al. 2007). Arthropod natural enemies and SIT together might be particularly effective as an eradication technique because the control tactics can complement one another (Knipling 1992). This is because the attack rates of insect parasitoids are often positively density dependent. Foraging efficiency is highest when host populations are high, and the efficacy of SIT is negatively density dependent. Overflooding is more easily achieved with low target populations. Thus, the success of parasitoids makes SIT more potent. Models predict that the combination of the two can result in a synergistic effect, i.e., together their capacity to control a pest population is greater than the sum of their individual contributions. Synergism has been demonstrated in a greenhouse experiment comparing the ability of parasitoids, SIT and their combination to control the Onion Leafminer, *Liriomyza trifoli* (Burgess) (Kaspi and Parrella 2006). An economic bonus is bestowed on some combined release programmes because the rearing facilities and means of release for mass-reared parasitoids and sterile males are often similar and do not require separate infrastructures.

Recent interest in SIT + parasitoid augmentation has centered on the suppression of tephritid fruit flies. This is due, in part, to the desire to improve the substantial SIT + insecticide-bait-sprays efforts underway both to eradicate invasive populations and to maintain barriers such as along the Mexican-Guatemalan border which prevents the northward spread of the Mediterranean Fruit Fly. Experiments comparing the efficacy of fruit fly parasitoids + SIT to either technique alone have yielded mixed results.

A pioneering Hawaiian field study combined sterile Mediterranean Fruit Flies with a larval parasitoid, *Diachasmimorpha tryoni* (Cameron). The study suggested that the two techniques were most effective when employed together (Wong et al. 1992). For many years, Mexico has successfully released sterile *Anastrepha* spp. along with *D. longicaudata* in their efforts to create/maintain fly free and low prevalence areas. Mediterranean Fruit Fly populations developing in field-caged coffee (*Coffea arabica* L.) were significantly more suppressed by SIT + *F. arisanus* than SIT alone, although parasitoid augmentation alone was also often more effective than SIT (Rendon et al. 2006). Based on these results, the MOSCAMED fruit fly suppression programme along the Mexican-Guatemalan border now includes augmentative releases of *F. ceratitivorus* Wharton, a biologically similar species that specializes on Mediterranean Fruit Fly (Lopez et al. 2003) and is easier to mass-rear, in hotspot areas and areas where bait sprays are problematic (Fig. 14.5). Alternatively, sterile Melon Flies (*Bactrocera curcurbitae* (Coquillett)) released on a non-crop source of infestation were superior to mass-released larval parasitoids (*Psyttalia fletcheri* (Silvestri)) in suppressing the numbers of adult flies subsequently eclosing. Such diversity of outcomes emphasizes that the natures of the pest, the parasitoid, and the environment are all likely to influence the outcome of any biological control effort, including augmentation.

In addition to tephritid control, encouraging experiments have combined sterile moths and parasitoids. For instance, damage to fruit in cages containing fertile male

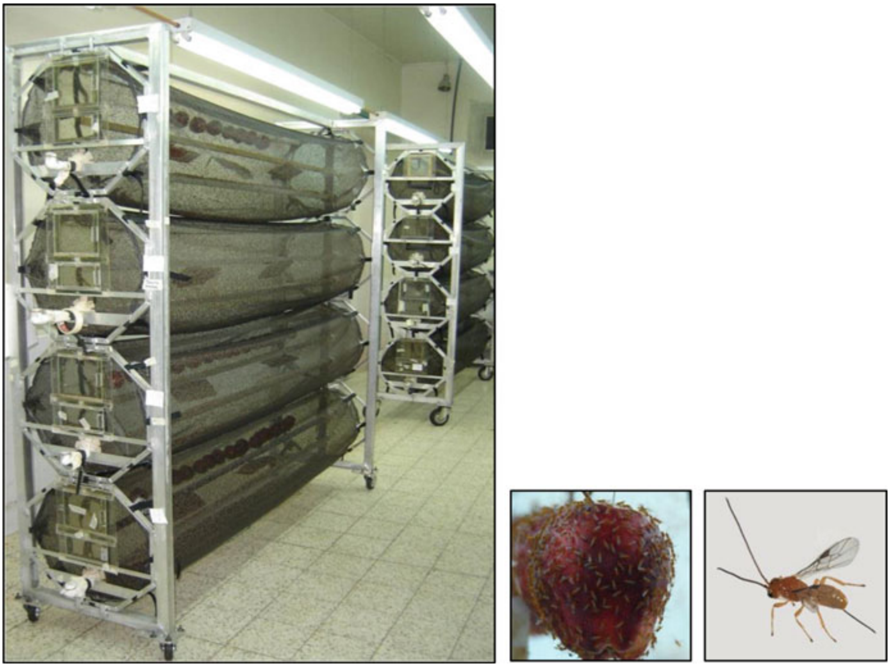

Fig. 14.5 The MOSCAMED programme in Guatemala is mass-rearing the egg parasitoid *F. ceratitivorus* to help combat the Mediterranean Fruit Fly. Apples are first pricked and exposed to Medfly adults for oviposition, and then placed in large sleeve cages for exposure to the parasitoid. In 2011, approximately 1.0–1.5 million parasitoids were released per week in hotspot areas to help eliminate recurrent Medfly detections in the coffee production region of southwest Guatemala (Photos courtesy USDA-APHIS-PPQ-CPHST, Guatemala City, Guatemala)

and female Codling Moths was lowest when sterile males and the egg parasitoid *Trichogramma platneri* Nagarkatti were introduced together (Bloem et al. 1998). In this case, the bisexual release of sterile moths may result in an abundance of sterile eggs being laid, which can then be capitalized upon through the inundative release of egg parasitoids. Field populations of the parasitoid might thus be maintained at more consistent and higher numbers and provide additional control. Similar lab and field cage experiments also were conducted to determine the acceptability and suitability of sterile False Codling Moth eggs to parasitism by *Trichogrammatoidea cryptophlebiae* Nagaraja (Carpenter et al. 2004).

14.6 Integrated Pest Management and Eradication

The United Nations Food and Agriculture Organisation (FAO) says “Integrated Pest Management (IPM) means the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified, and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms" (www.fao.org/agriculture/crops/core-themes/theme/pests/ipm/en/). IPM is therefore an ecologically-based pest control strategy that favours methods that are least disruptive to the environment and ecosystem services, by using complementary tactics to reduce natality and increase mortality of pests. Tactics widely used in IPM include selective or narrow-spectrum insecticides, pheromones, biological control (Classical, Inundative or Conservation), host plant resistance, cultural management practices such as habitat manipulation, modelling for prediction and decision support, and other knowledge-based approaches (Maredia et al. 2003). In IPM programmes many pests are often present, although only a few may be key pests.

IPM has emerged as the "best practice" systems approach for managing established pests, while minimizing non-target impacts from interventions. IPM in the field can also be integrated with a post-harvest systems approach to the export of fruits or other affected commodities, by taking into account the reduction in risk of pest prevalence at each stage, from field and harvest through post-harvest handling or quarantine procedures (e.g., Jang 1996), thus enabling market access. These systems approaches are designed to replace the need for fumigation with methyl bromide, which causes ozone layer depletion when released to the atmosphere and is being phased out under the Montreal Protocol (UNEP 2006) (see Chap. 10).

The increase in negotiated acceptance between trading countries of "areas of low prevalence" or "pest free areas" has meant that certified evidence of absence of catch in on-going surveillance (e.g., pheromone or fly trapping programmes with continuous zeros) can enable exports to markets free of certain pests without the need for post-harvest fumigation (Follett and Neven 2006). Alternative tactics for fruit commodities based on this approach include combinations such as low temperature and controlled atmospheres, and irradiation, as well as measures of host range and utilization that can indicate low risk of infestation. These systems are designed to help facilitate trade where eradication is not possible, but add to the on-going costs of pest management. Such on-going pest management costs are taken into account in developing the baseline for a cost-benefit case for supporting eradication.

Where pests have a wide distribution, there may be areas with pest suppression supported by buffer zones to reduce or prevent immigration. In such situations, the containment area may gradually expand where suppression is underway, using the "rolling carpet" approach (Hendrichs et al. 2005). This approach has been used successfully with Screwworm, Pink Bollworm and fruit fly programmes.

The term "Integrated Pest Eradication" (IPE) was proposed (Suckling and Brockerhoff 2010) to build on this well-established philosophical approach and extend it to dealing with the analogous case of invasive species that may be targeted by an eradication programme. An example of this approach might aim to use complementary tactics against different life stages, such as insecticides targeting larvae and SIT or pheromones for mating disruption against the adult stage. Features of individual tactics must be taken into account at the programme level. Features include availability, registration and approvals, costs, reliability and effectiveness, inter-compatibility, social acceptance and scalability. Unfortunately, some low-impact tactics are not available for all Orders of organisms, because of the pest biology. In some cases, tactics can work synergistically, which is ideal. An example is the combination of SIT and augmentative releases of parasitoids, as previously discussed (see Sect. 14.5).

The goal of eradication is implicitly far more challenging than continuing pest management, because it involves preventing the establishment of self-sustaining populations from occurring anywhere in the target zone, no matter what landscape is involved. Allee Effects (Liebhold and Tobin 2008) can contribute usefully to the extinction of pest populations, without necessarily killing the last individual, because very low density populations may go extinct by themselves. Some inversely density-dependent tactics, such as SIT or mating disruption that work better at low pest density, exploit this weakness.

The economic threshold for an eradication or containment response is high because these programmes typically cost many millions of dollars and can last several years. The cost and duration implies a degree of coordination that is usually only achieved at government level. A careful summation of cross-sectoral pest impacts ensures that unwarranted eradications are not undertaken. Host-specific plant pests (including plant pathogens) are less likely to trigger an eradication response on this basis, even when tools are available for surveillance and eradication.

Several basic conditions are essential for success in an eradication campaign. Tools must be available that can be used to monitor and control populations of the target organism, and the distribution of the invader should still be limited, known, and not expanding rapidly. Public support and adequate funding are also important (Myers and Hosking 2002; Brockerhoff et al. 2010).

The tools available for eradication may also be more limited than those for pest management, because pest management is typically applied in agricultural, forest or horticultural production systems where producers are more accepting of pesticides and other interventions than are urban populations. IPM typically is applied on private land, whereas eradications must target pest populations on both public and private lands. Land owners may not be sympathetic to government programmes, even when a cost-benefit analysis indicates economically-favorable outcomes from eradication of unwanted organisms.

Ironically, unwanted organisms are often discovered first in urban areas. Hence societal attitudes can directly affect the feasibility of eradication, particularly in cities or other sensitive ecosystems. Public attitudes to iconic amenity plants and trees also must be considered. Differences in public attitudes to different eradication tactics must be elucidated. More work is needed in this area, as well as in the development of new tools.

14.7 Challenges and Outlook

Significant advances have been made in the development, application and integration of tools available for eradication, and this is apparent in the increased rate of success of recent eradication programmes. As the rate of new organism incursions is accelerating, driven by increased global tourism and trade, a similar trend could be expected in the rate of spread and costs due to high impact pests. Examples include Red Imported Fire Ant and mosquitoes, where it is likely that governments would attempt containment or eradication if possible. This suggests that governments should increase their investment in this area, to avoid the phenomenon discussed as the "ambulance at the bottom of the cliff" during the recent US$45M eradication of an Australian Tussock Moth (called Painted Apple Moth in urban Auckland, New Zealand). Up to 40 aerial applications of *Btk* were applied together with other tactics (Brockerhoff et al. 2010).

The Australian government has attempted to proactively deal with the issues of who benefits and who pays for eradication in the following way. If the pest is only of public interest, then clearly the federal government is the interested party and will pay for the programme. Alternatively, if agriculture has a large interest (presumably because the unwanted organism is a known threat), then the costs may be shared with government according to a formula based on this information. This recognition of shared interest presumably helps to bring pests that might not otherwise be eradicated into the eradication realm. Examples are sector-specific pests with a narrow host range.

Other issues of equity arise during eradication programmes because parties at risk from an organism may not be geographically the same as the public directly affected by treatments where the organism is found. In this case, it is helpful to invest heavily in communications and, if necessary, in socially-acceptable solutions. In New Zealand, publication of the results from regular surveys indicating a high degree of support from affected residents helped the government to deal with vocal opposition from a minority of protestors based outside the affected area during the Painted Apple Moth eradication programme involving 30,000 acres of urban and suburban Auckland.

In some cases, eradication clearly is possible and justifiable as a desirable outcome for governments, affected parties, and the public. The substantial cost, commitment and effort needed for eradication require a substantial cost-benefit analysis, including the expected impacts of an invader and feasibility of eradication (Brockerhoff et al. 2010). Considerable progress has been made in our understanding of costs and benefits of eradication, and many recent programmes have provided significant financial benefits despite weak consideration of non-market values, such as impacts on amenity values. Nevertheless, constraints include increasing public interest and occasional strong opposition to such programmes. New media, such as internet-hosted libraries of videos from interested or affected parties, are being used by opponents of such programmes and present a major challenge to governments to present their case in support of intervention.

Many eradication programmes face the challenge of developing cost-effective treatments for large areas, often best achieved using aircraft. However, the aerial application of broad-spectrum insecticides used in previous decades against fruit flies in California (Barinaga 1991) is generally no longer acceptable. The aerial application of pheromones has been used for many years to slow the spread of Gypsy Moth in the eastern USA (http://da.ento.vt.edu), but even this tactic was withdrawn by the Governor of California after public opposition mounted to use of microencapsulated pheromone in a recent eradication programme for the Light Brown Apple Moth (www.cdfa.ca.gov – Light Brown Apple Moth Project, CEQA Mandated Findings 03/22/10). This example suggests that a change in public attitudes may be occurring, possibly because of increasing urbanization and reduced societal understanding of the need for pest management in food production. Alternatively, when the public understands the impact of a pest and the risks and benefits of aerial application of pesticides (e.g., *Btk* for Gypsy Moth suppression in eastern USA) the tactic may be accepted and controversy withdrawn when funding the programme.

We must increase the awareness and understanding among the public of the threat posed by some invasive species, and that a decision not to eradicate also can affect the public negatively. Unfortunately, the lack of effective socially-acceptable tools for eradication is often a significant limitation. More research is needed into tools with fewer non-target impacts to fill this gap. A critical requirement for the future is an improved understanding of the ecology and management of invasions, including modelling and other decision-support tools, as well as an expanded tool kit of options for cost-effective surveillance and eradication. The strong trend, supported by general cost-benefit analyses for certain types of high profile organisms (see Table 14.1), is a greater need for activity and knowledge in this area of applied ecology. Hence, the outlook for employment of new graduates interested in regulatory issues is arguably excellent as new invasive organism problems unfold. Further, we cannot underestimate the policy challenges faced by governments dealing with an increasing demand for resources just to maintain the *status quo*.

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