Chapter 19
Monitoring and Surveillance of Forest Insects

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19.1 Introduction and Overview

Monitoring of insect populations is widely used in entomology in the context of biodiversity studies, as an aspect of pest management, and for the detection of non-native invasive species (e.g. Prasad and Prabhakar 2012; Rabaglia et al. 2019; Seibold et al. 2019). Here we focus on monitoring and surveillance of forest insect 'pests' as well as the detection of non-native invasive species. In general, monitoring is undertaken to (i) obtain information on the presence or abundance of particular species; (ii) study their phenology (e.g. oviposition or flight periods); (iii) predict pest population size, spread and damage; or (iv) to determine if pest management activities such as insecticide treatments or mating disruption are required. These activities are critical aspects of integrated pest management (IPM) programs (Ravlin 1991; Ehler 2006; Chapter 17, this volume).

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Insect monitoring and surveillance can be done with a variety of methods including physical surveys, the use of insect traps, molecular methods, as well as aerial surveys and remote sensing (Prasad and Prabhakar 2012; Poland and Rassati 2019). Physical field surveys (i.e. by direct observation) focus on insect life stages, characteristic damage symptoms on host plants (e.g. defoliation) or other noticeable signs. Such surveys usually involve a combination of observations in the field, collecting and counting specimens, and recording and analyzing these data. Tools that have long been used to facilitate and standardize insect 'sampling' include sweep-nets and tree-beating sheets (e.g. Morris 1960; Harris et al. 1972). However, these methods are labor-intensive, time-consuming, and can only sample species and life stages that are present at the time when the activity is undertaken by a person in the forest.

An alternative method that is widely used and often more efficient involves the use of insect traps that are based on a variety of mechanisms that draw insects to traps and/or intercept their flights. There is a wide range of trap types such as passive interception traps, light traps, colored sticky traps, and traps baited with certain chemical attractants (e.g. Muirhead-Thompson 1991). In recent years, molecular methods have become increasingly important not only for diagnostic purposes (i.e. species identification) but also for insect monitoring. For example, analyzing eDNA collected from plant surfaces can be a very effective method to detect the presence of target species in an area (Valentin et al. 2018). Remote sensing and aerial surveys are useful for monitoring insect damage across larger geographic areas and where forest access on the ground is limited (Hall et al. 2016; Stone and Mohammed 2017).

Monitoring insects is a very broad and complex subject. This chapter focusses on some of the more important methods to provide an overview of the objectives and applications of monitoring and surveillance of forest insects. These are illustrated with several case studies on monitoring and surveillance of prominent forest insects.

19.2 Monitoring Insect Populations and Damage

There is no single monitoring method that is suitable for all species and purposes. If and how monitoring is done ultimately depends on one's objectives and the availability and suitability of monitoring tools for the target species. Some species can be easily observed because their damage or other signs are highly visible by a trained observer and sufficiently specific. Other insects are rather cryptic and difficult to observe, for example because they are feeding under the bark or in the wood of trees. In such cases, alternative methods such as attractant-baited traps can be very helpful if effective attractants and traps for the target species are available. In this section we introduce the most common conventional monitoring methods.

19.2.1 Ground-Based Monitoring Methods for Insect Life Stages, Damage Symptoms and Other Signs

19.2.1.1 Visual Surveys for Insect Life Stages

Field surveys for eggs, larvae, pupae or adults of target species are a common practice for many species. For example, in the United States, egg masses of spongy moth (*Lymantria dispar*, Erebidae) are counted to determine whether infestation levels are so high that treatments may be necessary to prevent defoliation (Liebhold et al. 1994) (Fig. 19.1). Counting egg masses on tree trunks and branches can be done from the ground, ideally during winter when there is no foliage to obscure egg masses and to provide sufficient lead time for planning management actions. Several procedures have been developed to obtain reliable estimates of spongy moth population density, such as the "fixed-radius" plot method where all trees within several 100 m^2 plots are counted and the average density of egg masses is calculated (Liebhold et al. 1994). Leaf miners and gall makers are also easily identified based on their characteristic symptoms and surveys looking for these symptoms are feasible. Other insects and life stages are commonly sampled with specific tools developed for this purpose.

Fig. 19.1 Egg masses of spongy moth on an oak tree trunk. Credit: Milan Zubrik, Forest Research Institute—Slovakia, Bugwood.org

19.2.1.2 Tools for Sampling Insects

Surveys for foliage-feeding insects are often done using ‘beat sheets’ in which a pole is used to beat branches and dislodge specimens onto a drop sheet where they can be collected and counted. The number of replicates depends on the size of the area of interest and the sampling accuracy required, but at least three trees should be sampled (Harris et al. 1972). This method has been used, for example, to sample and study the host range of conifer aphids in New Zealand (Redlich et al. 2019) and to sample predators of hemlock woolly adelgid (*Adelges tsugae*, Adelgidae), a severe pest of Eastern hemlock (*Tsuga canadensis*) in eastern North America (Mayfield et al. 2020) (Fig. 19.2). Suction traps using air suction are often used for sampling insects dispersing in large numbers such as aphids and thrips (e.g. Allison and Pike 1988) but they are used less with forest insects. Insects that are concealed inside wood or other plant tissues (e.g. bark beetles, wood borers) may be sampled by enclosing sections of tree stems, branches and twigs in emergence cages or by collecting tree parts and incubating them in chambers to collect the emerging adults (Ferro and Carlton 2011; Chapter 3, this volume).

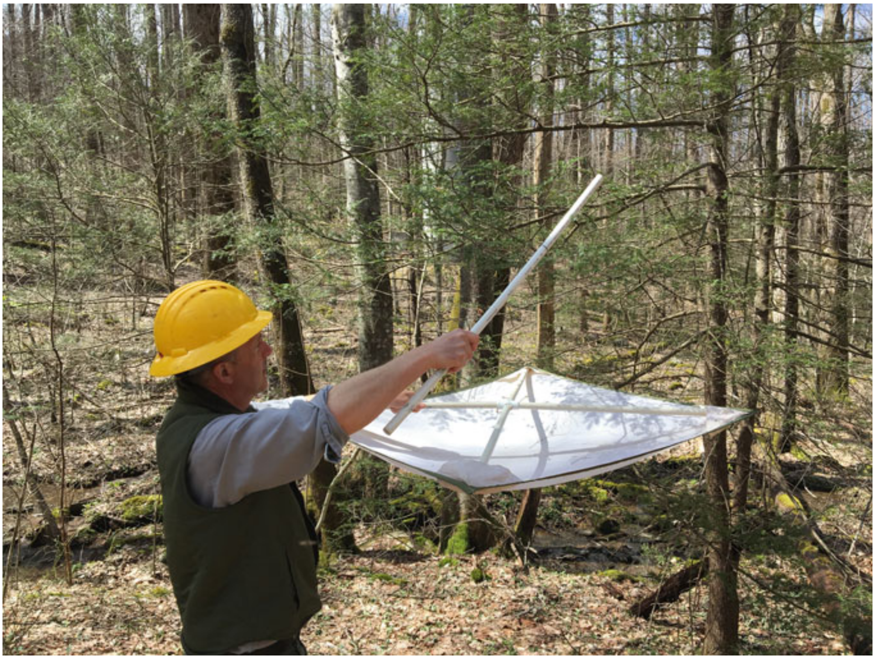


Fig. 19.2 Using a beat sheet to sample *Laricobius* beetles, predators of the hemlock woolly adelgid. Credit: A. Mayfield, USDA Forest Service

19.2.1.3 Surveys for Symptoms and Signs

The extensive mortality of pines caused by the southern pine beetle (*Dendroctonus frontalis*, Scolytinae) in the southern United States is highly visible. To monitor earlier signs of attack, before trees have succumbed to the beetles and when management interventions are still feasible to avert damage, surveys of boring dust and 'pitch tubes' created by the resin response of attacked trees are an effective method (Billings 2011) (Fig. 19.3).

Monitoring for the presence and relative abundance of the pine processionary moth (*Thaumetopoea pityocampa*, Thaumetopoeidae), a serious defoliator of pines and a public health risk in southern Europe, is done by counting the easily visible silken winter nests made by larvae in the crowns of pine trees (Gery and Miller 1985) (Fig. 19.4) (see also the case study on the pine processionary moth below).

19.2.2 Insect Monitoring Using Traps

Ground-based visual surveys for insect life stages or symptoms of attack may be labour-intensive and time-consuming. Trapping can be more effective, especially if an effective attractant is available that increases the catch rate and specificity of traps. Trapping is widely used for insect monitoring and there is a variety of trap types and mechanisms that may be generic or optimised for particular target species (e.g. Muirhead-Thompson 1991; Häuser and Riede 2015).

Fig. 19.3 'Pitch tubes' on a loblolly pine trunk caused by southern pine beetle attack. Credit: James R. Meeker, USDA Forest Service, Bugwood.org

Fig. 19.4 Nests of the pine processionary moth on Scots pine in Switzerland. Credit: Beat Forster, Swiss Federal Institute for Forest, Snow and Landscape Research, Bugwood.org

19.2.2.1 Passive Traps

Passive traps do not use any particular mode of attraction but simply intercept and trap insects as they are moving about. Examples include pitfall traps (cups buried at ground level that are filled with a liquid preservative that trap walking insects), Malaise traps (tent-like structures that intercept flying insects and trap them in a jar filled with a liquid preservative), window traps and other types of flight intercept traps (see Häuser and Riede (2015) and Knuff et al. (2019) for further references and Fig. 19.5). These trap types are commonly used for biodiversity studies but less so to sample forest pests, partly because they are non-specific and collect large numbers of insects from many species, which results in considerable sorting effort. Such passive traps are typically less sensitive than traps that involve some means of attraction.

19.2.2.2 Traps Involving Attraction of Insects by Light or Color

There are many trap types that attract insects with light, specific colors or silhouettes, chemical attractants (odorants such as insect pheromones and host plant volatiles), or a combination of two or more of these (Muirhead-Thompson 1991). Historically, light trapping was used for monitoring populations of insect pests that fly at night (such as moths and certain beetles). An advantage of light traps is that they capture both males and females (whereas traps baited with sex pheromones typically capture only males). Light traps used to require access to the electricity grid (i.e. mains power) which prohibited their use at most field sites but this is less of a problem now

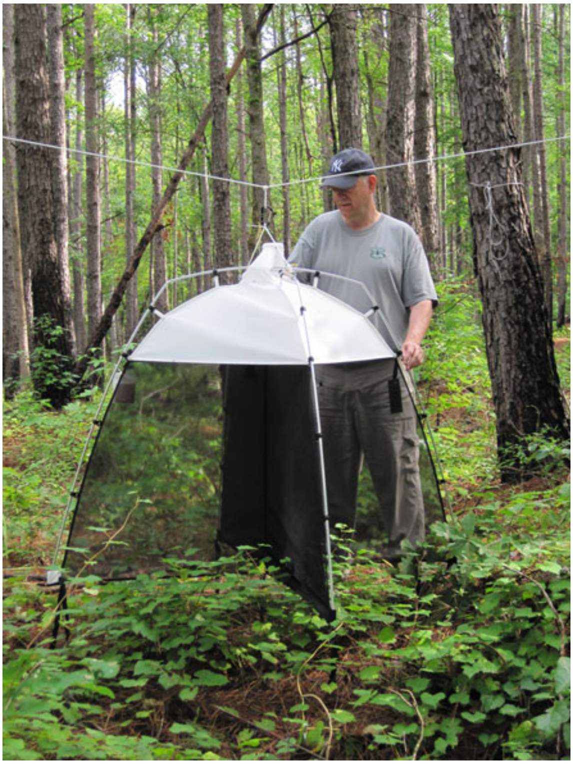


Fig. 19.5 A malaise trap for capturing flying insects. Credit: D. Miller, USDA Forest Service

with the wide availability of portable power sources. Still, today light trapping is used mainly in biodiversity studies because other methods are more species-specific and more effective.

Trap color on its own is exploited, for example, in yellow traps which are used mainly for monitoring agricultural and greenhouse pests. However, trap color can also affect captures of certain forest insects by synergizing attraction of bark beetles to chemical attractants (e.g. Kerr et al. 2017). Several species of longhorned wood boring beetles (Cerambycidae) respond more to black traps than clear or white traps (Campbell and Borden 2009; Allison and Redak 2017) while other cerambycids and jewel beetles (Buprestidae) are attracted to bright green traps or purple traps (Rassati et al. 2019). Bright green or yellow sticky traps mimic the color of foliage and can be used to monitor defoliators such as the beech leaf-mining weevil (Goodwin et al. 2020). Certain trap colors may also reduce catches of non-target species (e.g. Sukovata et al. 2020).

19.2.2.3 Traps Baited with Pheromones and Host Plant Volatiles

The most widely used traps for forest insects are those baited with odorant lures such as pheromones and host plant volatiles. Pheromones are chemicals that insects release for communication with conspecifics (Howse et al. 1998). The best-known pheromones are moth 'sex pheromones' that are released by females to attract males. Many bark beetles (Scolytinae) release 'aggregation pheromones' that facilitate aggregation on host trees (Byers 1989), and many wood boring longhorned beetles (Cerambycidae) emit 'sex-aggregation pheromones' that attract both sexes, primarily for mating (Hanks and Millar 2016). There are several other types of pheromones (Howse et al. 1998) but they are less important in the context of monitoring.

The chemical structures of pheromones have been identified for many forest insects, especially those of economic importance, and synthetic lures may be commercially available (El-Sayed 2020). Pheromones are often composed of several components and are more or less specific to their species or genus, especially in moths (Lepidoptera) (Löfstedt et al. 2016). For example, traps baited with the main pheromone component of spongy moth (7,8-epoxy-2-methyloctadecane, a 19-carbon epoxide), also known as 'disparlure', catch mainly spongy moth and several congenerics and are widely used for monitoring and detection purposes. The complete blend of the pheromone of spongy moth contains minor components which increase its species specificity (Gries et al. 1996). On the other hand, longhorned wood boring beetles share many of the same sex-aggregation pheromone components. For example, traps baited with racemic 3-hydroxy-2-hexanone can attract several species of Cerambycidae (Millar and Hanks 2017).

Not all insect species use pheromones, and those of many other species remain to be identified. However, host plant volatiles may be used as an alternative attractant for plant-feeding insects because many species use these cues when searching for their hosts. For example, many conifer-feeding bark beetles and woodborers are attracted to alpha-pinene and ethanol, two components that are commonly associated with conifers. Hence, alpha-pinene and ethanol are used to monitor beetles associated with conifers including species of *Arhopalus* (Cerambycidae), *Hylastes* and *Ips* (Scolytinae) (Brockerhoff et al. 2006; Miller and Rabaglia 2009). Likewise, many ambrosia beetles are attracted to ethanol which is an effective lure for species such as *Xyleborus* spp. and *Xylosandrus crassiusculus* (Scolytinae) (Miller and Rabaglia 2009; Reding et al. 2011). Plant volatiles that assist insects with finding their host plants are often referred to as 'kairomones'. While pheromones are 'information chemicals' that are involved in intraspecific communication, kairomones are used as cues for interspecific interactions.

Traps used with pheromones and host plant attractants come in a variety of shapes, sizes, and colours. They use different mechanisms for trapping insects either on a sticky surface or in a collection jar that is easy to enter for an insect but very difficult to exit (effectively a one-way entry). Multiple-funnel traps (also called Lindgren funnel traps after their inventor) are used mainly for bark beetles (Lindgren 1983). They consist of a stack of several funnels and a collection cup at the base (Fig. 19.6a). Panel traps are an alternative design that involves intersecting panels with a single funnel and a collection jar at the base (Fig. 19.6b). These panel traps are typically used for longhorned beetles, weevils and bark beetles. A fluoropolymer may be applied to traps to make them more ‘slippery’ so that beetles can’t hold on to the panel surface (Graham et al. 2010). Funnel and panel traps are mainly colored black so that they resemble the silhouette of a tree trunk, but they are available in other colors. For example, for monitoring emerald ash borer (*Agrilus planipennis*, Buprestidae), green funnel traps (with an attractant) are preferable (Poland et al. 2019). The most common trap design used for bark beetle monitoring in Europe is the so-called Theysohn slot-trap which is based on an alternative flight interception design (Fig. 19.6c).

Neither of these traps work well for Lepidoptera, Hymenoptera and other less ‘robust’ taxa with a comparatively soft cuticle. For these species, trap types with sticky surfaces are commonly chosen. Perhaps the most widely used of these is the Delta trap which has a roof-shaped design with a sticky substance either on the entire internal surface or on a removable sheet in the trap. A lure is placed inside the trap and insects attracted by this lure are trapped when they land on the sticky internal surface (Fig. 19.6d). An advantage of this design is that the captured insects are spread out on the sticky area which makes examining the catches easy, unless they need to be removed for closer inspection, which may be difficult. A potential disadvantage of delta traps is their propensity to become saturated with the target species. When that is a problem, bucket traps with a larger holding capacity can be used. Unwanted by-catch can be reduced by choosing traps colored green which attract fewer flower-visiting insects than yellow or white traps, for example (Sukovata et al. 2020).

19.2.3 Important Considerations for Trap-Based Monitoring Programs Targeting Bark and Wood Boring Beetles

There are many successful monitoring programs for bark and woodboring beetles in Europe, North America and elsewhere. For example, in Europe, trapping is widely used to monitor populations of the European spruce bark beetle (*Ips typographus*, Scolytinae), the most serious insect pest of spruce forests in Europe. The main purpose is to follow population trends, as described, for example, by Faccoli and Stergulc (2005). Typically, Theysohn slot-traps baited with pheromone (ipsdienol and methyl-butenol) dispensers are used to attract *I. typographus*, and the ratio of trap captures of the summer generation and the spring generation can be calculated to determine whether populations are growing or declining. However, there is some controversy about the extent to which trap captures reflect *I. typographus* population sizes and trends (see Sect. 19.4).

In the southern USA, forest managers use a trap-based monitoring system as part of an IPM program to manage the southern pine beetle (SPB), a major pest of southern pines (Clarke 2012). In the spring of every year, funnel traps baited with pheromone (frontalin) and kairomones (alpha-pinene and beta-pinene) are deployed

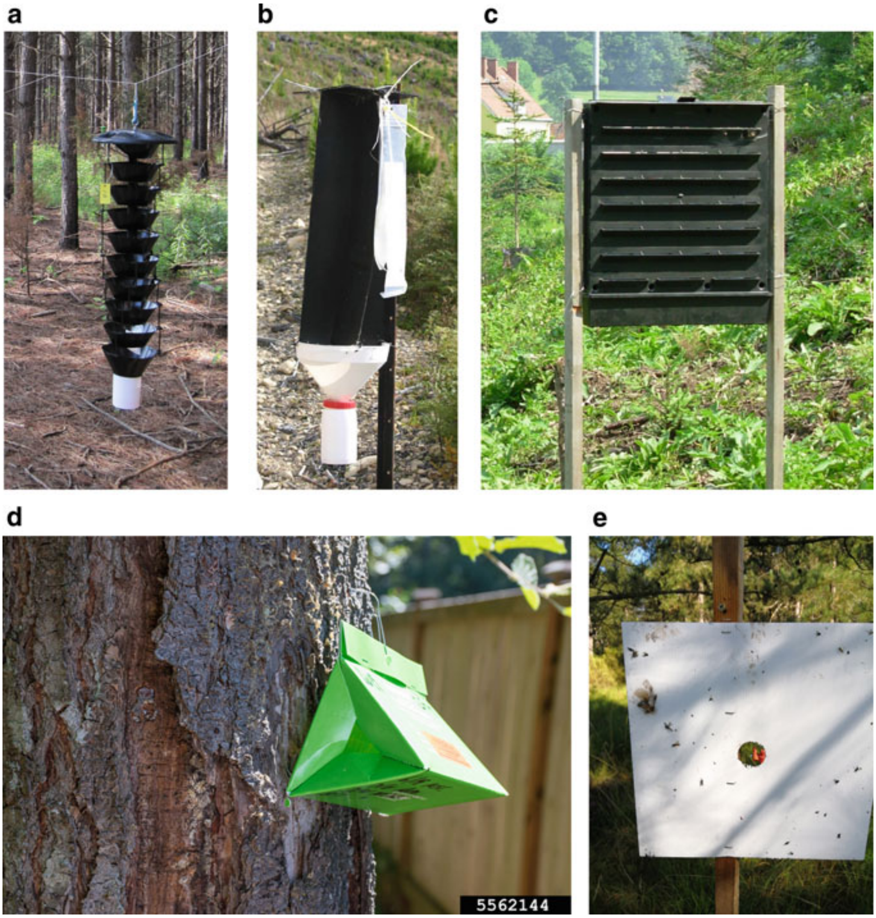


Fig. 19.6 Various traps used for insect monitoring and surveillance: **a** Lindgren-funnel trap. Credit: D. Miller, USDA Forest Service; **b** Panel trap with alpha-pinene and ethanol lures attached. Credit: J. Kerr, Scion, New Zealand; **c** Theysohn bark beetle trap. Credit: Gernot Hoch, BFW Institut für Waldschutz, Vienna, Austria; **d** Delta trap. Credit: Karla Salp, Washington State Department of Agriculture, Bugwood.org; **e** Sticky plate trap with pheromone lures in the center and a trapped pine processionary moth. Credit: Hervé Jactel, INRAe, France

at key locations in and around pine stands. Managers consider the number of SPB captured as well as the ratio of predators (the checkered beetle *Thanasimus dubius*, Cleridae) to SPB to determine if local epidemics are increasing, stable or collapsing. This information is used to determine the need for management efforts against SPB.

Operationally, the choice of trap type, lure type and trap position is a major concern for managers planning a trapping program, and these parameters depend on the target species. The efficacy of a trapping program for a single species or broad diversity can be affected by numerous factors such as trap location (canopy vs ground, forest edge vs forest interior), trap type and color, and trapping period and duration (e.g. Brockerhoff et al. 2012; Dodds 2014; Flaherty et al. 2019; Sweeney et al. 2020). Managers need to be clear about their objectives for a trapping program as there is no single scheme that can target all species equally.

Relative species-specificity of lures can be achieved for some species such as the engraver bark beetle *Ips paraconfusus* (Scolytinae) that uses a combination of (–)-ipsenol, (+)-ipsdienol and *cis*-verbenol as its pheromone blend, while frontalin is a common pheromone for various species of *Dendroctonus* (Scolytinae) (Byers 1989). Traps baited with genus-specific monochamol lures are attractive specifically to sawyer beetles (*Monochamus* spp., Cerambycidae) in North America, Europe and Asia, although traps baited with the bark beetle pheromone ipsenol may be equally attractive for *Monochamus* species (Ryall et al. 2015; Miller et al. 2016).

To capture multiple species, blends of multiple attractants can be used. For example, blends of certain hexanediols and hydroxyketones are broadly attractive to numerous woodborers in the longhorn beetle subfamily Cerambycinae (Hanks and Millar 2016). Traps baited with the host plant volatiles alpha-pinene and ethanol are broadly attractive to many bark and ambrosia beetles (Miller and Rabaglia 2009). A combination of alpha-pinene and ethanol and bark beetle pheromones attracts numerous species of woodborers including *Monochamus* species as well as numerous species of bark and ambrosia beetles, and associated predators (e.g. Miller et al. 2013, 2015; Alvarez et al. 2016; Chase et al. 2018).

19.2.4 Monitoring the Population Dynamics of Pine Processionary Moth with Pheromone Trapping

The pine processionary moth (PPM) is the main insect defoliator of pine forests in southern Europe and North Africa (Roques 2015). Severe defoliations by PPM caterpillars feeding on needles result in reduced tree growth (Jacquet et al. 2012) and increase the risk of mortality (Jacquet et al. 2014). The larvae have urticating hairs which can cause serious health problems in people and domestic animals (Vega et al. 2011). PPM populations exhibit cyclic outbreaks (Li et al. 2015) and even though the year of the next peak infestation can be forecasted, the amplitude of defoliation remains unpredictable (Toïgo et al. 2017). It was therefore important to develop a reliable method for monitoring and predicting PPM infestation levels in order to warn forest users and implement necessary control measures such as applications of the toxin of *Bacillus thuringiensis* (*Bt)* when populations get too large.

The conventional population monitoring of PPM is based on counts of winter nests made by larvae in the tree crown (Gery and Miller 1985), but this is tedious and inaccurate in mature or dense pine stands. Pheromone trapping has been considered an alternative method and has proven highly effective in the field (Einhorn et al. 1983). To develop pheromone trapping as a reliable sampling technique, a suitable trap design and trap position had to be identified and it needed to be shown that trap captures were indicative of actual population levels. Sticky plate traps hung at user-friendly heights of about 1.5 m above ground (Fig. 19.6e) appeared to be the most efficient (Jactel et al. 2006). It was also necessary to optimise the pheromone dose and the density of traps to improve the statistical correlations between mean trap capture and other measures of population density. Four sticky plate traps baited with 0.2 mg of the commercial pheromone ("pityolure") provide an accurate and cost-effective estimate of the total number of PPM per hectare (Jactel et al. 2006). This method was tested and further refined in a large operational trial in France (see Sect. 19.4).

19.2.5 *Monitoring Populations of the Invasive Woodwasp* Sirex Noctilio

Among the non-native invasive forest insects observed in commercial plantation forests in many southern hemisphere countries, the woodwasp *Sirex noctilio* F. (Siricidae) is probably the best known. The species is capable of widespread damage on cultivated pines within the invaded range, especially during population outbreaks (Lantschner and Corley 2015). *Sirex noctilio* is a woodboring species with a solitary lifestyle that infests pine trees. Following mating, females lay eggs by drilling holes in pine stems which they locate by following volatile cues associated with tree stress. During oviposition, the female introduces a symbiotic fungus (*Amylostereum areolatum)* and a phytotoxic venom which together can kill attacked trees (Slippers et al. 2015).

Population monitoring is an important aspect of *S. noctilio* pest management and is often carried out within the invaded range by looking for trees with signs of attack, rather than the insect itself. Attacked pines typically show crown chlorosis, and resin droplets on their stems resulting from oviposition by *S. noctilio.* Sequential sampling protocols and/or aerial surveys support estimations of tree damage and the application of control measures. However, sequential sampling is somewhat flawed as attacks are typically highly aggregated. This approach may underestimate attack levels, especially when populations are low such as in recently invaded sites (Carnegie et al. 2005; Lantschner and Corley 2015).

Alternatively, the trap-tree technique is used to detect early-stage populations. This consists of treating 4–10 trees with low doses of herbicide or careful girdling prior to the wasp flight season (Fig. 19.7). Foraging females are attracted to these artificially stressed trees which can then reveal the presence of *S. noctilio.* Felling of any attacked trees after the flight season may be necessary to avoid the build-up of local populations (Lantschner and Corley 2015). When billets (stem sections) from these trees are caged, the presence and abundance of natural enemies (especially parasitoids attacking the wood wasps) and their potential impact on the *S. noctilio* population can be estimated.

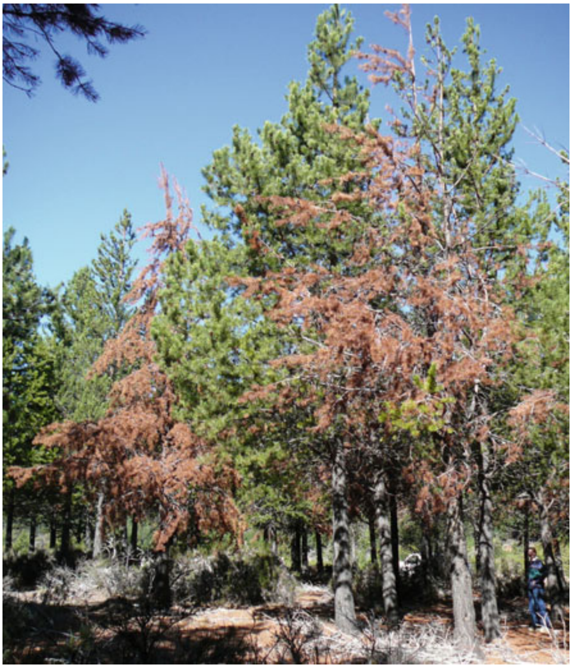


Fig. 19.7 Trap trees to attract Sirex wood wasps in a Pinus contorta plantation in Patagonia, Argentina. Credit: Juan Corley

Flight intercept traps (panel traps or funnel traps) baited with combinations of alpha-pinene and beta-pinene, which are also emitted by stressed trees, can be used to sample *S. noctilio* populations. However, trapping with these lures is usually not as effective as it is for many other insects (Batista et al. 2018). The development of new pheromone and kairomone lures which are based on attractive volatiles from conspecifics or from the wasp's fungal symbiont, may prove important as this type of lure can be highly specific and works well also at low population densities (Fernández Ajó et al. 2015).

The development of effective sampling methods to monitor *S. noctilio* populations within the invaded range is especially important since detecting small populations as early as possible during the invasion phase and understanding when and why *S. noctilio* populations increase is key to preventing regional spread and major economic impact in invaded areas. These should not only include effective trap and lure designs but also statistically valid sampling efforts, to provide quantitative data in diverse environmental conditions. This information is also needed to interpret the success of the control practices deployed.

19.3 Surveillance to Detect Invaders

Preventing the introduction of non-native species is the most effective and first line of defense, although some species may inevitably escape detection and become established. The greatest opportunity for eradication and cost-effective management is immediately after their introduction when their populations are still small and limited to a small area. Early detection followed by rapid assessment and response increases the likelihood of successful eradication or containment (Brockerhoff et al. 2010; Liebhold et al. 2016). There are a number of other purposes of surveillance including to demonstrate freedom from certain pests within an area (a potential requirement for international trade) and to verify the effectiveness of biosecurity measures (Kalaris et al. 2014).

Numerous methods and tools can be applied for surveillance and detection of non-native insects (e.g. Augustin et al. 2012; Kalaris et al. 2014; Poland and Rassati 2019). Many are similar to those used for monitoring native insects (see Sect. 19.2). But there are several key differences: (i) the main initial goal is to detect the *presence* of a non-native species, whereas determining its population size and spatial extent (i.e. delimitation) is a subsequent step; (ii) there is a rather large number of potential invaders, and surveillance often aims at detecting any of multiple species, although some programs are aimed at just one specific unwanted species; and (iii) one is virtually looking for a needle in a hay stack as the aim is to find a small population that could be anywhere. Consequently, methods that are highly sensitive and can cover large areas are preferable. However, if the identity of the target is unknown, methods suitable for a wide range of species are needed. For both cases, trapping with suitable trap type and lure combinations is a preferred option (e.g. Quilici et al. 2012). Below we describe two trapping programs to detect invaders (for spongy moth and non-native bark- and woodboring beetles). But as trapping can only target a limited number of species, more generic surveillance methods that can detect a wider range of species are also needed. Physical searching by trained biosecurity specialists to detect new non-native species is being carried out in several countries, often with a focus on high-risk sites. Engagement of the wider public in surveillance activities can also be highly effective. Examples of these approaches are given below.

19.3.1 High-Risk Site Surveillance

Early detection of non-native species is very important for successful responses to detections. Because the resources for surveillance are limited, efforts need to be focused on locations where non-native species are most likely to arrive and become established. By definition, such locations can be characterized by the likelihood of arrival of non-native pests and by the likelihood of establishment at those sites.

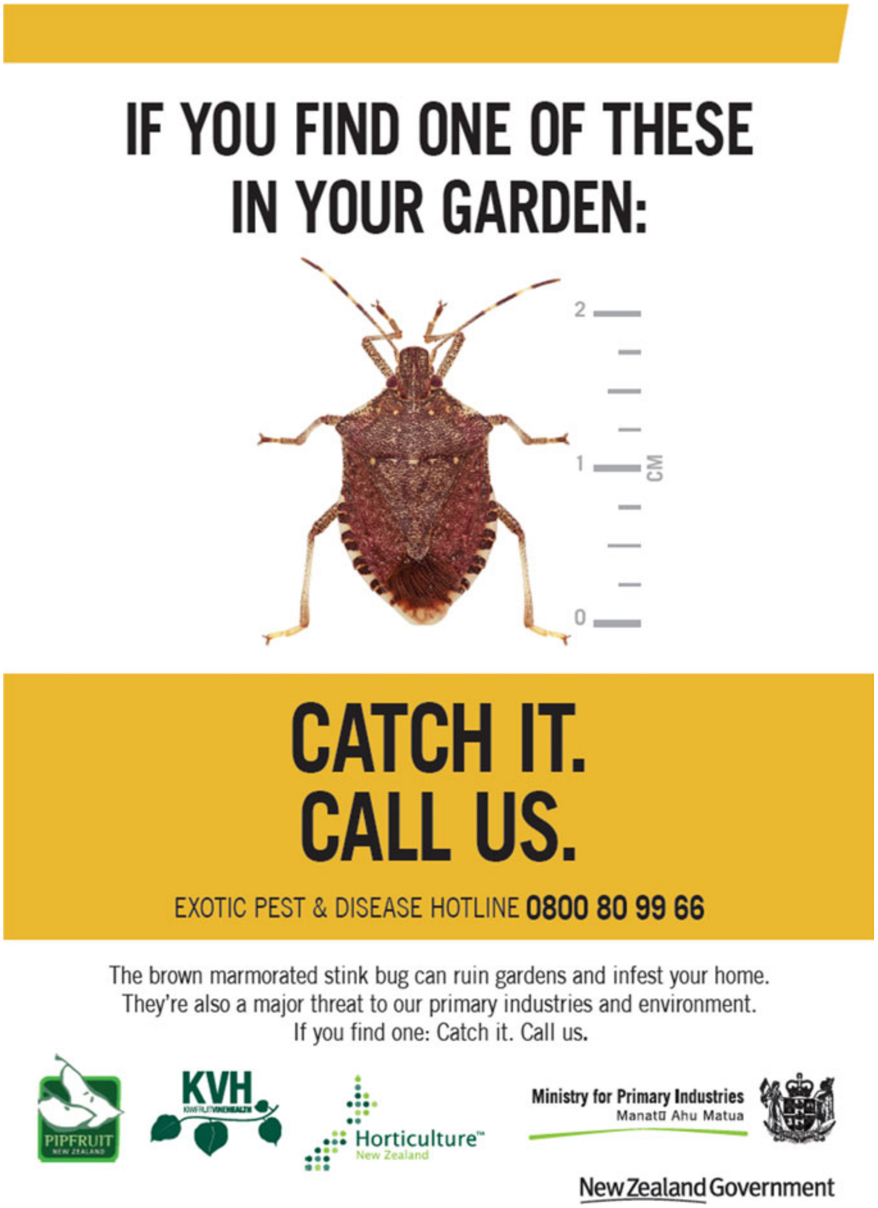
Insights about the likelihood of arrival can be gained from information about trade patterns, particularly regarding the volume and destinations of those types of imports that are known to be associated with species of concern (Colunga-Garcia et al. 2013; Kalaris et al. 2014). These sites tend to be concentrated around commercial and industrial areas, rather than in the forests that are at risk. The surroundings of air and sea ports are also considered high-risk sites although with today's fast and often containerized trade, there is more opportunity for organisms to escape at the eventual destinations of shipments, rather than at ports where shipments pass through. Larger metropolitan areas that are the destination of a large proportion of imported goods and insects transported with these (Branco et al. 2019) are focus areas for surveillance. Therefore, human population size and density can be used as simple proxies if more detailed information about trade flows is not available.

Sites that warrant particular attention are those where imported high-risk commodities arrive such as live plants (e.g. nurseries and garden centers) and wood packaging materials (e.g. recipients of large volumes of paving stones and tiles that are typically packed with pallets and case wood) (Liebhold et al. 2012; Haack 2006). Such information has been used to identify potential hotspots for invasion pressure in the United States where surveillance efforts should be particularly intensive (Colunga-Garcia et al. 2013). Similar concepts have been developed and implemented in other countries. For example, the New Zealand government operates a high-risk site surveillance system in the main urban areas with thousands of transect inspections every year, focusing on urban trees and parks near commercial and industrial areas as well as campsites in natural areas where overseas tourists may introduce pests inadvertently (Bulman 2008; Stevens 2008).

19.3.2 Engaging the Public in Surveillance Activities

Although most members of the public are not experienced in insect identification and detection of non-native species, they are far more numerous than trained professional surveillance staff. It is not uncommon for citizens to notice unusual tree damage and unusual insects in their neighborhood. Consequently, the public should be considered in a surveillance framework as contributing to 'passive surveillance' (e.g. Froud et al. 2008; Hester and Cacho 2017). In New Zealand, there is an established system by which the general public can contribute and report suspicious finds of insects and other species via a toll-free phone number, with about 4,000 notifications per year (Froud et al. 2008). Approximately 8% of all detections of new incursions were reported by the general public, slightly more than those reported by industry. The public is especially encouraged to assist with reporting particular high-risk species and New Zealand's biosecurity authority runs campaigns with newspaper advertisements, tv commercials and social media posts such as the "Catch it - call us" campaign (Fig. 19.8).

The development of a biosecurity board game targeted at both children and adults has proven useful as another way to increase the awareness of the public about biosecurity issues, including the purpose of surveillance. To enhance the ability of the public to identify and report potential biosecurity threats, mobile phone-based



IF YOU FIND ONE OF THESE IN YOUR GARDEN:

CATCH IT. CALL US.

EXOTIC PEST & DISEASE HOTLINE **0800 80 99 66**

The brown marmorated stink bug can ruin gardens and infest your home. They're also a major threat to our primary industries and environment. If you find one: Catch it. Call us.

Fig. 19.8 Advertising used for the "Catch it - call us" campaign by New Zealand's national biosecurity agency MPI to encourage reporting finds of an invasive insect. *Source* https://twitter.com/MPI_NZ/status/662489108065812480 apps have been developed including ‘Wild Spotter’ in the United States (www.wildspotter.org, Wild Spotter 2020), ‘Observatree’ in the UK (https://www.observatree.org.uk) and ‘Find-a-Pest’ in New Zealand (www.findapest.nz, Pawson et al. 2020). The Find-a-Pest app is effective in reducing the number of false positives (i.e. reports that were of no concern). False positives can be a problem because they occupy the attention and time of biosecurity officials.

19.3.3 Spongy Moth Detection Trapping

The program to detect new infestations of spongy moth along its invasion front and in uninfested regions of the United States is perhaps the largest trap-based pest detection and surveillance program in the world. Approximately 250,000 pheromone-baited spongy moth traps are placed annually by the Animal and Plant Health Inspection Service of the United States Department of Agriculture (USDA APHIS) to detect new populations (USDA 2019). In addition, the USDA Forest Service deploys more than 100,000 traps as part of the spongy moth ‘slow the spread’ program (Sharov et al. 2002; Bloem et al. 2014). The goal of this program is to minimize the rate of spongy moth spread into uninfested areas in central and southern US forests. Traps along the expanding population front are used to identify newly established populations. Any such populations are then treated to prevent them from growing and coalescing into larger infestations. This approach has successfully reduced the spread rate of spongy moth by > 70% from the historical spread rate of approximately 21 km per year to an average of approximately 6 km per year between 1990 and 2005 (Fig. 5.11a in Tobin and Blackburn 2007), and has a projected benefit-to-cost ratio of approximately 3:1 by delaying the onset of impacts and management expenditures that occur as spongy moth invades new areas (Tobin and Blackburn 2007). This intensive targeted surveillance has enabled the very high success rate of eradications of spongy moth populations, close to 100%, that were detected (Kean et al. 2020).

A similar but smaller detection program is carried out in New Zealand and in Australia. But intensive surveillance is costly and it would be difficult to fund similar programs multiple times for a large number of potential pests. However, it is possible to add lures for other species to spongy moth traps, and this was examined for pairs of spongy moth and 18 other well-known pest moths (Brockerhoff et al. 2013). Lures for more than half of the species could be combined without a substantial reduction in trap sensitivity for either species, and most of the other pairs still caught moths in numbers sufficient for detection purposes. Therefore, combining compatible lures for multiple target species could increase the number of targeted species without greatly increasing the cost of such surveillance programs.

19.3.4 *Trapping Programs to Detect Non-Native Bark Beetles and Wood Borers*

Bark beetles (Scolytinae) have long been a focus of surveillance programs for non-native forest insects. For example, following the detection of the European pine shoot beetle (*Tomicus piniperda*, Scolytinae) in 1992 in Ohio, a surveillance trapping program was initiated in 1993 in the northeastern United States to enable early detection of other non-native bark beetles (Bridges 1995). Trapping with attractant-baited traps focused on high risk sites including areas near ports, importer warehouses and lumberyards. In 1996, when the first established population of the Asian longhorned beetle (*Anoplophora glabripennis*, Cerambycidae) outside its native range was discovered in New York City (Haack et al. 2010), the threat posed by longhorned beetles became more obvious. There was a growing realization that the large-scale use of solid wood packaging material (WPM) in international trade was a dangerous pathway that made invasions of both wood borers and bark beetles more likely. Between 1985 and 2005, established populations of 25 exotic species of bark beetles and wood borers (Scolytinae, Cerambycidae, Buprestidae) were detected in the United States (Haack 2006) and most of these probably arrived with WPM. Subsequently, a nationwide surveillance trapping program for bark beetles and ambrosia beetles was initiated in the United States (see Sect. 19.3.5).

Several other countries have developed surveillance programs for bark and wood-boring insects, albeit on a smaller scale. For example, such a program was trialed in New Zealand from 2002–2005 using funnel traps baited with host plant attractants and/or bark beetle pheromones, targeting a range of conifer-infesting wood borers and bark beetles (Brockerhoff et al. 2006). Although that particular surveillance program did not lead to the detection of any species not already known to be present, it did confirm the suitability of the approach as numerous non-native Scolytinae and Cerambycidae were trapped near seaports, airports, cargo unloading sites, and in forests near such locations. The surveillance trapping program for bark beetles and wood borers in New Zealand was discontinued mainly because there was uncertainty whether expenditures for the program were justified. However, a benefit–cost analysis carried out later indicated that such a surveillance program is expected to provide economic net benefits even at a high trap density because the economic benefits of early detection, a greater likelihood of successful eradication and less pest damage, likely exceeded the costs of the surveillance program (Epanchin-Niell et al. 2014).

Intercept panel traps or multiple-funnel traps (described above) are used in most detection programs. However, Malaise traps may be more effective in the detection of numerous species of bark and wood boring beetles (Dodds et al. 2015) but there is a trade-off because Malaise-type traps are about five times more expensive than intercept or funnel traps. In addition, Malaise traps tend to capture many more non-target species and consequently require more labor for sorting samples. Given the apparent variability in trapping efficiency even at short distances, detection programs might be more cost effective by using a larger number of panel or funnel traps than Malaise-type traps. Another method that may be suitable for increasing the efficiency of detection trapping is to use a combination of lure blends so that each trap targets multiple species (rather than using separate traps each baited only for a particular species) (Chase et al. 2018; Fan et al. 2019; Rassati et al. 2019). This would either reduce the number of traps needed, or it would lead to an increased number of traps available for detecting particular species. There is a potential disadvantage of using lure blends in that it may reduce the number of insects caught of some species (Miller et al. 2017). However, for the purpose of detection, it is only necessary to trap at least one individual of a target species, so this disadvantage may be tolerable.

19.3.5 Early Detection of Bark and Ambrosia Beetles in the US

Bark and ambrosia beetles (Scolytinae) are some of the most important insects affecting forests in North America, and are the most commonly intercepted group of beetles at US ports of entry (Haack 2006). From 1984–2008, more than 8,000 interceptions of bark and ambrosia beetles, from 85 different countries, were reported at US ports (Haack and Rabaglia 2013). To increase the likelihood of early detection of such beetles, the USDA Forest Service began a pilot project in 2001 (Rabaglia et al. 2008) and then implemented in 2007 a national project for the early detection and rapid response (EDRR) of non-native bark and ambrosia beetles across the US (Rabaglia et al. 2019). The target species were selected based on their frequency of interception, the potential damage a species may cause in the US, and the availability of effective traps and lures for the species. The Scolytinae species selected were *Hylurgops palliatus*, *Hylurgus ligniperda*, *Ips sexdentatus*, *Ips typographus*, *Orthotomicus erosus*, *Pityogenes chalcographus*, *Tomicus minor*, *Tomicus piniperda*, *Trypodendron domesticum*, and *Xyleborus* species.

Three Lindgren funnel traps were used at each survey location, and each trap was baited with one of the following three lures or lure combinations: (i) ultra-high release (UHR) ethanol lure only, a general attractant for woodboring insects in hardwood and some coniferous hosts, (ii) UHR alpha-pinene and UHR ethanol lures together, which are general attractants for woodboring insects in coniferous hosts (Miller and Rabaglia 2009), and (iii) a three-component exotic *Ips* lure of ipsdienol, cis-verbenol and methyl-butenol, a specific combination for *I. typographus* and several other conifer-feeding exotic bark beetles (Bakke et al. 1977). Trapping began based on local phenology of bud break and knowledge of early emergence of bark and ambrosia beetles, from late February to early May, depending on the State, and lasted typically for 12 weeks.

Since 2010, the project focused on five high- risk states (California, Florida, Georgia, New York, and Texas), based on interceptions at ports-of-entry, the number of established non-native species, the amount of forest land, and transportation corridors. Other states were surveyed only every 3–7 years, depending on their risk and available funding. Within each state, trapping was carried out in wooded areas or parks near high-risk sites where potentially infested solid wood packing material (e.g. wooden crates and pallets) were imported, stored, or recycled. Taxonomists identified all of the bark and ambrosia beetles and the data were shared at www.barkbeetles.info.

More than 840,000 specimens of bark and ambrosia beetles had been collected and identified in forty-eight states (including Alaska and Hawaii), Puerto Rico, and Guam from 2007–2016 (Rabaglia et al. 2019). Within the continental U.S., the survey captured specimens of approximately 300 species out of the approximately 550 that occur in the U.S. Forty-three of the species collected were non-native species established in the U.S. The three most common species in traps were *Xyleborinus saxesenii*, *Xylosandrus crassiusculus*, and *Xylosandrus germanus*, three well-established non-native species with strong responses to ethanol-baited traps.

The primary goal of EDRR is the early detection of species new to North America. In the first few years of the pilot phase of EDRR, five species of scolytines new to North America were found in traps, and since 2007, three additional species new to North America were found: *Xyleborinus octiesdentatus*, *Xylosandrus amputatus*, and *Xyleborinus artestriatus* (Rabaglia et al. 2019). Assessments and follow up surveys to delimit the distribution of the new species were conducted soon after but these beetles were established over large areas and eradication was not feasible. Eradication of xyleborine ambrosia beetles, such as these three species, can be particularly challenging. Their cryptic nature, wide host range (these species breed in most hardwood trees), and their inbred, polygynous biology, allows them to go undetected and to quickly spread from just a few individuals.

It is likely that some, if not most, of the species newly detected during the beginning years of EDRR were present in the U.S. for decades. These legacy species were soon detected with the start of surveys such as EDRR. Since 2010, there have been no detections of species new to North America in EDRR traps. It is possible that all non-native species established in the states surveyed before 2010 have been detected and any new detections will be of recent introductions allowing for a more effective rapid response. It is also possible that the implementation of international protocols, such as ISPM 15, and awareness of the risk of moving wood products has reduced the number of wood boring insects introduced into the U.S.

19.3.6 Development of Survey Tools for an Invasive Longhorn Beetle in Canada

The brown spruce longhorn beetle (BSLB), *Tetropium fuscum* (Cerambycidae), native to Europe, was discovered in Halifax, Nova Scotia, Canada in 1999, infesting mature red spruce (Smith and Hurley 2000). About one third of trees displaying signs of resin flow on the trunk and spheroidal exit holes were dead but most were alive and appeared healthy, suggesting BSLB was successfully colonizing and killing trees (O'Leary et al. 2003). The Canadian Food Inspection Agency (CFIA) declared

BSLB a regulated quarantine pest in spring of 2000 and led a multiagency “BSLB task Force” in a survey and eradication program. The regulated area was delimited using intensive ground surveys and the visual signs of infestation, examining > 52,000 conifers on > 47,000 residential properties in greater Halifax in 2000.

Lindgren funnel traps (Lindgren 1983) baited with the same three lure combinations used by the EDRR program in the US (i.e. ethanol and alpha-pinene, ethanol alone, or a three-component exotic *Ips* lure) had been deployed in Halifax by CFIA since 1995 for exotic woodborer surveillance, but had failed to detect BSLB. Thus, members of the Task Force collaborated to develop survey tools to detect spread of BSLB and monitor the progress of the eradication program. Decks of freshly cut spruce logs (Post and Werner 1988) were deployed along major highways from Halifax in 2000–2002. Log decks detected BSLB in two new locations outside of the regulated area but were labor-intensive and slow. In 2003, log decks were replaced by intercept panel traps (Czokajlo et al. 2001; de Groot and Nott 2001) baited with a synthetic “spruce blend” lure, consisting of five major monoterpenes emitted from infested spruce (Sweeney et al. 2004). Adding an ethanol lure increased detection rates (Sweeney et al. 2004, 2006) and from 2004–2006, these baited traps detected BSLB in 25 sites outside of the regulated area, prompting CFIA to expand the regulated area in spring of 2007.

In 2006, Silk et al. (2007) identified a male-produced sex-aggregation pheromone, (*E*)-6,10-dimethyl-5,9,-undecadien-2-ol (“fuscumol”), that synergized attraction of both sexes of BSLB when combined with spruce blend and ethanol. In 2007, operational surveys with the more sensitive pheromone-baited traps detected BSLB in 16 sites outside of the newly expanded regulated area, and CFIA switched the goal from eradication to slowing the spread (CFIA 2017). By spring of 2015, BSLB had been detected in more than 100 sites outside of the 2007 regulated area and CFIA declared the entire province of Nova Scotia infested (CFIA 2017).

This case study highlights the importance of inter-agency collaboration and rapid technology transfer in the development of operational survey tools. It also highlights the critical need for effective survey tools for early detection when containment or eradication of an invasive species is still feasible (Brockerhoff et al. 2010; Tobin et al. 2014; Liebhold and Keen 2018).

19.4 Making Sense of Trap Catch Data, and Statistical Considerations

19.4.1 Relationships Between Trap Catch and Local Population Size

The relationship between trap catch and local population density of forest insects, tree damage or tree mortality is not always strong. For example, while pheromone-baited traps can be useful for determining whether *I. typographus* populations are growing or declining (Faccoli and Stergulc 2006), and low catches were indicative of low levels of damage occurring, high catches were not well correlated with infestation levels near traps (Lindelöw and Schroeder 2001). In another study, no relationship at all was found between trap catch of *I. typographus* and attacks of trees nearby (Wichmann and Ravn 2001). Likewise, in North America, a study of western pine beetle (*Dendroctonus brevicomis*) suggested that pheromone-baited funnel traps were not useful for predicting mortality of pines nearby (Hayes et al. 2009). Conversely, pheromone trap catch of spruce beetle (*Dendroctonus rufipennis*) provided reliable estimates of Engelmann spruce mortality around the trap, albeit with large variance (Hansen et al. 2006; Negrón and Popp 2018).

Relationships between pheromone trap catch and indicators of population size were found to be more reliable for several Lepidoptera species. For example, catches of eastern spruce budworm (*Choristoneura fumiferana*, Tortricidae) by traps baited with sex pheromone showed a strong relationship with densities of spruce budworm larvae in the following year, which allowed prediction of outbreaks in eastern Canada up to six years in advance (Sanders 1988). However, at high population densities, trap catch was less indicative of population trends. Nevertheless, pheromone traps have been used for decades to monitor spruce budworm populations. Pheromone trap catch of the Nantucket pine tip moth (*Rhyacionia frustrana*, Tortricidae) in Georgia was moderately to highly correlated with population density and damage for the first adult generation but less so for subsequent generations within a year (Asaro and Berisford 2001). In France, pheromone trapping of the pine processionary moth was developed for population monitoring (Jactel et al. 2006) and tested from 2010 to 2016 across 50 pine plantations. This showed that trap catch is highly correlated with the annual number of attacked trees and can be used to predict infestations in the following year. Pheromone trap catch of a close relative, the oak processionary moth (*Thaumetopoea processionea*, Thaumetopoeidae), was less well correlated with local population densities in the U.K. (Straw et al. 2019). Nevertheless, the presence of nests within 250 m from a trap was successfully determined in 91% of cases.

Several important points need to be taken into consideration when evaluating relationships between trap catch and other indicators of insect presence, abundance, and damage: (i) traps can capture insects that have flown tens or hundreds of meters from where they had been feeding on a tree so that trap catch is not necessarily related to populations in the immediate neighborhood of a trap; (ii) insect populations can be highly patchy in space (Safranyik et al. 2004) and small numbers of traps may not provide an accurate indication of larger-scale abundance or damage, but a larger number of traps deployed at a site may do so (Schroeder 2013); (iii) when local populations are large, pheromone traps "compete" with many natural pheromone sources, and the same applies to traps baited with host plant volatiles when these are located in areas with an abundance of naturally occurring host plant volatiles (Wermelinger 2004; Schroeder 2013); (iv) the relationship between trap catch and population size may or may not be relevant depending on whether the purpose of trapping is for prediction of damage or just for detection of the presence of a species (as in pest detection and delimitation surveys) (Brockerhoff et al. 2013). Consequently, the choice of trapping or an alternative method depends on the purpose of the activity. If prediction of population size is important, then a larger number of traps across a forest may be needed to obtain a better estimate and other factors such as the amount of host trees and the condition of sites need to be considered (Schroeder 2013). Furthermore, conclusions or inferences from trap catch data strongly depend on context such as catches of the same insect species in previous years or in traps at other locations in the same year.

19.4.2 Pheromone Trap Attraction Range

Beyond the intrinsic capture efficiency of an attractant-baited trap, it is important to know its attraction range, the area around a trap over which the target species is drawn towards the trap. The attraction range is relevant for validating correlations between trap catch and local population level at the same spatial scale. It is important for making inferences about the effective sampling area, i.e. the portion of the landscape where the target species can be detected, especially for surveillance of alien invasive pests (Kriticos et al. 2007). Additionally, knowledge of when the interception zones of adjacent traps overlap assists with designing pheromone trap networks (Manoukis et al. 2014) to optimize trap density, save time and reduce costs of trapping programs.

A common and convenient method of estimating the attraction range is based on analyzing interference between adjacent attractant-baited traps, considering that competition for insect capture would occur if two neighboring traps are sufficiently close to have overlapping attraction ranges (i.e. are at a distance shorter than twice their attraction range) (Schlyter 1992). To evaluate the distance between adjacent pheromone traps that would minimize competition and thus approximate the attraction range (or radius), a number of studies have been conducted with more or less complex grids, circles or groups of traps (Wall and Perry 1987; Schlyter et al. 1987; Elkinton and Cardé 1988; Oehlschlager et al. 2003; Jactel et al. 2019). Although the attraction range of pheromone traps for forest insects can vary greatly depending on trap design and the rate of release of pheromone lures, it is typically in the order of a few tens to hundreds of meters.

19.5 Other Detection Techniques Including Detector Dogs, E-Noses, Acoustic Detection and Molecular Techniques

19.5.1 Detection of Volatiles Emitted by Target Species

Most insects have a particular smell that may be related to pheromone production, some other biochemical process or other organisms associated with them. This can be exploited for surveillance purposes either by using chemical detection devices or with trained dogs. In several countries, trained detector dogs (or 'sniffer dogs') are used at airports to detect imports infested with insects or to find smuggled or prohibited goods (USDA 2012). However, detector dogs can also be used in urban areas and in plant nurseries to detect trees or plants for planting that are infested by an unwanted insect. In Austria and other countries in Europe, dogs have been trained to detect *Anoplophora* beetles in wood packaging material, live plant imports, and in urban or rural areas (Hoyer-Tomiczek and Sauseng 2013). Such dogs can be very effective; for example, 15,000 plants imported from Asia were screened over a period of three days, and the dogs detected five plants that were infested by citrus longhorned beetle (*Anoplophora chinensis*, Cerambycidae) (Hoyer-Tomiczek and Sauseng 2013). In the US, an *Anoplophora* dog detection program was found to be 80–90% successful in detecting infested trees (Errico 2013). However, detector dogs are mainly suitable for particular target species; their use for generic detection of insects and fungi is limited due to the ubiquitous presence of these organisms.

Conventional analytical identification of volatile organic compounds (VOCs) can also be used for surveillance purposes. Typically, this involves headspace analysis by gas chromatography (GC) and mass spectrometry to characterize the volatiles associated with a target species. Once identified, the environment can be screened for these volatiles using a similar procedure. For example, volatiles emitted by the brown marmorated stinkbug (*Halyomorpha halys*, Pentatomidae) in a confined space were identified in this way, and it was then tested whether detectable concentrations of these volatiles could be isolated in a larger environment (Nixon et al. 2018). However, the highly diluted volatiles proved difficult to detect, and the sensitivity of this technique may rarely be sufficient for practical application in the field.

Another potentially suitable approach for detecting volatiles of target species is the use of electronic noses (e-noses). Proof-of concept studies have demonstrated the potential suitability of bio-electronic noses for detection purposes, but no such devices are ready for application on an operational basis, although considerable progress has been achieved (e.g. Oh et al. 2011; Du et al. 2013). It is expected that such devices will be available for practical use sometime in the 2020s (Glatz and Bailey-Hill 2011).

19.5.2 Acoustic Detection

Many insects produce sounds or vibrations for communication or in conjunction with movement or feeding (e.g. Hill 2008; Mankin et al. 2011). These acoustic and vibrational signals can be detected with a variety of sensors and devices, most of which are portable (Mankin et al. 2011). A key advantage of this technique is that it allows the detection of species that are hidden from sight such as wood borers and bark beetles inside wood, and it is non-destructive. As many species produce characteristic sounds, it may be possible to identify the type of organism or even the species by acoustic analysis (Bedoya et al. 2021). This technique has its limitations, though, as these signals are often very quiet and sensors need to be very close to the source, and background noise can be a problem (Mankin et al. 2011). For example, the detection of bark beetle chirps under the bark of trees or logs is only possible within a distance of less than one meter and preferably much closer (Bedoya et al. 2022). Although operational application has been limited so far, acoustic detection of the red palm weevil (*Rhynchophorus ferrugineus*, Curculionidae), an invasive pest of palms that feeds inside palm trees is possible with a mobile acoustic detection system with > 80% accuracy (Herrick and Mankin 2012). Acoustic and low-frequency vibrational signals can also be detected with laser vibrometers. A portable laser vibrometer can be used to detect Asian longhorned beetles infesting trees or logs (Zorović and Čokl 2015).

19.5.3 Molecular Techniques and eDNA

Molecular techniques are increasingly used in a monitoring and surveillance context to identify insects. Eggs, larvae and pupae, which are difficult to identify using morphological characters, can often be identified with DNA barcoding using the mitochondrial COI gene (Frewin et al. 2013; Madden et al. 2019). There are also a wide range of molecular tools that are suitable for the detection and diagnosis of potentially invasive organisms on infested imports. These commonly use polymerase chain reaction (PCR) amplification in the laboratory but mobile PCR-based or loop-mediated isothermal amplification (LAMP) devices that can be used in the field are now available (Arif et al. 2013; Baldi and La Porta 2020), although these are used much more for pathogens than for insects. However, the use of environmental DNA (eDNA) has been shown to be effective in revealing the presence of small populations of invasive insects that may be difficult to detect with other methods (Valentin et al. 2018). Analysis by eDNA techniques of samples of plant material or rain water run-off on tree trunks could be a useful approach for surveillance and early detection of known target species.

19.6 Aerial Surveys and Remote Sensing

19.6.1 Aerial Surveys

When surveys are required for very large areas and ground-based surveillance and trapping programs are not practical, aerial surveys are often used. In North America, for example, aerial overview surveys of forest lands have been one of the foundations of forest pest management for decades (Hall et al. 2016). Aerial surveys are critical for assessing pest impacts in remote areas as well as for insects that impact forests at the landscape level. Yearly identification and mapping of numerous forest insect pests such as eastern spruce budworm, southern pine beetle, Douglas-fir tussock moth (*Orgyia pseudotsugata*, Erebidae) and mountain pine beetle (*Dendroctonus ponderosae*, Scolytinae), provide assessments of infestations on forest lands (Aukema et al. 2006; Bouchard et al. 2006; Taylor and MacLean 2008; Hall et al. 2016). Aerial surveys can be affected by weather conditions and navigation but they are relatively accurate. For example, a comparison of aerial sketch mapping of annual defoliation by eastern spruce budworm and defoliation assessments on the ground showed that 85% of aerial mapping correctly classified defoliation as either nil to light (0–30%) or moderate to severe (31–100%) (Taylor and MacLean 2008). Apart from assessing current impacts, these data can be analyzed together with data on historical outbreak patterns to predict spatiotemporal patterns of future epidemics (see Aukema et al. 2006 for an example on mountain pine beetle).

Considerable effort goes into aerial forest health surveys. For example, in British Columbia, aerial overview surveys in 2019 were conducted for 80% of the province with 658 flight hours logged over 129 flight days (Westfall et al. 2019a). These revealed that a total of 5.9 million ha of forested lands were damaged by $\geq$ 46 agents (biotic and abiotic). Combined with directed ground inspections, these identified major infestations of 15 insect species and 10 diseases in coniferous forests while deciduous forests recorded impacts from 6 insect species and 2 diseases. Areas damaged by insects were greatest for the western balsam bark beetle in coniferous stands (3.2 million ha) and the aspen leaf miner in hardwood stands (1.3 million ha). Linking the incidences and expansions of tree mortality and defoliation with inventory databases permits accurate determinations of tree mortality and potential losses from such infestations, thereby broadly guiding management efforts such as stand thinning, sanitation and salvage logging, and insecticide applications.

Typically, aerial surveys are conducted by trained professionals per specific guidelines (see Westfall et al. 2019b, for example, for British Columbia). Surveyors identify tree species and damage agents from small planes or helicopters, sketch mapping types of damage and boundaries of disturbances directly on forest cover maps. The use of GIS and GPS has greatly improved the accuracy of aerial surveys. The use of aerial photography and remote sensing (see below) adds additional overlays to maps. Ground truthing of infestations is an important step to verify the accuracy of aerial surveys. In addition to species identification of causal agents, ground truthing can provide important information on the stage of infestations. In pine stands attacked by the mountain pine beetle, forest health professionals can assess attack densities on trees and the ratio of trees currently under attack to those that were attacked the previous year, providing a measure of risk for further attacks the following year. Integrating such data with inventory data on susceptible volumes of trees in the area helps determine the likelihood of further expansion of infestations.

Ground truthing can also help prevent over-reactions to apparent insect damage by forest managers. For example, sawflies can cause extensive defoliation on hemlocks in coastal forests of British Columbia (Nealis and Turnquist 2010). The visibility of red foliage over thousands of hectares can cause concern with forest managers resulting in initial impulses to log the area before timber is degraded by disease or checking. Ground truthing provides the opportunity to document that damage occurs on old foliage while new, current year foliage is untouched by sawflies. Moreover, sawfly infestations are generally short-lived due to the effects of natural enemies. Examinations of branches in the field can readily verify high rates of parasitism of sawfly pupae. The use of drones or unmanned aerial vehicles (UAVs) with cameras can add significant benefits to ground truthing efforts, enabling surveyors the chance to examine crowns of tall trees and survey expansive regeneration stands that are difficult to traverse in person. Potential UAV applications are covered in the following section.

19.6.2 Remote Sensing of Forest Insect Damage

The use of remote sensing for forest health monitoring has increased substantially in recent years as research progress has made this an increasingly accessible and potentially powerful tool. Remote sensing involves high-resolution multi-spectral imagery acquired by satellites, aircraft or UAVs, which is processed (e.g. corrected for topography and atmospheric conditions) and analyzed (Hall et al. 2016; Stone and Mohammed 2017; Torresan et al. 2017). Satellite imagery can be of sufficient spatial resolution to enable identification of individual tree crowns or even individual branches, although there is a trade-off between resolution and the area displayed (i.e. the high-resolution 1.2-m pixel size of the Worldview-3 satellite sensor has an image width of only 13 km whereas the Landsat-8 satellite sensor has an image width of 185 km but a pixel size of 30 m, too coarse to display individual tree crowns) (Hall et al. 2016). Optical remote sensing captures the reflection of sunlight from trees and other structures, and the more separate spectral bands are recorded by a sensor, the better the spectral resolution and visualization of symptoms. The detection of insect damage is typically done by identifying damage-specific changes in spectral reflectance between images recorded from the same location in successive years, although a single image may sometimes suffice. The detection of change can be automated and there are many different approaches for doing this (Hall et al. 2016).

A review of uses of satellite imagery for detection of forest insect damage in North America has been compiled by Hall et al. (2016), including some 50 examples for mountain pine beetle, spruce beetle, eastern spruce budworm, western spruce budworm (*Choristoneura occidentalis*, Tortricidae), jack pine budworm (*Choristoneura pinus*, Tortricidae), spongy moth, and others. However, the uptake for operational use of satellite-based remote sensing data for forest health surveys has been limited so far. This has been attributed to several complicating factors including the requirement for species-specific spectral identification of insect damage, the limited time window when damage can be detected and atmospheric conditions/cloud cover need to be suitable, and difficulty with damage classification which typically occurs on a continuum rather than in specific classes (such as light, moderate, and severe) (Hall et al. 2016).

Despite some challenges, there is rapid progress with image resolution and analysis, and it can be expected that this technology will be adopted increasingly for operational use. When insect damage is sufficiently severe and detectable in satellite images, then this methodology is already relatively powerful. For example, a study in Sweden investigated the onset of infestations of Norway spruce by the invading Hungarian spruce scale insect (*Physokermes inopinatus*, Coccidae) which causes characteristic black 'sooty mold' on the foliage (Olsson et al. 2012). Using SPOT satellite data, 78% of damage was detected successfully, and retrospective data analysis was able to identify the year when this characteristic damage first occurred (Olsson et al. 2012). One way in which damage symptoms can be identified with greater reliability is by combining data from passive light sensors with data from active systems like LiDAR (Light Detection and Ranging) and Radar sensors (Stone and Mohammed 2017).

Multispectral analysis of aerial imagery taken by aircraft uses the same principles as that of satellite imagery but it has the advantage of user-controlled timing of image acquisition when symptoms and atmospheric conditions are ideal. However, taking images by manned aircraft can become expensive when larger areas need to be surveyed. Using UAVs for this purpose is increasingly feasible and may be more cost-effective than using larger manned aircraft, especially when surveys involve smaller areas. Torresan et al. (2017) reviewed several studies that tested UAVs equipped with visible and near-infrared or hyperspectral cameras to detect and classify forest insect damage. The use of UAVs for this purpose was promising with a detection reliability of ca. 75–90%. A UAV remote sensing application for detecting bark beetle damage on individual urban trees was developed by Näsi et al. (2018) with similar levels of accuracy of identification of healthy, infested, and dead trees.

19.7 Outlook

The need for monitoring and surveillance of forest insects is likely to grow in importance. Insect outbreaks appear to become more frequent and more severe as multiple disturbance factors including climate change and other anthropogenic impacts disturb forest ecosystems. Likewise, international trade is expected to increase and involve ever more trading partners around the world, which will facilitate more arrivals and establishments of non-native species, despite our efforts to curb these. To keep up with these trends, early detection of both incursions of non-native species and outbreaks of native species will be critical to enable effective responses.

There is a large pool of methods for monitoring and surveillance and more are becoming available with the rapid progress of science and technology. Conventional methods such as surveillance of forests and high-risk sites by trained experts as well as trapping using targeted and broad-spectrum attractants will remain important. Trapping programs are likely to become more effective for a wider range of species as new attractants are being developed. Nevertheless, many species will remain for which trapping is not an option. A disadvantage of these conventional methods is their limited spatial coverage.

Several new technologies are being developed or refined that enable monitoring and surveillance over larger areas including enhanced aerial surveillance and remote sensing using a variety of platforms. Progress with big data analysis and modelling also plays a role here. New developments in acoustic, chemical, and molecular detection methods and tools are also playing an increasingly important role. For example, the use of eDNA is promising for a range of surveillance applications. However, many of these methods are costly, and large-scale implementation would require large budgets. Conversely, better education and raised awareness among the wider public would be valuable without necessarily being costly. Citizen science projects are emerging in many countries and this is a promising development.

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