New Zealand Journal of Forestry Science

40 suppl. (2010) S117-S135

www.scionresearch.com/nzjfs

Eradication of invasive forest insects: concepts, methods, costs and benefits†

Eckehard G. Brockerhoff[1,*], Andrew M. Liebhold[2], Brian Richardson[3], David M. Suckling[4]

[1] *Scion, PO Box 29237, Christchurch 8540, New Zealand*
[2] *US-Forest Service, Northern Research Station, 180 Canfield St., Morgantown, WV 26505, USA*
[3] *Scion, Private Bag 3020, Rotorua 3046, New Zealand*
[4] *The New Zealand Institute for Plant and Food Research, PO Box 4704, Christchurch, New Zealand*

(Received for publication 29 June 2009; accepted in revised form 3 March 2010)

*corresponding author: eckehard.brockerhoff@scionresearch.com

---

Abstract

Invasive exotic insects can cause substantial damage to trees and the environment, and may reduce biodiversity. They can have a large negative economic effect on the forest industry, urban amenity trees and numerous other sectors, and they may necessitate extensive management expenditures. For such high-impact invaders, eradication is desirable but also difficult and often highly controversial. It requires substantial input of resources and commitment from managers and stakeholders, including the general public. Appropriate tools for surveillance and control of the target species must be available if success is to be achieved. This review outlines the sequence of steps required in well-managed operations; examines characteristics of successful and unsuccessful eradication campaigns; describes methods and tools known to be effective against specific pests; and discusses the analysis of costs and benefits of eradication programmes.

Feasibility of eradication is increased by early detection, which is facilitated by systematic surveillance. A strong positive relationship exists between size of the affected geographical area and the cost of eradication. Treatment costs for large populations may be prohibitive. Five recent campaigns against lepidopteran species in New Zealand have provided substantial economic benefits, despite the fact that various non-market values were not considered.

Although progress has been made in the development, utilisation and integration of eradication tools, some insects are still not amenable to treatment. There is a need for new methods shown to have a minimal effect on other organisms, including human beings. Public attitudes to eradication programmes must always be taken into account during planning and deployment.

Keywords: Biological invasions; forest pests; cost–benefit analysis; eradication; tactics; tools.

---

† *Based on a presentation at the OECD Workshop at the IUFRO International Forestry Biosecurity Conference, 17 March 2009, Rotorua, New Zealand. The Workshop was sponsored by the OECD Co-operative Research Programme on Biological Resource Management for Sustainable Agricultural Systems, whose financial support made it possible for the invited speakers to participate in the Workshop.*

ISSN 0048 - 0134 (print)
ISSN 1179-5395 (on-line)

Introduction

Invasions of exotic (non-native, non-indigenous) insects and the diseases they carry represent a major threat to trees and to forest ecosystems (e.g. Liebhold et al., 1995; Mack et al., 2000; Lovett et al., 2006; Brockerhoff et al., 2010). The rate of establishment of such organisms beyond their natural range is increasing as a result of expanding international trade and the transporting of plants (e.g. Chorneskey et al., 2005; Lockwood et al., 2007). While most exotic species have little impact and are rarely noticed, some cause substantial damage to trees and to the environment, and may have catastrophic effects on biodiversity (Mack et al., 2000). A few invaders have caused gradual, and in some cases near-complete, disappearance of their host species. Examples include: Dutch elm disease caused by the pathogens *Ophiostoma ulmi* (Buisman) Nannf. and *Ophiostoma novo-ulmi* Brasier, in conjunction with their bark beetle vectors, *Scolytus* spp. (Brasier, 1991); and the emerald ash borer (*Agrilus planipennis* Fairmaire) (Poland & McCullough, 2006). The economic impact of invaders, in terms of tree damage or mortality, management and control, trade restrictions, and other costs, can be enormous (e.g. Pimentel et al., 2000; Colautti et al., 2006; Holmes et al., 2009). National management plans designed to combat exotic pest incursions have been developed in both New Zealand and Australia (Gadgil et al., 2003).

Several authors (e.g. Leung et al., 2002) have suggested that limitation of arrivals by closing pathways is the most efficient strategy for management of biological invasions. Unfortunately, the increase in global trade precludes the effective intervention across all invasion pathways, and, consequently, exotic species are likely to continue to arrive. For particular invaders that are expected to have a major impact, total elimination of the species from a given area (i.e. eradication) may be the best option among the responses possible. Benefits of successful eradication include the prevention of indefinite accumulation of deleterious effects and economic impacts, but these benefits may be outweighed if eradication costs escalate or if the operation becomes impractical due to the large size of the invaded area (Sharov & Liebhold, 1998; Myers et al., 2000; Liebhold & Tobin, 2008).

Although some believe that eradication is impossible to achieve (e.g. Dahlsten et al., 1989), many examples of successful eradication operations exist, including: the elimination of several tree-defoliating Lepidoptera in New Zealand and North America (e.g. Myers & Hosking, 2002; Suckling et al., 2007a); the screwworm fly (*Cochliomyia hominivorax* (Coquerel)) in the United States of America (USA) (Myers et al., 1998), Central America (Galvin & Wyss, 1996), and North Africa (Gillman, 1992); the Mediterranean fruit fly or 'medfly' (*Ceratitis capitata* (Wiedemann)) in Mexico, parts of Central America, Chile, California (Hendrichs et al., 2002) and New Zealand (Holder et al., 1997); and the red imported fire ant (*Solenopsis invicta* Buren) in New Zealand (Sarty, 2007). Also, many mammalian and plant invaders have been eradicated from islands (e.g. Veitch & Clout, 2002). Despite such successes, eradication is generally considered to be difficult, often requiring substantial input of resources and commitment from managers and stakeholders (e.g. Myers & Hosking, 2002; Simberloff, 2002, 2003). Conditions essential for success of campaigns include availability of tools for monitoring and controlling populations of the organism; public support; adequate funding; and, in most cases, early detection (i.e. limited distribution) (Myers & Hosking, 2002; Simberloff, 2002). Integration of these requirements and techniques with knowledge about population dynamics is still inadequate (Liebhold & Tobin, 2008). New and improved tools with fewer non-target impacts are needed. For example, the undesirable effects of broad-spectrum insecticides on other species have restricted their usefulness. Even the bacterial insecticide *Bacillus thuringiensis* Berliner (var. *kurstaki*) (*Btk*), which is specific to Lepidoptera, can affect non-target species. The aerial application of this specific biological control in urban areas has proven unpopular with some affected residents (Richardson & Thistle, 2002).

This review summarises the steps of well-managed eradication campaigns. Characteristics of successful and unsuccessful campaigns against forest insects are examined, and tactics and tools are reviewed, with a focus on recent improvements and developments of "greener" methods. An overview of costs and benefits of eradications is also given.

Steps required for a successful eradication campaign

Several attempts have been made to develop procedures for the planning and implementation of responses to incursions of forest insect pests and diseases. For example, Hosking (2001) developed an "Emergency Response Guide." It is useful to consider the necessary requirements of eradication programmes across specific stages (Hosking, 2001; Myers & Hosking, 2002). Features of successful campaigns have been reviewed by Simberloff (2002).

Here we provide an updated framework that summarises the sequence of responses and actions needed for planning, during the operational phase and for reviewing of any incursion response and eradication. As soon as the presence of an exotic forest insect has been reported, the following steps should be taken:

1. detection and identification of the organism;
2. assessment of risks and impacts;
3. delimitation to determine the extent of the

ISSN 0048 - 0134 (print)
ISSN 1179-5395 (on-line)

infestation;

4. evaluation of appropriate treatment options available for the target species (including availability of tools and their non-target impacts);
5. consideration of the characteristics of the affected geographical area (e.g. urban vs. forest, proximity to dwellings etc.);
6. acquisition of funds;
7. communication with stakeholders, including the public (ongoing);
8. decision about whether to eradicate, contain, or do nothing;
9. detailed planning and execution of the operation;
10. monitoring of population size and spread;
11. regular review of progress;
12. termination of the operation when it is considered to be successful or when circumstances are no longer favourable;
13. final review and analysis of procedures and factors contributing to success or failure; and
14. publication of the findings as a contribution to definition of best practice and to advance the 'science of eradication.'

Successful and unsuccessful eradication campaigns

Size of the affected geographical area and cost of operations

Eradications of several tussock moths and other defoliators in New Zealand during the last 15 years have shown that the extent of the affected area has a major influence on the cost and effort required for eradication (Figure 1, Table 1). Even "limited infestations" (covering less than 100-2000 ha) incurred eradication costs of ca. NZ$4–7 million. These expenses included risk assessment, delimitation surveys, communication programmes, treatment, and research. Total costs increase with the size of the infestation, and may become prohibitive if many thousands of hectares are affected. A similar relationship between cost and area of infestation has been described for the eradication of two invasive plants (Rejmanek, 2000). Sharov and Liebhold (1998) developed a bioeconomic model that simulated the growth rate of an invader population, assuming the cost of eradication to be proportional to the colony area. Their analysis revealed two "optimal" management strategies: (i) eradication; and (ii) the slowing of spread. Relative size of the affected area indicated which alternative is preferable. Practical difficulties also increase when the area to be treated is large. In general terms, the likelihood of success decreases as the size of the infested area increases (Figure 2).

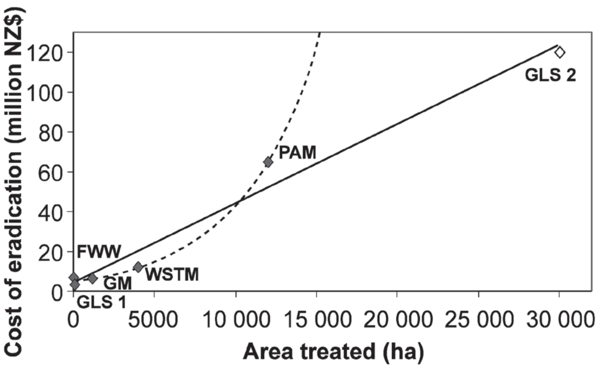

FIGURE 1: Relationships between the area affected by incursions (treated area or known affected area) and cost of recent eradication campaigns against defoliating Lepidoptera in New Zealand (NZ$ value current at end of campaign). Filled diamonds represent successful eradication campaigns; the single open diamond (GLS 2) represents an incursion for which eradication was not attempted. The linear relationship includes all points; the exponential relationship excludes the incursion GLS2 where eradication was not attempted. GLS 1, gum leaf skeletoniser (*Uraba lugens* Walker), Mt. Maunganui eradication 1997–1998; GLS 2, gum leaf skeletoniser, Auckland 2003, eradication not attempted; FWW, fall webworm (*Hyphantria cunea* Drury) eradication 2003-2006; GM, Hokkaido gypsy moth (*Lymantria umbrosa* (Butler)) eradication 2003-2005; WSTM, white-spotted tussock moth (*Orgyia thyellina* Butler) eradication 1996-1998; PAM, painted apple moth (*Teia anartoides* Walker) eradication 1999-2006.[1] For more information see text and Table 1.

Characteristics of suitable and unsuitable target species

An eradication campaign is most likely to be successful if the target species has all or most of the following characteristics:

- low rate of reproduction;
- ease of detection (e.g. via visual identification or the use of attractants in traps) at low population density. This is essential for detection, delimitation of the population and for confirmation of eradication;
- limited host range; and
- availability of suitable treatments with a minimum effect on non-target species.

---

[1] *Compiled from Myers and Hosking (2002); Harris Consulting (2003); Hosking et al. (2003); Journeaux (2003); Ross (2003b); Sutton (2005); Anderton (2006); Suckling et al. (2007a); MAF (2008); and John Bain (Scion, Rotorua, New Zealand, pers. comm.).*

ISSN 0048 - 0134 (print)
ISSN 1179-5395 (on-line)

TABLE 1: Costs and averted economic impacts associated with actual and planned eradication of forest insect pests in New Zealand. Costs are derived from unpublished New Zealand Ministry of Agriculture and Forestry reports and are shown in New Zealand dollar value current at the end of each campaign.

Organism	**Eradication Period**	**Eradication cost (NZ$ million)**	**Estimated economic impact over 20 years (NZ$ million)**	**Approximate averted cost (economic impact less cost of eradication, NZ$ million)**	**Reference(s)**
White-spotted tussock moth, (*Orgyia thyellina*)	1996 – 1998	12	25 – 177	13 – 165	MoF (1997); Horgan (1997); Myers and Hosking (2002).
Gum leaf skeletoniser (1), (*Uraba lugens)*	1997 – 1998	4	101 – 142	97 – 138	Journeaux (2003); J. Bain, Scion, pers. comm.
Painted apple moth, (*Teia anartoides*)	1999 – 2006	65^	58 – 356	-7 – 291	MAF (2002); Anderton (2006); Suckling et al. (2007a).
Fall webworm, (*Hyphantria cunea*)	2003 – 2006	7	19 – 83	12 – 76	Anderton (2006).
Gum leaf skeletoniser (2)*	2003	120†	101 – 142	-19 – 22†	Journeaux (2003); Ross (2003a, 2003b).
Hokkaido gypsy moth, (*Lymantria umbrosa*)	2003 – 2005	6	3 – 291#	-3 – 285	Sutton (2005); Harris Consulting (2003).

* Eradication was not attempted due to an unfavourable cost–benefit analysis.

^ Budgeted figure was >$90M, but eradication was achieved for less.

† Eradication cost estimate based on Ross (2003b) (mean value of the estimated range of $90–$150 million).

Value calculated according to Harris Consulting (2003).

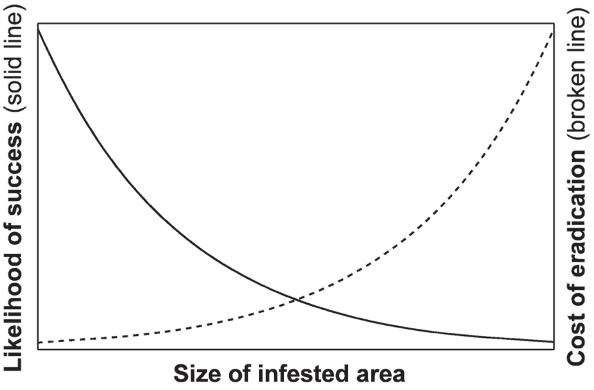

FIGURE 2: Generalised relationships between the size of the area infested by an invader and the cost and likelihood of success of eradication campaigns. Note, these relationships are likely to be non-linear, probably exponential.

Species lacking several of these characteristics are likely to be difficult to eradicate, especially if the affected area is extensive. Insects with limited dispersal potential (e.g. flightless species) may or may not be responsive to treatment. Allee effects (reduction in fitness at low population density (Liebhold & Tobin, 2008; Liebhold, 2010)) are likely to be more common among flight-capable species. Flying insects may therefore be easier to eradicate than flightless species, which tend to aggregate (Robinet & Liebhold, 2009). Parthenogenetic insects, being free from Allee effects associated with mate-location failure, would be more difficult to eradicate (Liebhold & Tobin, 2008). A large number of insects exhibit co-operative behaviour (e.g. some tree-killing bark beetles can only overcome host defences if they aggregate in large numbers) which is likely to cause Allee effects and may facilitate eradication (Liebhold & Tobin, 2008).

Examples of taxa that are likely to be good targets for eradication, according to these criteria, include many Lepidoptera and Coleoptera, as outlined in the case studies below. Conversely, many species of Hemiptera (e.g. aphids) and Thysanoptera (thrips) are poor targets for eradication because they are difficult to detect, have a high reproduction rate, and/or are parthenogenetic. Although a few are host-specific or respond to known attractants (e.g. Monterey pine aphid (*Essigella californica* (Essig)) (El Sayed, 2008)), they are usually too widespread and well-established when first detected (e.g. Teulon & Stufkens, 2002). New attractants for aphids and thrips may be developed in the future but currently few of the existing surveillance and eradication tools are effective for such Hemiptera and Thysanoptera (Suckling et al., 2009).

Surveillance and early detection

Early detection of a newly established colony is crucial for the success of eradication programmes. For most species it is almost impossible to eradicate a population unless it is detected early enough for spread to be limited. Conversely, the value of early detection diminishes if neither eradication nor containment is contemplated.

Continuous surveillance programmes designed for early detection of any new insect pest are likely to increase the success rate of eradication programmes and reduce their cost, but intensive surveillance programmes are expensive. An alternative strategy relying on minimal surveillance or notification by interested individuals will involve acceptance of the fact that populations are likely to have become more extensive. In this case, eradication procedures will probably be more costly and their success less likely. Therefore, there is an inherent trade-off between detection and eradication effort. Bogich et al. (2008) used mathematical models to show that in the case of a gypsy moth (*Lymantria dispar* (L.)) incursion, moderate investment in both detection and eradication provided the best outcome.

Early detection can be accomplished using either of two types of surveillance, passive and active surveillance. Many incursions have been detected through passive surveillance, i.e. chance encounters. Examples of this are the detection of the white-spotted tussock moth (*Orgyia thyellina* Butler) and of the painted apple moth (*Teia anartoides* Walker) in New Zealand by members of the public. However, passive surveillance may be inefficient and inadequate to support eradication. For example, at the time of the detection of Asian longhorn beetle (*Anoplophora glabripennis* (Motschulsky)) in and around New York City (Haack et al., 2010) and of emerald ash borer in Michigan (Poland & McCullough, 2006), populations had spread so far that their eradication was expensive or impossible, respectively.

Active surveillance involves regular surveys in urban, rural and natural areas, and this is more likely to lead to early detection. An example of this type of programme is the annual general survey carried out in forest plantations in New Zealand (Carter, 1989; Bulman et al., 1999), involving searches for visual indicators of damage caused by insects and pathogens. Although detection of newly arrived insects is limited in such general surveys, a review of 10 recently established forest pests and diseases in New Zealand has shown that six (mostly fungal pathogens) were first detected by this method (Myers & Hosking, 2002). Surveillance at high-risk sites such as ports, airports and other cargo unloading areas, is more likely to result in early detection.

Availability of detection tools

The sensitivity of surveillance programmes can be increased by use of traps baited with attractants. Synthetic host attractants are available for certain wood- and bark-boring insects, and trapping programmes have been implemented for their detection in New Zealand (Brockerhoff et al., 2006), Australia (Wylie et al., 2008) and the USA (Rabaglia et al., 2008). Synthetic sex pheromone attractants are available for many Lepidoptera and other taxa (El-Sayed, 2008) and some are used for pest detection. In the USA, more than 100 000 traps are set annually in order to detect gypsy moth populations in previously uncolonised areas (Sharov et al., 2002a). In Canada, pheromone traps have been used since the 1970s to detect new introductions of gypsy moth (Nealis, 2002; Régnière et al., 2009). In New Zealand, a gypsy moth surveillance programme which started in 1993 led to the discovery of a single moth in 2003 (Ross, 2005), later identified as the closely related Hokkaido gypsy moth (*Lymantria umbrosa* (Butler)), which responds to the same lure. For many insects, attractants are not yet available and consequently their detection is difficult. Surveillance trapping currently relies on frequent checking, often of empty traps. Use of 'smarter' traps, using image recognition and telecommunications technology, may provide a new approach to surveillance and reduce costs in the near future. Human checking would still be required, but sample freshness would be improved and date/time of trapping could be recorded more precisely.

The availability of sensitive tools for detecting and delimiting populations is a critical feature of any eradication programme. Traps located in grid patterns can help to define the spatial limits of a population (Suckling et al., 2005, 2007a). Spatial characterisation is important because it improves the definition of potential treatment locations and may provide information about the feasibility of eradication (e.g. Suckling et al., 2005). Without accurate information on a population's distribution, treatments are likely to be less specific and need to be applied more broadly over a larger area, increasing costs and non-target effects. Recent efforts to eradicate the Asian longhorn beetle from Chicago and New York City without sensitive, efficient detection tools meant that treatments (tree removal and stem injection of systemic insecticides) had to be applied over larger areas than would otherwise have been necessary (Haack et al., 2010).

Case studies of eradication programmes

Gypsy moth in North America

Gypsy moth is a polyphagous defoliator native to most of temperate Europe, Asia and North Africa. During recurrent outbreaks, host trees may be completely defoliated, causing a plethora of ecological and socio-economic impacts. The species has become established in much of eastern North America, originating from a single accidental introduction (from Europe) near Boston around 1870 (Liebhold et al., 1989). Eradication from the Boston area was attempted from ca. 1890–1900, but because tools available for detection and suppression of populations were ineffective, the campaign was unsuccessful (Dunlap, 1980). Gypsy moth currently occupies approximately one third of its potential range in North America (Morin et al., 2005). Between 1965 and 1990, radial spread in the mid-Atlantic states was only ca. 20 km per year (Liebhold et al., 1992; Tobin et al., 2007). This slow rate is partly attributable to the fact that the females in North American populations do not fly. Natural dispersal occurs only via windborne dispersal of first instars. Accidental human relocation of egg masses attached to objects such as vehicles, firewood, and lawn furniture causes most of the population spread by 'hitchhiking'. Liebhold et al. (1992) concluded that were it not for the accidental movement of life stages, gypsy moth spread would only proceed by about 2 km per year. Live material transported beyond the advancing population front produces isolated colonies which grow and then coalesce (Liebhold & Tobin, 2006). This type of stratified dispersal is common and increases the rate of spread (Shigesada et al., 1995).

This knowledge about the population biology of gypsy moth spread has served as the foundation of a national programme to slow the invasion spread of this insect in the USA (Sharov et al., 2002a; Tobin et al., 2004). Pheromone traps are placed in a 2 × 2 km grid pattern over a 100 km wide band ahead of the advancing population front. Once detected, any new colonies are eradicated. In the late 1990s most eradication treatments used aerial applications of *Btk*. More recently, the majority of treatments have used mating disruption (over 80% by area). Between 1996 and 2008 over 1.4 million ha were treated with mating disruption formulations (Figure 3), making it one of the world's largest semiochemical-based pest management programmes. Mating disruption is preferred because its effect is confined to the gypsy moth (Thorpe et al., 2006; Hajek & Tobin, 2009). Mating disruption is more effective in low-density populations than in moderate or high-density populations (Sharov et al., 2002b). The programme has been very successful as it reduced radial spread by over 50% and benefits have been found to greatly exceed the cost (ca. US$10 million annually) (Tobin, 2008).

Unfortunately, gypsy moth life stages are occasionally transported well beyond the front of the infested area and as far as the Pacific coast of North America. More than 100 000 pheromone traps are placed annually in more distant, uninfested locations in order to detect new colonies. When catches occur higher-density grids of traps are deployed to identify population boundaries and to confirm eradication. Between 1980

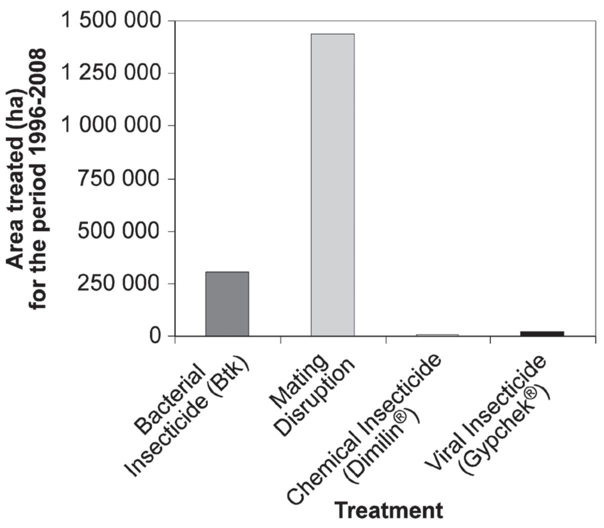

FIGURE 3: Treatments used for eradication and slowing of spread of gypsy moth populations in the US, 1996–2008. Btk (*Bacillus thuringiensis);* Dimilin® (diflubenzuron) and Gypchek® are proprietary insecticides. Source: "The Gypsy Moth Digest" (US FS, 2009).

and 2007, 238 new isolated populations were detected (Hajek & Tobin, 2009). Mating disruption is rarely used for eradication outside the main containment area because it also leads to shut-down of traps used for population monitoring.

Almost all gypsy moth eradication projects were successful, and trapping and treatment programmes have achieved containment of gypsy moth populations. The only failed attempts at eradication were those associated with the initial population near Boston and a problematic case in Midland, Michigan in the 1960s (Dreistadt, 1983). The remarkable overall success has been due to the availability of pheromone traps for detection, delimitation and monitoring, considerable research progress that provided a wealth of knowledge on this insect, and to computer modelling which provided information about the growth of isolated populations (Liebhold & Tobin, 2006). Collectively, this enabled highly effective responses. Finally, gypsy moth colonies are known to exhibit a strong Allee effect at low densities, primarily due to mate-location failure. This creates a population size threshold below which extinction is inevitable, and this can be exploited in eradication programmes (Liebhold & Bascompte, 2003; Tobin et al., 2009).

White-spotted tussock moth in New Zealand

An incursion of the white-spotted tussock moth, *Orgyia thyellina* (Lepidoptera: Lymantriidae) was detected in parts of Auckland, New Zealand, in April 1996 (Myers & Hosking, 2002; Hosking et al., 2003; MAF, 2008). This polyphagous defoliator of broadleaved trees, native to parts of north-east Asia, had not been considered as a potential invader, prior to the incursion in New Zealand. Little was known about the species, but it was thought to have significant pest potential because closely-related Lymantriidae are important pests elsewhere. Absence of Lymantriidae in New Zealand suggested that few natural enemies would be present. A delimitation survey indicated that the infested area included 700 ha of urban residential property, parks and reserves as well as gullies with shrubland (Hosking et al., 2003). A decision was made to eradicate the insect. With addition of a buffer zone to include any areas of undetected fringe spread, the targeted treatment area was 4000 ha. Quarantine regulations restricting the movement of plant material were enforced and inspections of other items were carried out to prevent spread beyond the infested area (Hosking et al., 2003). Aerial and ground-based applications of *Btk* were chosen as the main treatment. The population was monitored initially by using caged females as lures in sticky traps. Once the pheromone had been identified, artificial lures were used.

This programme was successful because the presence of the insect was detected at an early stage; delimitation, monitoring and treatment tools were available; a plan based on advice from a science panel was followed; and funding was adequate (Hosking et al., 2003). Although there was some public opposition to aerial application of *Btk*, a comprehensive communication campaign addressed most of the concern.

Painted apple moth in New Zealand

The painted apple moth, *Teia anartoides* (Lepidoptera: Lymantriidae) was detected in West Auckland, New Zealand, in 1999. In Australia this insect is known as a pest with a wide host range (Elliott et al., 1998). An initial impact assessment (MAF, 2000) predicted that damage to plantation forestry, urban amenity trees, horticulture, natural areas, human health and international trade would be significant if the insect became established. An eradication campaign was planned and ground-based spraying with Lorsban 50 W ® and Decis Forte® was carried out in conjunction with surveys of the location of potential host trees (Alan Flynn, Ministry of Agriculture and Forestry, Auckland, pers. comm.; Suckling et al., 2007a). Areas requiring treatment and host removal were identified. Delimitation and population monitoring was conducted using sticky delta-traps baited with live females from a laboratory colony (Suckling et al, 2007a). The arboreal habits of the insect and the height of many host trees meant that ground-based methods were inadequate (Richardson, 2002), and the infested area increased to ca. 12000 ha. From January 2002, aerial spraying of *Btk* over the entire affected area resulted in decline of the population and in the following year less than 10% of the previous year’s trap catch was recorded (Suckling et al., 2007a). Aerial application of *Btk* continued in 2003 and the sterile insect technique (SIT) was included as soon as the population had declined sufficiently to enable overflooding with sterile males (Suckling et al., 2007a). From 2004, no further captures were recorded, and eradication was declared in 2006 (Anderton, 2006).

The programme was successful, despite initial setbacks, because effective tools for monitoring and control were available and their use was integrated for best effect. Input from a scientific advisory group and from a research programme accompanied the campaign. Detailed investigation of life cycle and host range were carried out in quarantine facilities and in the field, and some endemic New Zealand tree species were found to be suitable hosts (Burnip et al., 2003; Charles et al., 2007; Stephens et al., 2007). The effectiveness of aerially applied *Btk* was assessed (Charles et al., 2005; Richardson et al., 2005), and the radiation dosage for optimisation of SIT was explored (Wee et al., 2005; Suckling et al., 2007a). Community consultation and communication methods were reviewed (van Santen et al., 2004). An effective pheromone was identified (El-Sayed et al., 2005a; Gries et al., 2005) but proved to be unstable in the field, however, the continued use of caged females as lures was effective. Modelling the results of repeated release and recapture of sterile males, relative to catches of wild males, gave managers an estimate of the probability of success as the operation proceeded (Kean & Suckling, 2005). The active research programme alongside the programme clearly contributed to the success of the operation.

Asian longhorn beetle in North America

The Asian longhorn beetle (*Anoplophora glabripennis*; Coleoptera: Cerambycidae) is a wood borer native to northeastern Asia. It was first recorded as an exotic invader in Brooklyn, New York in 1996 (Haack et al., 1997). Further infestations were found in Chicago, Illinois in 1998; in Jersey City, New Jersey in 2002; and in Toronto, Ontario in 2003 (Haack et al., 2010). Wood borers are often intercepted in wooden packaging materials, and this is the assumed pathway for arrivals of this species. ALB caused mortality of broadleaved trees, especially maples and poplars, and authorities decided to aim for eradication. Detection and delimitation surveys relied on visual signs of beetle activity (egg-laying scars on the bark, exit holes, wilting of attacked trees) because effective attractants were not available. Quarantine measures were enforced to prevent unintentional spread in firewood. Initially, treatment consisted of the destruction of affected trees. Asymptomatic host trees located within several hundred metres of infestations were treated with the systemic insecticide imidacloprid (Poland et al., 2006; Haack et al., 2010). As of 2008, more than 40 000 trees have been removed and a further 800 000 treated with insecticide. Total costs have exceeded US$370 million (Haack et al., 2010). Prophylactic treatment with systemic insecticides has been effective.

These programmes were accompanied by research in the invaded countries and in the native range into the biology and ecology of the insect. Social research needs, and the development of tools for detection, delimitation and treatment were also investigated (e.g. Smith, 2000; USDA-FS, 2000; Smith et al., 2001; Poland et al., 2006; Haack et al., 2010). Eradication of ALB has been declared in Illinois and Jersey City, New Jersey (Haack et al., 2010) . Populations in New York appear to be spreading and eradication efforts continue. In 2008, a large infestation in a natural forest was discovered near Worcester, Massachusetts (Haack et al. 2010). This will be more difficult to eradicate because of its larger size, the number of affected trees, and the fact that firewood was taken from the area before the infestation was detected, which may have caused further spread. In spite of experience gained from the Brooklyn incursion and knowledge about the introduction pathway (Haack et al., 1997), further incursions have occurred in North America and also in several European countries (see summary by Haack et al., 2010).

Other eradication programmes

The citrus longhorn beetle (*Anoplophora chinensis* (Forster)) has been intercepted frequently in the USA, sometimes in wooden packaging but mainly in imported bonsai and other trees for planting. This insect has not become established in North America, despite several breaches of the border, but several invasions have been noted in central and southern Europe, where eradication programmes similar to those described for Asian longhorn beetle are in progress (see Haack et al., 2010). An infestation in Lombardy, Italy, may have spread too far for eradication to be practicable. Examples of other invading wood borers are the European brown spruce longhorn beetle (*Tetropium fuscum* (F.)), now resident in Nova Scotia, Canada (CFS, 2009); and the emerald ash borer (*Agrilus planipennis*), which spread from Detroit, Michigan to a large area in the north-eastern USA (Poland & McCullough, 2006). Neither of these populations is amenable to eradication due to their geographic extent, lack of suitable attractants and the inadequacy of available detection and treatment methods. Eradication of Asian longhorn beetle and citrus longhorn beetle will be difficult for the same reasons. An attractant recently developed for the brown spruce longhorn beetle (Sweeney et al., 2004) may assist eradication efforts if new colonies are detected.

Tactics and tools

Host plant destruction

Tree destruction is effective for eradication of insects that are host-specific and have not spread too far. In the late 1800s, infested forests were burned in unsuccessful attempts to eradicate gypsy moth from Massachusetts, USA (Myers et al., 2000). This method can also be successful for the eradication of plant pathogens carried by insect vectors and other pathogens (e.g. Gadgil et al., 2000; Sosnowski et al., 2009), and it is used for wood borers (Poland & McCullough, 2006). Plant parts that may harbour live insect material are destroyed by burning, burying, or chipping. It is essential that these plant parts are not transported out of the infested area to prevent unintended spread. The felling of trees is often unpopular with the public, however, particularly in urban situations.

Quarantine

Quarantine and movement control reduce the risk of spread in plant material and other objects that may harbour the insect. Unfortunately, quarantine measures are often ignored, for example, when firewood is transported beyond the designated control area (e.g. Poland & McCullough, 2006; Haack et al., 2010).

Physical removal

In the late 1800s, egg masses were removed manually from infested forests in unsuccessful attempts to eradicate gypsy moth from Massachusetts, USA (Myers et al., 2000). During eradication of the fall webworm (*Hyphantria cunea* (Drury)) in Auckland, New Zealand in 2003/2004, plastic sheets covering the ground and trees were used to trap emerging insects. This procedure prevented movement of insects from sites treated earlier by other methods.

Aerial spraying with insecticide

Aerial delivery of solid or liquid material is usually more effective than ground-based spraying because large areas can be treated quickly, good coverage of target surfaces is possible, and costs are usually lower. Aerial application has been used in many recent eradication campaigns in both urban and forested areas.

Concerns are often expressed about the use of pervasive and potentially toxic substances, especially in urban or environmentally sensitive areas. These concerns must always be addressed. Application of any material will cause anxiety among residents, leading to suspicion about effects on human health and questions about the need for an eradication programme.

Efficient aerial application will achieve eradication with minimum amounts of the active ingredient, minimum cost, and minimum environmental impact. Although factors influencing spray deposition and drift are generally well-understood (Matthews, 1979; Yates et al., 1967), a large number of interacting factors affect droplet movement and need to be integrated. Several computer models simulating aerial spray application have been developed. The agricultural dispersal (AGDISP) modelling system (Bilanin et al., 1989; Teske et al., 2003) is most commonly used and has been well-validated (Bird et al., 1996, 1999; Richardson et al., 1995). It has been incorporated into a number of geographical information system (GIS)-based decision support tools e.g. “SpraySafe Manager” (Ray et al., 1999; Schou et al., 2001) and “Spray Advisor” (currently under development by the United States Forest Service).These systems have been used extensively to improve the effectiveness of eradication operations (Richardson & Thistle, 2002). Specific improvements include:

- definition of buffer zones required to ensure that an insect-lethal dose of pesticide covers the entire target area (Richardson, 2002);
- evaluation of operational effectiveness (through deposition-monitoring and bioassay) (Richardson et al., 2005; Richardson & Kimberley, 2010);
- definition of operational specifications;
- response to public enquiries; and
- evaluation of unexpected results.

Requirements for further research and development have also been highlighted. In particular, there is a need for the development of models of spray deposition that are sensitive to the complexity of terrain encountered in many large-scale spraying operations. Real-time integration of input variables describing meteorological conditions and operational parameters (e.g. flying height, ground speed) with spray simulation model predictions would allow optimisation of operational performance. Further work is also required on the extent to which spray deposition profiles within plant canopies are affected by spray application characteristics (Richardson & Thistle, 2006). The link between dose distribution and biological efficacy is poorly understood even though it has significant influence on the success of an eradication operation (Richardson et al., 2004). Some of these considerations apply large-scale use of mating-disruption techniques for which ground-based deployment is not feasible or practical.

Sterile insect technique

The sterile insect technique (SIT) is a good example of a tactic with few, if any, non-target effects. This method has been used for eradication of agricultural pests, parasites and disease vectors during the past 50 years (e.g. Hendrichs, 2000). Examples are the eradication of screwworm fly (e.g. Galvin & Wyss, 1996) and medfly (Hendrichs et al., 2002). The technique involves rearing, sterilising (via irradiation) and release of large numbers of sterile insects. When sterilised insects mate with wild insects of the target species, eggs produced by females are not viable or lead to infertile offspring, and populations eventually disappear without any residual effects. This technique cannot be applied to all species, however. It is probably most suitable for use with males that mate only once; have limited dispersal; and are univoltine and oligophagous. Detailed knowledge is required about the biology and response of the target species to radiation (Suckling, 2003). The number of sterile insects must exceed numbers in the wild colony. Millions of insects per week must be reared, treated and released in order to achieve an effective ratio (Kean et al., 2007). Possible new approaches include the use of attractants for female moths, and automated quality assessment using machine vision (Simmons et al., 2010). Mass-rearing capability may provide opportunities for the export of irradiated insects to other countries: consignments of codling moth (*Cydia pomonella* (L.)) raised and sterilised in Canada have been shipped to South Africa.

Use of pheromones and other semiochemicals

“Semiochemicals” are compounds that play an important role in intra-specific and inter-specific communication of insects (Howse et al., 1998). Examples include: sex pheromones, which attract mates; aggregation pheromones which attract conspecifics, for example to co-ordinate bark beetle mass attacks; and plant volatiles which attract (kairomones) or repel (allomones) specific organisms. Thousands of semiochemicals have been identified (El-Sayed, 2008) and many have been synthesised artificially. They are an essential component of surveillance trapping, delimitation, and population monitoring, as well as many insect control techniques, including mass trapping, lure-and-kill, and mating disruption (Howse et al., 1998). Larger numbers of attractants have been identified for male than for female insects. The long-term containment and near eradication of Dutch elm disease in New Zealand was facilitated by pheromone trapping and examination of the beetle vector (*Scolytus multistriatus* (Marsham)). Individuals carrying spores of the fungal pathogen acted as indicators of the proximity of infected trees, which were felled and destroyed (Gadgil et al., 2000). Published identification of an attractant should be verified before use because subtle differences in composition can alter effectiveness (e.g. El-Sayed et al., 2005b).

Mass trapping

The use of traps for surveillance and monitoring is well established but despite this, mass trapping is not widely used in eradication programmes. This is partly due to the fact that mass trapping suffers from some conceptual problems (Howse et al., 1998; Yamanaka, 2007). There are far more effective attractants for male than for female insects, and a higher level of removal of males is needed to achieve the same level of population suppression, particularly in species where males can mate multiple times. The number of traps required may be prohibitive (Roelofs et al., 1970) unless the population to be eradicated is small. Trap saturation may also present problems. However, mass trapping has been successful for eradication when used in conjunction with other techniques (Howse et al., 1998; El-Sayed et al., 2006).

Lure-and-kill

Insect attractants (usually a sex pheromone attracting males) can be combined with a contact insecticide in order to reduce insect populations (Brockerhoff & Suckling, 1999; El-Sayed et al., 2009). The lure-and-kill technique can be regarded as a variant of mass trapping, but because a large number of insect-lethal droplets can be deployed at comparatively low cost, even over a wide area, it can be effective. Adequate control can be achieved even in moderately abundant populations (e.g. Suckling & Brockerhoff, 1999). With a larger number of pheromone-emitting droplets, lure-and-kill may also cause a mating disruption effect (Suckling & Brockerhoff, 1999). Use of the powerful parapheromone methyl eugenol with bait sprays to control tephritid fluit flies is one of the best examples of lure-and-kill eradication strategy (see El-Sayed et al., 2009). A major disadvantage is that the insecticide used may present a real or perceived risk to human health, although the technique is highly species-specific and has low non-target effects.

A variation of the lure-and-kill technique is used against bark beetles and involves the spraying of aggregation pheromones on to trees which are then treated with systemic insecticide (note, this is usually referred to as mass trapping). Successful control and containment have been achieved by this method (Gray & Borden, 1989), but to our knowledge the use for eradication has not been attempted.

Mating disruption

Application of pheromones in order to disrupt mating is a well-known pest management technique but it has also been used for the eradication of some insect species (Cardé & Minks, 1995; Howse et al., 1998). Mating disruption does not cause mortality but prevents males from locating females and therefore prevents reproduction. The technique, used most commonly for

Lepidoptera, involves the release of a synthetic sex pheromone that results in aerial concentration sufficient to prevent males from following the pheromone plume of calling females (Suckling et al., 1999). Many release devices and chemical formulations have been developed. Some of these can be deployed from aircraft for large-scale application and area-wide control. The best known example of use in eradication is the campaign against gypsy moth in North America where more than 1.2 million ha have been treated since 1996 (Sharov et al., 2002a; Hajek & Tobin, 2009). Mating disruption is not used for eradication of isolated populations because it interferes with the use of traps for monitoring purposes. The current programme for containment or eradication of the light brown apple moth (*Epiphyas postvittana* (Walker)) in California initially relied on aerial application of sex pheromones for mating disruption (Suckling & Brockerhoff, 2010). Even though there is no documented evidence of deleterious effects on other organisms, and in spite of positive results obtained from trials conducted in Canterbury, New Zealand (Brockerhoff et al., 2008), protest from members of the public eventually led to replacement of the use of pheromones with sterile insect technique as the main tactic, highlighting the need for communication with the public during programmes.

Future tactics

There is a clear need for new eradication strategies that do not affect non-target organisms and do not arouse public opposition. Attractants, repellents and other classes of semiochemicals are useful against insects that are dependent on volatile substances for mate location, host location and other features of their life cycle. The limitations of suitable deployment and delivery systems for these compounds must be overcome.

A new approach is based on manipulation of one species in order to control another (Suckling et al., 2007b). Known as “mobile mating disruption”, this technique is being tested against light brown apple moth, using sterile male medflies (*Ceratitis capitata*) to distribute a moth female sex pheromone which causes disruption. It is under consideration for use in the current eradication programme in California where the public does not appear to object to release of sterile insects. Surveys in New Zealand suggest there is less opposition to the release of sterile insects than to the deployment of sprayable chemicals (J. Gamble, Plant&Food Research, Auckland, pers. comm.). A second example of this approach is the recent demonstration that an ant-trail pheromone can be used to disrupt foraging by the Argentine ant, *Linepithema humile* (Mayr) (Suckling et al., 2008). Interference with the pheromone trail prevents foragers from returning to the nest. Recent trials indicate that formulations remaining chemically stable for several weeks can be developed for use in areas such as national parks (D. M. Suckling et al., unpublished data).

Integrated pest eradication (IPE)

Based on the concept of integrated pest management (IPM), the term “integrated pest eradication” (IPE) has been coined to describe the systematic use of several eradication tools in combination. The inter-compatibility, cost, effectiveness, and scalability of different methods all vary and need to be taken into account when several are used in conjunction. Some tactics are not applicable to all insect taxa, and the range of treatments likely to assist eradication is greater for Lepidoptera than for Coleoptera, Diptera and Hemiptera. Insecticides used in IPE should be restricted to narrow-spectrum products and so-called “green chemistry” formulations. This is critical for the success of eradication programmes, since it influences public attitudes and can have an effect on the outcomes of other tactics, including biological control.

Costs and benefits of eradication

Much of the following discussion is based on data from programmes carried out in New Zealand between 1996 and 2006. Eradication costs cited in Table 1 are based on actual expenses incurred. Total programme costs are the sums of annual appropriations, less any savings, without any discounting or inflation adjustment (Colin Holden, MAF NZ, pers. comm., June 2009).

Assessments of the benefits of eradication are based on estimates of averted costs associated with the economic impacts of population establishment and spread. Variations of the approach taken by Horgan (1994, 1997) were used for all impact assessments, and numerous pest-specific assumptions and considerations were incorporated. Taking the white-spotted tussock moth campaign as an example, averted costs and losses included impacts on commercial forestry, on residential property owners, and on urban amenity values (Horgan, 1997). Effects on horticulture, international trade and human health were considered but could not be quantified due to lack of data (Horgan, 1997). Each of the impact categories included several components: for example impacts on commercial forestry included tree growth losses, monitoring expenses and control costs, while recognising relationships between these impacts.

Cost estimates for any given invader will vary according to the assumptions made and also because there are numerous sources of uncertainty. Commercial forest growth losses attributable to the white-spotted tussock moth were initially estimated to be ca. NZ$98 million net present value, based on predicted rate of geographic spread, an expected annual loss of 2.6% harvested timber volume in perpetuity, and a 10% discount rate (MoF, 1997; Horgan, 1997). Control measures

ISSN 0048 - 0134 (print)
ISSN 1179-5395 (on-line)

were expected to limit damage, and the sum of expenditure on treatment plus residual harvest losses was expected to be much lower than the “do nothing” impact cost estimate (NZ$26–35 million; Horgan, 1997). In an unpublished report to New Zealand Treasury, the New Zealand Institute of Economic Research (NZIER) reviewed the assumptions in Horgan’s 1997 cost–benefit analysis and concluded that the net benefits of eradication had probably been over-estimated. However, the expectation of lower benefits had been associated with uncertainty about the rate of spread; the timing of the onset of widespread effects; the magnitude of various types of damage; the cost of eradication; and the likelihood that eradication could be achieved. Ultimately, the eradication programme proved to be successful and actual costs were well below the lowest economic impact estimates. The benefit : cost ratio was at least 2 : 1 for the lowest and approximately 8 : 1 for the medium impact estimate (Table 1). Since a number of potentially significant factors could not be assessed, impact estimates were probably more conservative than suggested by NZIER (unpublished data) (for a description of losses that were not assessed and other caveats, see Holmes et al., 2009). In this and most of the other cost-benefit analyses considered here, damage costs were estimated in terms of net present value (NPV) accumulated over a period of 20 years. Unless re-invasion were to occur, these costs would be averted over a longer period, thus increasing the benefits. Similarly, should re-invasion be likely, the analysis would have to take account of the need for repeated eradication treatments.

In all recent eradication programmes involving Lepidoptera in New Zealand, benefits (i.e. averted costs of economic and environmental impacts) far exceeded the approximate mid-range values of eradication costs (Table 1). Eradication costs exceeded the lowest impact estimates in two of the five cases (gypsy moth and painted apple moth). The expected economic impact values appear to be reasonable when compared with costs attributed to these pests in regions where they have become established. For example, the annual cost of controlling gypsy moth in the USA is estimated to be approximately US$11 million excluding tree damage, timber volume losses and non-market losses (Pimentel et al., 2000). In Canada, projected annual losses (hardwood timber sales and domestic exports only) due to gypsy moth were estimated at C$1.9–5.0 million (Colautti et al., 2006). Projected costs for other invaders of Canada’s forests, including balsam woolly adelgid (*Adelges piceae* (Ratzeburg)), brown spruce longhorn beetle and Dutch elm disease were also in this range (Colautti et al., 2006). Pimentel et al. (2000) estimated that losses caused by exotic forest pests collectively total US$ 2.1 billion annually. Pimentel et al. (2000) and Colautti et al. (2006) both stated that their loss estimates were conservative because certain direct costs and non-market economic losses could not be quantified. However, Holmes et al. (2009) drew attention to the fact that accounting values and economic losses were conflated in both studies. The use of financial accounting methods for this type of analysis is potentially misleading because it does not allow for steps that could be taken to reduce these losses. Holmes et al. (2009) argued that the use of accounting methods and final product markets would have led to overestimated losses, and that the impacts could instead have been measured in markets for timber inputs. However, the omission of losses such as reduction of ecosystem services and landscape aesthetics would have led to an opposite bias. In fact, losses in non-market economic values may well have exceeded direct economic losses (Holmes et al., 2009). For example, non-market impacts of the gypsy moth in the USA are considered to exceed the impacts on timber production (Leuschner et al., 1996). Given these large non-market impacts, the cost estimates of Pimentel et al. (2000) and Colautti et al. (2006) are likely to be conservative. Many of these arguments apply to cost-benefit analysis of the eradication of species listed in Table 1, and indicate that overall benefits of eradication were substantial. Investment in eradication of a high-impact invader appears to be well-justified when the outcome is successful.

Conclusion

The eradication of a wide range of invading insects is certainly possible and justifiable, but should not be undertaken unless expected impacts of the invader, feasibility of eradication and cost-benefit analysis have been considered. There is clear evidence that some invaders threaten entire industries, significant amenity values, and the integrity of ecosystems while others have virtually no impact. It is not always possible to predict the impact of an invader, and caution is necessary as invasive species can behave unexpectedly in a novel environment. Advances in terms of tool development, application and integration have increased success rates in recent eradication operations. Early detection through the implementation of effective surveillance programmes is critical to increase the probability of successful eradication. Increased understanding about costs and benefits of eradication has shown that recent programmes have provided financial gains as well as benefits in non-market values. Unsuccessful programmes may be beneficial, even if they are not financially viable, if the outcome is temporary containment or reduced spread of a pest. It is also clear that public attitudes to eradication programmes must be taken into account. However, while eradication treatments may be controversial among parts of the public, these need to be weighed against the long-term impacts of invaders which would also impact the public directly. Apart from economic impacts, invaders may lead to damage to urban trees, increased long-term use of insecticides, and dermatitis caused by urticating hairs of some Lepidoptera.

Lack of suitable tools often limits feasibility, and more research is needed particularly on the development of treatments with minimal non-target impacts. Improved understanding of the ecology and management of the invading species, use of computer modelling and employment of realistic accounting methods will increase the practicability and therefore the benefits of eradication programmes in the future.

Acknowledgements

Thanks are due to the many people in the Ministry of Agriculture and Forestry, Biosecurity New Zealand, and Scion who provided data from recent eradication programmes in New Zealand, and also to Patrick Tobin, US Forest Service, for information about the gypsy moth "Slow the spread" programme. Comments on an earlier version of the manuscript from Melanie Newfield, Ministry of Agriculture and Forestry, and Ian Hood, Ruth Gadgil and Ruth Falshaw, Scion, are much appreciated. This review was funded by the New Zealand Foundation for Research, Science and Technology through Contracts C02X0501 ("Better Border Biosecurity", www.b3nz.org) and C04X0302 ("Forest Biosecurity and Protection"), and the US Forest Service. Support from the Organisation for Economic Co-operation and Development (OECD) for production of this contribution to the IUFRO conference on "Biosecurity in a Global Context" is gratefully acknowledged.

References

Anderton, J. (2006). *Two Auckland pest moth populations declared eradicated. New Zealand Minister of Biosecurity,* [press release]. Retrieved 25 March 2009, from http://www.beehive.govt.nz/node/25234

Bilanin, A. J., Teske, M. E., Barry, J. W., & Ekblad, R. B. (1989). AGDISP: The aircraft dispersion model, code development and experimental validation. *Transactions of the American Society of Agricultural Engineers, 32*(1), 327-334.

Bird, S. L., Esterly, D. M., & Perry, S. G. (1996). Off-target deposition of pesticides from agricultural aerial spray applications. *Journal of Environmental Quality, 25,* 1095-1104.

Bird, S. L., Perry, S. G., Ray, S. L., Teske, M. E., & Scherer, P. (1999). *An evaluation of AgDrift 1.0 for use in aerial applications*. Spray Drift Task Force Study No. M98-003. EPA MRID No. 44908901, Washington DC, USA: United States Environmental Protection Agency.

Bogich, T. L., Liebhold, A. M., & Shea, K. (2008). To sample or eradicate? A cost minimization model for monitoring and managing an invasive species. *Journal of Applied Ecology, 45,* 1134-1142.

Brasier, C. M. (1991). *Ophiostoma novo–ulmi* sp. nov., causative agent of current Dutch elm disease pandemics. *Mycopathologia, 115,* 151-161.

Brockerhoff, E. G., & Suckling, D. M. (1999). Development of an attracticide against lightbrown apple moth (Lepidoptera: Tortricidae). *Journal of Economic Entomology, 92,* 853-859.

Brockerhoff, E. G., Barratt, B. I. P., Beggs, J. R., Fagan, L. L., Kay, N., Phillips, C. B., & Vink, C. J. (2010). Impacts of exotic invertebrates on New Zealand's indigenous species and ecosystems. *New Zealand Journal of Ecology, 34,* 158-174.

Brockerhoff, E. G., Jones, D. C., Kimberley, M. O., Suckling, D. M., & Donaldson, T. (2006). Nationwide survey for invasive wood-boring and bark beetles (Coleoptera) using traps baited with pheromones and kairomones. *Forest Ecology and Management, 228,* 234-240.

Brockerhoff, E. G., Suckling, D. M., Coker, G., Gous, S., Kimberley, M., & Richardson, B. (2008). *Evaluation of pheromone formulations for mating disruption of light brown apple moth (LBAM) in Eyrewell Forest, New Zealand*. Report for USDA-APHIS. Christchurch, New Zealand: Scion.

Bulman, L. S., Kimberley, M. O., & Gadgil, P. D. (1999). Estimation of the efficiency of pest detection surveys. *New Zealand Journal of Forestry Science*, *29,* 102-115.

Burnip, G., Kay, M. K., Charles, J. G., Chhagan, A., Karunaratne, L., van den Broeke, L., Hackett, J., Connolly, P., Barrington, A. M., & Suckling, D. M. (2003). *Painted apple moth host plant testing.* Report for MAF. Lincoln, New Zealand: HortResearch.

Cardé, R. T., & Minks, A. K. (1995). Control of moth pests by mating disruption: successes and constraints. *Annual Review of Entomology, 40,* 559-585.

Carter, P. C. S. (1989). Risk assessment and pest detection surveys for exotic pests and diseases which threaten commercial forestry in New Zealand. *New Zealand Journal of Forestry Science, 19,* 353-374.

Canadian Forest Service (CFS). (2009). *Brown spruce longhorn beetle.* Retrieved 25 June 2009, from ttp://cfs.nrcan.gc.ca/index/brownsprucelonghornbeetle.

Charles, J. G., Allan, D. J., Chhagan, A., & Jamieson, L. E. (2005). Effectiveness of Foray 48B over time after application against the painted apple moth. *New Zealand Plant Protection, 58,* 12-16.

Charles, J. G., Kean, J. M., & Chhagan, A. (2007). Developmental parameters and voltinism of the painted apple moth, *Teia anartoides* Walker (Lepidoptera: Lymantriidae) in New Zealand. *New Zealand Entomologist, 29,* 27-36.

Chornesky, E. A., Bartuska, A. M., Aplet, G. H., Britton, K. O., Cummings-Carlson, J., Davis, F. W., Eskow, J., Gordon, D. R., Gottschalk, K. W., Haack, R. A., Hansen, A. J., Mack, R. N., Rahel, F. J., Shannon, M. A., Wainger, L. A., & Wigley, T. B. (2005). Science priorities for reducing the threat of invasive species to sustainable forestry. *BioScience, 55,* 335-348.

Colautti, R. I., Bailey, S. A., van Overdijk, C. D. A., Amundsen, K., & MacIsaac, H. J. (2006). Characterised and projected costs of nonindigenous species in Canada. *Biological Invasions, 8,* 45-59.

Dahlsten, D. L., Garcia, R., & Lorraine, H. (1989). Eradication as a pest management tool: concepts and contexts. In D. L. Dahlsten, & R. Garcia (Eds.), *Eradication of exotic pests*, (pp. 3-15). New Haven, Connecticut, USA: Yale University Press.

Dreistadt, S. H. (1983). An assessment of gypsy moth eradication attempts in Michigan (Lepidoptera: Lymantriidae). *Great Lakes Entomologist, 16,* 143-148.

Dunlap, T. R. (1980). The gypsy moth: A study in science and public policy. *Journal of Forest History*, *24,* 116-126.

Elliott, H. J., Ohmart, C. P., & Wylie, F. R. (1998). *Insect pests of Australian forests: Ecology and management*. Sydney, Australia: Reed International Books.

El-Sayed, A. M. (2008). The Pherobase: Database of insect pheromones and semiochemicals. Retrieved 10 June 2009, from http://www.pherobase.com.

El-Sayed, A. M., Gibb, A. R., Suckling, D. M., Bunn, B., Fielder, S., Comesky, D., Manning, L. A., Foster, S. P., Morris, B. D., Ando, T., & Mori, K. (2005a). Identification of sex pheromone components of the painted apple moth: A tussock moth with a thermally labile pheromone component. *Journal of Chemical Ecology, 31,* 621-646.

El-Sayed, A. M., Gibb, A. R., & Suckling, D. M. (2005b). Chemistry of the sex pheromone gland of fall webworm, *Hyphantria cunea* discovered in New Zealand. *New Zealand Plant Protection, 58,* 31-36.

El-Sayed, A. M., Suckling, D. M., Wearing, C. H., & Byers, J. A. (2006). Potential of mass trapping for long-term pest management and eradication of invasive species. *Journal of Economic Entomology, 99,* 1550-1564.

El-Sayed, A. M., Sucking, D. M., Byers, J. A., Jang, E. B., & Wearing, C. H. (2009). Potential of 'lure and kill' in long term pest management and eradication of invasive species. *Journal of Economic Entomology, 102,* 815-835.

Gadgil, P. D., Bulman, L. S., Dick, M. A., & Bain, J. (2000). Dutch elm disease in New Zealand. In C. P. Dunn (Ed.), *The elms: breeding, conservation, and disease management* (pp. 189-199). Boston, MA, USA: Kluwer Academic Publishers.

Gadgil, P., Dick, M., Simpson, J., Bejakovich, D., Ross, M., Bain, J., Horgan, G., Wylie, R. (2003). *Management plan response to an incursion of pine pitch canker in Australia or New Zealand*. Canberra, ACT, Australia: Forest Health Committee on behalf of the Forestry and Forest Products Committee.

Galvin, T. J., & Wyss, J. H. (1996). Screwworm eradication program in Central America. *Annals of the New York Academy of Sciences, 791,* 233-240.

Gillman, H. (1992). *The New World screwworm eradication programme. North Africa 1988-1992*. Rome, Italy: Food and Agriculture Organization of the United Nations.

Gray, D. R., & Borden, J. H. (1989). Containment and concentration of mountain pine beetle (Coleoptera: Scolytidae) infestations with semiochemicals: validation by sampling of baited and surrounding zones. *Journal of Economic Entomology, 82,* 1399-1405.

Gries, R., Khaskin, G., Clearwater, J., Hasman, D., Schaefer, P. W., Khaskin, E., Miroshnychenko, O., Hosking, G., & Gries, G. (2005). (*Z*, *Z*)-6,9-Heneicosadien-11-one: Major sex pheromone component of painted apple moth, *Teia anartoides*. *Journal of Chemical Ecology, 31,* 603-620.

Haack, R. A., Law, K. R., Mastro, V. C., Ossenbruggen, H. S., & Raimo, B. J. (1997). New York's battle with the Asian long-horned beetle. *Journal of Forestry, 95*(12), 11-15.

Haack, R. A., Hérard, F., Sun, J., & Turgeon, J. J. (2010). Managing invasive populations of *Anoplophora chinensis* and *A. glabripennis*: a worldwide perspective. *Annual Review of Entomology, 55,* 521-546.

Hajek, A. E., & Tobin, P. C. (2009). North American eradication of Asian and European gypsy moth. In A. E. Hajek, T. R. Glare, & M. O'Callaghan (Eds.), *Use of Microbes for control and eradication of invasive arthropods* (pp. 71-89). Dordrecht, The Netherlands: Springer.

Harris Consulting (2003). *Asian gypsy moth, assessment of potential economic impacts*. Report for MAF Policy, Wellington, New Zealand.

Hendrichs, J. (2000). Use of the sterile insect technique against key insect pests. *Sustainable Development International, 2,* 75-79.

Hendrichs, J., Robinson, A. S., Cayol, J. P., & Enkerlin, W. (2002). Medfly area wide sterile insect technique programmes for prevention, suppression or eradication: The importance of mating behavior studies. *Florida Entomologist, 85,* 1-13.

Holder, P. W., Stephenson, B., Chadfield, K., Frampton, R. (1997). The finding of Mediterranean fruit fly in Auckland, New Zealand and the Ministry of Agriculture's response. *The Weta, 20*(1), 4-6.

Holmes, T. P., Aukema, J. E., VonHolle, B., Liebhold, A., & Sills, E. (2009). Economic impacts of invasive species in forests past, present, and future. *The Year in Ecology and Conservation Biology. Annals of the New York Academy of Sciences, 1162,* 18-38.

Horgan, G. (1994). *Economic impact of Asian gypsy moth*. Report for Ministry of Forestry. Rotorua, New Zealand: Forest Research Institute.

Horgan, G. (1997). *White-spotted tussock moth eradication: cost-benefit analysis revisited*. Rotorua, New Zealand: New Zealand Forest Research Institute.

Hosking, G. (2001). *An emergency response guide for forestry incursions*. Report number 12568. Rotorua, New Zealand: Forest Research Institute.

Hosking, G., Clearwater, J., Handiside, J., Kay, M. K., Ray, J., & Simmons, N. (2003). Tussock moth eradication - a success story from New Zealand. *International Journal of Pest Management, 49,* 17-24.

Howse, P. E., Stevens, I. D. R., & Jones, O. T. (1998). *Insect pheromones and their use in pest management*. London, UK: Chapman & Hall.

Journeaux, P. (2003). Economic assessment on the impact of the gum leaf skeletoniser, *Uraba lugens* in New Zealand. Hamilton, New Zealand: Ministry of Agriculture and Forestry, MAF Policy.

Kean, J. M., & Suckling, D. M. (2005). Estimating the probability of eradication of painted apple moth from Auckland. *New Zealand Plant Protection, 58,* 7-11.

Kean, J. M., Stephens, A. E. A., Wee, S. L., & Suckling, D. M. (2007). Optimizing strategies for eradication of discrete-generation lepidopteran pests using inherited sterility. In M. J. B. Vreysen, A. S. Robinson, & J. Hendrichs (Eds.), *Area-wide control of insect pests from research to field implementation* (pp. 211-220). Dordrecht, The Netherlands: Springer.

Leung, B., Lodge, D. M., Finnoff, D., Shogren, J. F., Lewis, M. A., & Lamberti, G. (2002). An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proceedings of the Royal Society of London Series B-Biological Sciences, 269,* 2407-2413.

Leuschner, W. A., Young, J. A., Walden, S. A., & Ravlin, F. W. (1996). Potential benefits of slowing the gypsy moth's spread. *Southern Journal of Applied Forestry, 20,* 65-73.

Liebhold, A. M., & Bascompte, J. (2003). The Allee effect, stochastic dynamics and the eradication of alien species. *Ecology Letters, 6,* 133-140.

Liebhold, A. M., & Tobin, P. C. (2006). Growth of newly established alien populations: comparison of North American gypsy moth colonies with invasion theory. *Population Ecology,* 48, 253-262

Liebhold, A.M., & Tobin, P.C. (2008). Population ecology of insect invasions and their management. *Annual Review of Entomology,* 53, 387-408.

Liebhold, A. M., & Tobin, P. C. (2010). Exploiting the Achilles Heels of Pest Invasions: Allee Effects, Stratified Dispersal and Management of Forest Insect Establishment and Spread. *New Zealand Journal of Forestry Science, 40 Suppl.,* 25-33.

Liebhold, A., Mastro, V., & Schaefer, P. W. (1989). Learning from the legacy of Leopold Trouvelot. *Bulletin of the Entomological Society of America, 35,* 20-21.

Liebhold, A. M., Halverson, J. A., & Elmes, G. A. (1992) Gypsy moth invasion in North America: a quantitative analysis. *Journal of Biogeography, 19,* 513-520.

Liebhold, A. M., MacDonald, W. L., Bergdahl, D., & Mastro, V. C. (1995). Invasion by exotic forest pests: a threat to forest ecosystems. *Forest Science, 30,* 1-49.

Lockwood, J. L., Hoopes, M. F., & Marchetti, M. P. (2007). *Invasion Ecology*. Malden, MA, USA: Blackwell Publishing.

Lovett, G. M., Canham, C. D., Arthur, M. A., Weathers, K. C., & Fitzhugh, R. D. (2006). Forest ecosystem responses to exotic pests and pathogens in eastern North America. *BioScience, 56,* 395-405.

Mack, R. N., Simberloff, D., Lonsdale, W. M., Evans, H., Clout, M., & Bazzaz, F.A. (2000). Biotic invasions: Causes, epidemiology, global consequences, and control. *Ecological Applications, 10,* 689-710.

Ministry of Agriculture and Forestry (MAF). (2000). *Potential economic impact on New Zealand of the painted apple moth*. Wellington, New Zealand: MAF Policy.

Ministry of Agriculture and Forestry (MAF). (2002). *Painted apple moth: Reassessment of potential economic impacts*. Wellington, New Zealand.

Ministry of Agriculture and Forestry (MAF), Biosecurity New Zealand. (2008). *Pest risk analysis for six moth species: lessons for the biosecurity system on managing hitchhiker organisms*. Wellington, New Zealand: Ministry of Agriculture and Forestry, Biosecurity New Zealand.

Matthews, G. A. (1979). *Pesticide Application Methods*. New York, NY, USA: Longman Group Limited 1979, Longman Inc.

Ministry of Forestry (MoF). (1997). *Tussock moth eradication cost benefit analysis*. Wellington, New Zealand.

Morin, R. S., Liebhold, A. M., Luzader, E. R., Lister, A. J., Gottschalk, K. W., & Twardus, D .B. (2005). *Mapping Host-Species Abundance of Three Major Exotic Forest Pests*. Research Paper NE-726. Newton Square, PA, USA: USDA Forest Service, Northeastern Research Station.

Myers, J. H., & Hosking, G. (2002). Eradication. In G. J. Hallman, & C. P. Schwalbe (Eds.), *Invasive Arthropods in Agriculture – Problems and Solutions* (pp. 293-307). Enfield, NH, USA: Science Publishers.

Myers, J. H., Savoie, A., & van Randen, E. (1998). Eradication and pest management. *Annual Review of Entomology, 43,* 471-491.

Myers, J. H., Simberloff, D., Kuris, A. M., & Carey, J. R. (2000). Eradication revisited: dealing with exotic species. *Trends in Ecology and Evolution, 15,* 316-320.

Nealis, V. G. (2002). Gypsy moth in Canada: case study of an invasive insect. In R. Claudi, P. Nantel, & E. Muckle-Jeffs (Eds.), *Alien invaders in Canada's waters, wetlands, and forests* Fo42-329/2002E, (pp. 151-159). Ottawa, ON, Canada: Natural Resources Canada.

Pimentel, D., Lach, L., Zuniga, R., & Morrison D. (2000). Environmental and economic costs of nonindigenous species in the United States. *BioScience, 50,* 53-65.

Poland, T. M., & McCullough, D. G. (2006). Emerald ash borer: invasion of the urban forest and the threat to North America's ash resource. *Journal of Forestry, 104,* 118-124.

Poland, T. M., Haack, R. A., Petrice, T. R., Miller, D. L., & Bauer, L. S. (2006). Laboratory evaluation of the toxicity of systemic insecticides for control of *Anolophora glabripennis* and *Plectodera scalator* (Coleoptera: Cerambycidae). *Journal of Economic Entomology, 99,* 85-93.

Rabaglia, R., Duerr, D., Acciavatti, R., & Ragenovich, I. (2008). *Early detection and rapid response for non-native bark and ambrosia beetles*. Washington DC, USA: USDA Forest Service, Forest Health Protection (www.fs.fed.us/foresthealth/publications/EDRRProjectReport.pdf).

Ray, J. W., Richardson, B., Schou, W. C, Teske, M. E., Vanner, A. L., & Coker, G. C. (1999). Validation of SpraySafe Manager, an aerial herbicide application decision support system. *Canadian Journal of Forest Research, 29,* 875-882.

Régnière, J., Nealis, V., & Porter, K. (2009). Climate suitability and management of the gypsy moth invasion into Canada. *Biological Invasions, 11,* 135-148.

Rejmanek, M. (2000). Invasive plants: approaches and predictions. *Austral Ecology, 25,* 497-506.

Richardson, B. (2002). Evaluating the concept of targeted aerial spraying for insect control using Btk. *New Zealand Plant Protection,* 55, 168-171.

ISSN 0048 - 0134 (print)
ISSN 1179-5395 (on-line)

Richardson, B., & Thistle, H. (2002). The role of aerial application simulation models for pest eradication operations in urban environments. In S. L. Goldson, & D. M. Suckling (Eds.), *Defending the Green Oasis: New Zealand Biosecurity and Science* (pp. 125-135). Christchurch, New Zealand: New Zealand Plant Protection Society.

Richardson, B., & Thistle, H. W. (2006). Measured and predicted aerial spray interception by a young *Pinus radiata* canopy. *Transactions of the American Society of Agricultural and Biological Engineers, 49*(1), 15-23.

Richardson, B., & Kimberley, M. O. (2010). Lessons learned from monitoring the effectiveness of the Asian gypsy moth aerial spraying eradication programme. *Applied Engineering in Agriculture* (in press).

Richardson, B., Ray, J., Miller, K., Vanner, A., & Davenhill, N. (1995). Evaluation of FSCBG, an aerial application simulation model. *Applied Engineering in Agriculture, 11,* 485-494.

Richardson, B., Kimberley, M. O., & Schou, W. C. (2004). Defining acceptable levels of herbicide deposit variation from aerial spraying. *Applied Engineering in Agriculture, 20,* 259-267.

Richardson, B., Kay, M. K., Kimberley, M. O., Charles, J. G., & Gresham, B. A. (2005). Evaluating the benefits of dose-response bioassays during aerial pest eradication operations. *New Zealand Plant Protection, 58,* 17-23.

Robinet, C., & Liebhold, A. M. (2009). Dispersal polymorphism in an invasive forest pest affects its ability to establish. *Ecological Applications, 19,* 1935-1943.

Roelofs, W. L., Glass, E. H., Tette, J., & Comeau, A. (1970). Sex pheromone trapping for red-banded leaf roller control: theoretical and actual. *Journal of Economic Entomology, 63,* 1162-1167.

Ross, M. (2003a). Gum leaf skeletoniser long term management approved. *Biosecurity, 47,* 8.

Ross, M. (2003b). *Gum leaf skeletoniser response, Auckland – Feasibility of eradication*. Wellington, New Zealand: Ministry of Agriculture and Forestry.

Ross, M. G. (2005). *Response to a gypsy moth incursion within New Zealand*. Wellington, New Zealand: Ministry of Agriculture and Forestry.

Sarty, M. (2007). Fire ant eradicated at Port of Napier. *Biosecurity, 73,* 11.

Schou, W. C., Richardson, B., Teske, M. E., & Thistle, H. W. (2001). SpraySafe Manager 2 – Integration of GIS with an aerial herbicide application decision support system. Paper No. 011050. St Joseph, MI, USA: American Society of Agricultural Engineers.

Sharov, A. A., & Liebhold, A. M. (1998). Bioeconomics of managing the spread of exotic pest species with barrier zones. *Ecological Applications, 8,* 833-845.

Sharov, A. A., Leonard, D., Liebhold, A. M., Roberts, E. A., & Dickerson, W. (2002a). “Slow the Spread” A national program to contain the gypsy moth. *Journal of Forestry, 100,* 30-36.

Sharov, A. A., Leonard, D., Liebhold, A. M., & Clemens, N. S. (2002b). Evaluation of preventive treatments in low-density gypsy moth populations. *Journal of Economic Entomology, 95,* 1205-1215.

Shigesada, N., Kawasaki, K., Takeda, Y. (1995). Modeling stratified diffusion in biological invasions. *American Naturalist, 146,* 229-251.

Simberloff, D. (2002). Today Tiritiri Matangi, tomorrow the world! Are we aiming too low in invasives control? In C. R. Veitch, & M. N. Clout (Eds.), *Turning the tide: the eradication of invasive species* (pp. 4-12). Occasional Paper of the IUCN Species Survival Commission No. 27, IUCN SSC Invasive Species Specialist Group. Gland, Switzerland, and Cambridge, U.K: International Union for Conservation of Nature.

Simberloff, D. (2003). Eradication: preventing invasions at the outset. *Weed Science, 51,* 247-53.

Simmons G. S., Suckling, D. M., Carpenter, J. E., Addison, M. F., Dyck, V. A., & Vreysen, M. J. B. (2010). Improved quality management to enhance the efficacy of the sterile insect technique for lepidopteran pests. *Journal of Applied Entomology,* (in press).

Smith, M. T. (2000). Biocontrol and IPM for the Asian longhorned beetle [*Anoplophora glabripennis*]. *IPM Practitioner, 22*(7), 1-5.

Smith, M. T., Bancroft, J., Li, G., Gao, R., & Teale, S. (2001). Dispersal of *Anoplophora glabripennis* (Cerambycidae). *Environmental Entomology, 30,* 1036-1040.

Sosnowski, M. R., Fletcher, J. D., Daly, A. M., Rodoni, B. C., & Viljanen-Rollinson, S. L. H. (2009). Techniques for the treatment, removal and disposal of host material during programmes for plant pathogen eradication. *Plant Pathology, 58,* 621-635.

Stephens, A. E. A., Suckling, D. M., Burnip, G. M., Flynn, A., & Richmond, J. (2007). Field records of painted apple moth (*Teia anartoides*: Lep.: Lymantriidae) on plants and inanimate objects in Auckland, New Zealand. *Australian Journal of Entomology, 46,* 152-159.

Suckling, D. M. (2003). Applying the sterile insect technique for biosecurity: Benefits and constraints. *New Zealand Plant Protection, 56,* 21-26.

Suckling, D. M., & Brockerhoff, E. G. (1999). Control of lightbrown apple moth (Lepidoptera: Tortricidae) using an attracticide. *Journal of Economic Entomology, 92,* 367-372.

Suckling, D. M., & Brockerhoff, E. G. (2010). Invasion biology, ecology, and management of the light brown apple moth (Tortricidae). *Annual Review of Entomology, 55,* 285-306.

Suckling, D. M, Green, S. R., Gibb, A. R., & Karg, G. (1999). Atmospheric pheromone concentrations affect the behaviour of lightbrown apple moth (Lepidoptera: Tortricidae) in the orchard *Journal of Chemical Ecology, 25,* 2011-2025.

Suckling, D. M., Gibb, A. R., Dentener, P. R., Seldon, D. S., Clare, G. K., Jamieson, L., El-Sayed, A. M., Baird, D., & Kriticos, D. (2005). Gum leaf skeletoniser *Uraba lugens* in New Zealand: pheromone trapping for delimitation and phenology. *Journal of Economic Entomology, 98,* 1187-1192.

Suckling, D. M, Barrington, A. M., Chhagan, A., Stephens, A. E. A., Burnip, G. M., Charles, J. G., & Wee, S. L. (2007a). Eradication of the Australian Painted Apple Moth *Teia anartoides* in New Zealand: Trapping, inherited sterility, and male competitiveness. In M. J. B. Vreysen, A. S. Robinson, & J. Hendricks (Eds.), *Area-wide Control of Insect Pests* (pp. 603–615). Vienna, Austria: International Atomic Energy Agency.

Suckling, D. M., Jang, E. B., Carvalho, L. A., Nagata, J. T., Schneider, E. L., & El-Sayed, A. M. (2007b). Can ménage-à-trois be used for controlling insects? *Journal of Chemical Ecology, 33,* 1494-1504.

Suckling, D. M., Peck, R. W., Manning, L. A., Stringer, L., Cappadonna, J., & El-Sayed, A. M. (2008). Pheromone disruption of Argentine ant trail integrity. *Journal of Chemical Ecology, 34,* 1602-1609.

Suckling, D. M., Williams, D. G., Woods, B., Baker, G., Crisp, P., Stephens, A. E. A., El-Sayed, A. M., & Stringer, L. D. (2009). *Integrated Pest Eradication for Perennial Horticulture: A Review of Current Technologies*. Canberra, Australia: Cooperative Research Centre for Plant Biosecurity.

Sutton J. (2005). Asian gypsy moth eradicated. New Zealand Minister of Biosecurity, press release. Retrieved 26 March 2009, from http://beehive.govt.nz/release/asian+gypsy+moth+eradicated.

Sweeney, J., De Groot, P., MacDonald, L., Smith, S., Cocquempot, C., Kenis, M., & Gutowski, J. M. (2004). Host volatile attractants and traps for detection of *Tetropium fuscum* (F.), *Tetropium castaneum* L., and other longhorned beetles (Coleoptera: Cerambycidae). *Environmental Entomology, 33,* 844-854.

Teske, M. E., Thistle, H. W., & Ice, G. G. (2003). Technical advances in modeling aerially applied sprays. *Transactions of the American Society of Agricultural Engineers, 46*(4), 985-996.

Teulon, D. A. J., & Stufkens, M. A. W. (2002). Biosecurity and aphids in New Zealand. *New Zealand Plant Protection, 55,* 12-17.

Thorpe, K., Reardon, R., Tcheslavskaia, K., Leonard, D., & Mastro, V. (2006). *A review of the use of mating disruption to manage gypsy moth, Lymantria dispar (L.)* Report 2006–13, Morgantown, WV, USA: United States Department of Agriculture, Forest Health Technology Enterprise Team.

Tobin, P. C. (2008). *Cost analysis and biological ramifications for implementing the gypsy moth Slow the Spread Program*. General Technical Report NRS-37. United States Department of Agriculture, Forest Service.

Tobin, P. C., Sharov, A. A., Liebhold, A. M., Leonard, D. S., Roberts, E. A., & Learn, M. R. (2004). Management of the gypsy moth through a decision algorithm under the Slow-the-Spread Project. *The American Entomologist, 50,* 200-209.

Tobin, P. C., Liebhold, A. M., & Roberts, E. A. (2007). Comparison of methods for estimating the spread of a non-indigenous species. *Journal of Biogeography, 34,* 305-312.

Tobin, P. C., Robinet, C., Johnson, D. M., Whitmire, S. L., Bjørnstad, O. N., & Liebhold, A. M. (2009). The role of Allee effects in gypsy moth (*Lymantria dispar* (L.)) invasions. *Population Ecology, 51,* 373-384.

United States Department of Agriculture-Forest Service (USDA-FS). (2000). *Asian longhorned beetle research roundup*. North Central Research Station News. Saint Paul, Minnesota: USDA-Forest Service.

United States Forest Service (US FS). (2009). *The gypsy moth digest.,*Retrieved 24 June 2009, http://www.na.fs.fed.us/fhp/gm.

van Santen, L., Goven, J., & Langer, L. (2004). The role of community involvement in future incursion responses. *New Zealand Journal of Forestry, 49*(3), 38.

Veitch, C. R., & Clout, M. N. (Eds.). (2002). *Turning the tide: the eradication of invasive species*. Occasional Paper of the IUCN Species Survival Commission No. 27, IUCN SSC Invasive Species Specialist Group. Gland, Switzerland, and Cambridge, UK: *I*nternational Union for Conservation of Nature.

Wee, S. L., Suckling, D. M., Burnip, G. M., Hackett, J., Barrington, A., & Pedley, R. (2005). Effects of substerilizing doses of gamma radiation on adult longevity and level of inherited sterility in *Teia anartoides* (Lepidoptera: Lymantriidae). *Journal of Economic Entomology, 98,* 732-738.

Wylie, F. R., Griffiths, M., & King, J. (2008). Development of hazard site surveillance programs for forest invasive species: a case study from Brisbane, Australia. *Australian Forestry, 71*(3), 229-235.

Yamanaka, T. (2007). Mating disruption or mass trapping? Numerical simulation analysis of a control strategy for lepidopteran pests. *Population Ecology, 49,* 75-86.

Yates, W. E., Akesson, N. B., & Coutts, H. H. (1967). Drift hazards related to ultra-low volume and dilute sprays by agricultural aircraft. *Transactions of the American Society of Agricultural Engineers, 9*(3), 628.

ISSN 0048 - 0134 (print)
ISSN 1179-5395 (on-line)