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REVIEW

Improved biosecurity surveillance of non-native forest insects: a review of current methods

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Abstract
Biosecurity surveillance has been highlighted as a key activity to discover non-native species at the initial stage of invasion. It provides an opportunity for rapidly initiating eradication measures and implementing responses to prevent spread and permanent establishment, reducing costs and damage. In importing countries, three types of biosecurity activities can be carried out: *border surveillance* targets the arrival stage of a non-native species at points-of-entry for commodities; *post-border surveillance* and *containment* target the establishment stage, but *post-border surveillance* is carried out on a large spatial scale, whereas *containment* is carried out around infested areas. In recent years, several surveillance approaches, such as baited traps, sentinel trees, biosurveillance with sniffer dogs or predatory wasps, electronic noses, acoustic detection, laser vibrometry, citizen science, genetic identification tools, and remote sensing, have been developed to complement routine visual inspections and aid in biosecurity capacity. Here, we review the existing literature on these tools, highlight their strengths and weaknesses, and identify the biosecurity surveillance categories and sites where each tool can be used more efficiently. Finally, we show how these tools can be integrated in a comprehensive biosecurity program and discuss steps to improve biosecurity.

Keywords Acoustic detection · Baited traps · Biosurveillance · Citizen science · Remote sensing · Sentinel trees

Key messages

- Biosecurity surveillance is a key activity to discover non-native species at the initial stage of invasion.
- Several surveillance tools have been developed to complement routine visual inspections and aid in biosecurity capacity both at the arrival stage (*border surveillance*) and at the establishment stage (*post-border surveillance* and *containment*). Optimal implementation of these tools in time and space is fundamental to enhance efficacy.
- Biosecurity programs may be enhanced by combining multiple surveillance tools and strategies into a comprehensive program that encompasses various location and spatiotemporal scales.

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Introduction

Management of non-native forest insect pests is one of the most demanding challenges faced by forest health practitioners (Brockerhoff and Liebhold 2017). The rate of global movement of these insects is continuously increasing (Aukema et al. 2010; Roques 2010; Brockerhoff and Liebhold 2017), and adopted preventive measures can reduce (Allen et al. 2017) but not stop invasions (Haack et al. 2014). In this context, biosecurity surveillance plays a key role (Hulme 2014). Non-native species management becomes increasingly difficult and expensive as populations of non-native pests establish and expand into new areas (Liebhold and Tobin 2008). Thus, discovering a non-native species at the initial stage of its invasion provides an opportunity for rapidly initiating mitigation measures and implementing responses to prevent its permanent establishment and spread, reducing costs and damage (Epanchin-Niell and Liebhold 2015).

Biosecurity surveillance efforts can be classified depending on the targeted invasion stage (Hulme 2014). *Pre-border biosecurity* includes development of policies that allow commodities to be imported safely (Hulme 2014). *Border surveillance* targets the very initial stage of the invasion process (arrival stage) to prevent establishment of a non-native species either directly (e.g., rejecting cargo or destroying infested materials) or indirectly (e.g., culling host material). Such activities are generally carried out at the main points-of-entry for imported commodities, such as seaports, airports, post-entry plant quarantine facilities, cargo depots, or mail centers. *Post-border surveillance* and *containment* target the first establishment stage and attempt to discover a non-native species when its population level is still low and when eradication and management strategies are most likely to succeed (Liebhold and Tobin 2008). *Post-border surveillance* is carried out on a large spatial scale, whereas *containment* is carried out around infested areas.

Biosecurity surveillance efforts can also be classified depending on the targeted species or group of species. *Specific surveillance* targets a single species or a very narrow and well-defined group of species or guild. *Generic surveillance* instead may target a broad range of species, belonging to several genera or families. Finally, biosecurity efforts can be categorized as *active surveillance*, generally undertaken by pest specialists (e.g., phytosanitary personnel), and *passive surveillance*, generally relying on members of the public and community to report suspect insects to biosecurity institutions (Hulme 2014).

Visual inspections routinely carried out by inspectors at points-of-entry represent the first line of defense against non-native species (Saccaggi et al. 2016). These standard procedures resulted in the detection of hundreds of thousands of insects (Haack 2001; Brockerhoff et al. 2006a; McCullough et al. 2006; Roques and Auger-Rozenberg 2006; Lee et al. 2016), rejection of infested cargo shipments and passengers, and compilation of several databases that further our understanding of introduction pathways and detection programs (Kenis et al. 2007; Meurisse et al. 2018). Nevertheless, visual inspections are not adequate to stop all insect invasions (Bacon et al. 2012; Caley et al. 2015). Increased global trade in recent decades has not been matched by a corresponding increase in the capacity of inspection agencies to inspect shipments in many countries (Saccaggi et al. 2016). For example, only a very small percentage (2%/year) of incoming shipments is actually inspected in the USA (McCullough et al. 2006). Furthermore, illegal trade and fraudulent certification of shipments cause commodities and associated insects to be imported without any inspection (Bisschop 2012; Haack et al. 2014). Thus, in recent years, considerable research has been conducted to develop effective and efficient surveillance tools, methods, and strategies to integrate with visual inspections and aid in biosecurity capacity (reviewed by Augustin et al. 2012).

Here, we review the existing literature on biosecurity tools and strategies that are currently available for *border surveillance*, *post-border surveillance* and *containment*, in order to identify: (a) strengths and weaknesses; (b) biosecurity surveillance categories and environments in which each may be most useful; (c) an approach to integrating different tools in a comprehensive biosecurity program; and (d) steps to improve biosecurity. We broadly reviewed the scientific literature, proceedings, and technical reports on biosecurity surveillance and detection of non-native species and highlighted examples of different tools, strategies, and applications. We did not use specific criteria to select articles included in this review.

Baited traps

Traps baited with attractants are commonly used for *active surveillance* of non-native species because traps and lures are efficient, commercially available at low costs, and have wide application across several purposes (Augustin et al. 2012; Suckling 2015). Traps can be used in the context of *border surveillance* at points-of-entry for imported commodities to capture insects before they become established in nearby trees or forested areas (Brockerhoff et al. 2006b; Bashford 2008; Wylie et al. 2008; Rassati et al. 2015a; Fan et al. 2018), but also in the context of *post-border surveillance* and *containment* around new infestations to detect the possible presence of non-native species in a given area or to assess their population level (Tobin et al. 2007; Faccoli et al. 2016). Furthermore, baited traps can be used for *specific surveillance* to capture a certain target species (e.g., a quarantine species) as well as for *generic surveillance* to capture multiple species (Table 1). For instance, hundreds of thousands of gypsy moth traps are deployed in grids along the leading edge of the infestation and in uninfested areas of the USA to detect and eradicate new isolated infestations (Tobin and Blackburn 2007). The USDA Early Detection and Rapid Response (EDRR) program deploys hundreds of traps targeting bark and ambrosia beetles (Coleoptera: Curculionidae: Scolytinae) at high-risk sites in the USA (Rabaglia et al. 2008; CAPS 2018) and has led to discovery of several new species at the national or state level.

Planning trapping programs requires selection of the optimal trapping protocols based on program objectives and the target species. Several variables, such as trap type (Augustin et al. 2012), trap color (Elkinton et al. 2010; Rassati et al. 2018a), trap surface treatments (Graham and Poland 2012;

Table 1 Biosecurity categories and main advantages/disadvantages of the techniques that can be used for surveillance of non-native forest insects

Technique	Biosecurity categories	Main advantages	Main disadvantages
Visual inspections	Border, containment, active	Allows preventive control measures (e.g., cargo rejection)	Small percentage of shipments inspected
		Generates useful data for further analysis	Not practical for broadscale surveys
Baited traps	Border, post-border, containment, specific, generic, active, passive	Efficient and relatively inexpensive	Not applicable if lures are not available
		Semiochemicals available for many species	Only effective for adults
		Can be deployed over large areas	Only effective during flight period
		Can be integrated with cameras	Labor intensive when many traps are used
Sentinel trees	Post-border, containment, generic, specific, active	Allows detection of species for which lures are not available	Labor intensive if numerous trees have to be planted
			Not applicable for insects developing in mature trees
Biosurveillance			
Sniffer dogs	Border, containment, specific, active	Highly sensitive odor recognition	Detection ability not equally efficient for all insects
		Can detect both larvae and adults	Limited work hours per day
		Can detect infestations with no visible symptoms	Long training for difficult situations (e.g., ports)
		Nondestructive	
Predatory wasps	Post-border, containment, generic, active	May detect cryptic species before symptoms are visible	Limited survey time period
		Nondestructive	Limited prey range
E-noses	Border, containment, generic, specific, active	Nondestructive	Sensor calibration and sensitivity constraints
		Can be applied to bulk samples	Training and methods development needed
		Can detect both larvae and adults	
		Can detect infestations with no visible symptoms	
Acoustic detection and laser vibrometry	Border, containment, generic, specific, active	Can detect infestations with no visible symptoms	Requires target insects to be active
		Nondestructive	Requires contact or close proximity with test surface
		Allows repeated measurements	Signal-to-noise ratio constraints
			Energy loss at sensor/substrate interface
Genetic tools			
Barcoding	Border, post-border, containment, generic, specific, active	May allow identification of unknown adults captured in traps	Need equipped laboratory
		May allow identification of immature specimens	Missing reference sequence in public databases
			Errors occurring in public databases
			Do not allow a quick response
Portable platform	Border, post-border, containment, generic, specific, active	Quick response may trigger rapid control measures	Need specific primers
		May allow identification from frass or fecal pellets	Cost
		Easy of use even by non-experts	

Table 1 (continued)

Technique	Biosecurity categories	Main advantages	Main disadvantages
Remote sensing and aerial survey	Post-border, containment, specific, generic, active	Efficient at large spatial scale	Only useful for insects causing evident damage
		May detect infestations before visual symptoms are evident	Time lag in onset of visible symptoms delays detection
Citizen science	Post-border, containment, generic, specific, active, passive	Inexpensive	Less useful for small or cryptic species
		Can exploit Internet and smartphone technology	Requires data validation by experts
		Broad educational benefits	Low data quality if volunteers are not trained a priori
		Generation of real-time reports and maps	

Allison et al. 2016), and type of collection cup (Allison and Redak 2017), can affect trap effectiveness. In addition, using the optimal attractive lure(s) is fundamental. Kairomones are not species specific and thus are mainly used for multiple species or guilds (i.e., *generic surveillance*; e.g., Rabaglia et al. 2008), when pheromones are unknown, or to synergize pheromone attraction (Hanks and Millar 2016; Fang et al. 2018). Pheromones are often species specific (Wyatt 2017) and thus more suitable for *specific surveillance*, although some groups, such as Cerambycidae, use pheromones that are broadly shared among several species, which allows common components to be used for generic surveys (Hanks and Millar 2016; Millar et al. 2018). Furthermore, traps may be baited with a single species attractant or with multiple lures for several species (Schwalbe and Mastro 1988). In the latter case, several pheromones (Brockerhoff et al. 2013) or pheromones and kairomones (Hanks et al. 2012; Rassati et al. 2014; Fan et al. 2018) can be used simultaneously in the same trap to capture a broad range of species. It is also important to consider the attraction range of the lures which can vary greatly depending on the type of lure and target insect (Schlyter 1992; Dodds and Ross 2002; Dunn et al. 2016; Hanula et al. 2016). This information is essential for determining trap position and density. Finally, surveillance may be less effective if trap placement is not optimal in terms of both trapping site and trap position within the site. For example, trapping at ports with large volumes of imports and in nearby broadleaf forests may detect a greater diversity of non-native wood-boring beetles compared with trapping at smaller ports and in nearby conifer forests (Rassati et al. 2015a); similarly, within the same forest, more cerambycid and buprestid species can be captured in forest canopies, while more ambrosia beetles can be captured in the forest understory (Ulyshen and Sheehan 2017; Flaherty et al. 2018; Rassati et al. 2018a).

Baited traps have some limitations (Table 1). For instance, only adult insects are intercepted during flight. In addition, traps are only useful for insects for which lures, either generic or specific, are available. Furthermore, traps must be monitored frequently to prevent loss or degradation of captured insects, which then need to be stored, sorted, and identified, adding costs to trapping programs. New technologies such as incorporation of Internet- or smartphone-linked cameras (Rassati et al. 2016a; Potamitis et al. 2017) and real-time PCR analysis of bulk samples from trap catches (Robideau et al. 2016) may enhance efficiency of trapping programs. In addition, the use of simple, inexpensive traps and involvement of citizen volunteers can expand trapping surveys beyond the temporal and spatial scale currently feasible for regulatory agencies (e.g., Steininger et al. 2015), thus allowing the use of traps also in the context of *passive surveillance*.

Sentinel trees

Biosecurity programs can incorporate the use of sentinel trees, whose definition is quite broad. They can be defined as both locally important tree species planted in the vicinity of high-risk sites (Wylie et al. 2008) and trees that may be treated by girdling, wounding, or with semiochemicals to render them attractive to the target species (i.e., trap trees; McCullough et al. 2009) that are inspected at regular intervals for signs of infestation. This approach is especially useful for *active post-border surveillance* and *containment*. For example, sentinel trees can be exploited to monitor the development of an active invasion of a given species (i.e., *specific surveillance*), as demonstrated for the Asian longhorned beetle (Hérard et al. 2009) or the emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae) (Hughes et al. 2015), especially when artificial traps and lures are not available (Table 1). Nonetheless, these kinds of sentinel trees have limitations. They are almost inapplicable over vast areas, as the high cost and labor required for maintenance of numerous trees would strongly decrease the overall cost-effectiveness of the program (Bashford 2008). Furthermore, they are not practical for some xylophagous insects that develop in large mature trees and they are not applicable for *generic surveillance*. Alternatively, sentinel trees may be defined as tree species present in botanical gardens and arboreta of exporting and importing countries (Britton et al. 2010; Paap et al. 2017) or planted outside their native region that are exposed to pests and diseases of the new region (Roques et al. 2015; Barham 2016). Sentinel trees in the exporting country cannot be considered as a true surveillance tool, as this approach is aimed at *pre-border* risk assessment through identifying those species most likely to become pests prior to possible introduction (Roques et al. 2015). On the other hand, sentinel trees present in botanical gardens located in importing countries may be considered a surveillance tool for *post-border detection.* Botanical gardens can be potentially attractive for non-native species introduced in nearby areas, given that they present a high diversity of tree species, both natives and exotics. For instance, the invasive Polyphagous Shot Hole Borer, *Euwallacea* sp. (Coleoptera: Scolytinae), and its fungal symbiont, *Fusarium euwallaceae*, were first detected in South Africa during routine surveys of tree health in botanical gardens (Paap et al. 2018). Given the importance of such sites, the International Plant Sentinel Network (IPSN) was launched in 2013 (Barham et al. 2016) to coordinate surveys and activities carried out at botanical gardens on a global scale, with the ultimate aim of providing valuable data to plant protection agencies on new potential pests and pathogens. Tree species present in urban areas of importing countries can also be considered sentinel trees (Paap et al. 2017). Urban areas are hubs for international trade (Colunga-Garcia et al. 2010) and thus particularly prone to new insect introductions. Urban trees are often subject to several abiotic stresses that predispose them to insect attacks. Thus, inspection at regular intervals of these trees and sampling plant parts from both asymptomatic (e.g., Ryall et al. 2011) and symptomatic trees (Bullas-Appleton et al. 2014) can strongly increase surveillance capacities. The Canadian Food Inspection Agency, for example, currently uses the practice of collecting and incubating bolts from sick and dying trees in Canada's largest cities considered most at risk of bark- and wood-boring beetles introduction, a strategy that led to the first detection of the longhorn beetle *Trichoferus campestris* in Ontario (Bullas-Appleton et al. 2014).

Biosurveillance: sniffer dogs and predatory wasps

To date, two approaches using the perception ability of other organisms have been investigated for *active surveillance*: the use of dogs and the use of predatory insects. Dogs have an acute sense of smell and are able to detect minute traces of target scent, including some produced by insects (Brooks et al. 2003; Lin et al. 2011; Zahid et al. 2012; Hoyer-Tomiczek et al. 2016). Thus, dogs can be used at points-of-entry for *specific border surveillance*, as demonstrated for the Asian longhorned beetle (Hoyer-Tomiczek et al. 2016), and at sites near active infestations for *containment* of target species, as demonstrated for the red palm weevil *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae; Suma et al. 2014). However, dogs are not equally efficient in detecting all insects (Phoon 2015) and several months are required to train dogs to reliably detect insects in difficult situations, such as those occurring at seaports (Hoyer-Tomiczek et al. 2016). Additionally, dogs have physiological constraints that limit their use to just a few hours a day (Table 1).

For broadscale surveillance, predatory insects may prove more useful than sniffer dogs. The use of predators to survey for cryptic target taxa consists of analyzing the community of prey species found by predators, such as in the nests of the buprestid-hunting wasp *Cerceris fumipennis* (Hymenoptera: Crabronidae), which hunts emerald ash borer and other buprestid species (Rutledge et al. 2011, 2013; Careless et al. 2014). Although this approach is limited by the short period of time during which nest observations can be made (Dube and Chandler 2017), the limited hunting range of wasps (Nalepa et al. 2013), and the diversity of prey (i.e., mainly adult buprestids) (Careless et al. 2014), it remains an interesting tool for *generic post-border surveillance* and *containment* (Table 1), especially when combined with other trapping devices (Nalepa et al. 2015).

Electronic noses

Electronic noses, or E-noses, detect the presence of pests through the perception of odors (Röck et al. 2008). These odors can vary broadly, including volatiles emitted by stressed or damaged trees (volatile organic compounds or VOCs) and pheromones produced by insects (Cellini et al. 2017). E-noses are able to characterize the odor profile of VOCs emitted by a damaged sample and then determine whether it is similar or different from a non-damaged sample (Jansen et al. 2011). These features make the E-nose a suitable tool for several applications in agricultural and forestry sectors (Wilson 2013) as well as for *border surveillance* and *containment* (Table 1). Portable models, for example, can be used for distinguishing between healthy and damaged plants at points-of-entry, nurseries, or infested areas, as demonstrated for the red palm weevil (Rizzolo et al. 2015). In addition, E-noses are able to distinguish insects based on their chemical emissions (Lan et al. 2008; Negri and Bernik 2008; Henderson et al. 2010) and therefore could be used to detect the presence of a given non-native species inside shipping containers. The main advantages of E-noses are that they allow for repeated nondestructive analyses, can be applied to bulk samples, and can detect both adult and larval damage even if symptoms are not visible (Cellini et al. 2017; Table 1). Nonetheless, there are several issues that limit routine adoption of E-noses for biosecurity including occurrence of drift effects over time due to sensor degradation, loss of sensitivity in the presence of high water vapor, and need for considerable development of the methodology prior to application (Harper 2001; Cellini et al. 2017). Further progress might overcome these limitations and lead to development of E-nose models that can be attached to drones to detect insect-produced volatiles or stress-induced host volatiles across a broad spatial scale.

Acoustic detection and laser vibrometry

Thousands of insects communicate using sounds or vibrations (Mankin et al. 2011). Humans began developing applications to detect insects exploiting acoustic signals soon after sound recording became possible, and acoustic systems are now available for many agricultural and stored product insects (Mankin 2012). Acoustic technology may also detect insects feeding inside imported wood products and plants for planting, as well as inside trees without external symptoms around infested areas, providing opportunities for both *border surveillance* and *containment* of cryptic non-native species (Chesmore and Schofield 2010; Juanes 2018; Table 1). Although promising, the use of passive acoustics monitoring has not reached full potential due to limitations in observation technologies, data processing capacity, and acoustics software development. Furthermore, one main limitation of this technology is that acoustic sensors must be mounted on or attached to the target surface which is time-consuming, can damage the host material being tested, and can influence accuracy of measures (Zorović and Čokl 2015; Liu et al. 2017).

Detection instruments that do not require contact with the test surface, such as microphones, have also been developed (Zorović and Čokl 2015). However, there is substantial loss of energy when vibration waves cross from the target substrate to air, resulting in the need for amplification which, in turns, leads to issues with background noise (Mankin et al. 2011). To overcome these limitations, laser vibrometry has recently been tested. A laser Doppler vibrometer (LDV) measures vibrations without contacting the test surface, so that no interference with the substrate is involved, and recordings are carried out directly from the vibrating surface via the laser beam (Zorović and Čokl 2015). The main limitation of laser vibrometry and other acoustic techniques is the requirement that the insects are actively moving or feeding and therefore creating vibrational signals. Nonetheless, interesting applications of the above-described techniques have been developed, i.e., laser vibrometry approaches for detection of Asian longhorned beetle larvae (Zorović and Čokl 2015) and bioacoustic sensors for detection of red palm weevil larvae (Hetzroni et al. 2016).

Genetic tools for species identification

One important requirement of early detection programs is the need for rapid and accurate identification of captured insects. In the case of *generic surveillance*, the first screening is performed morphologically by expert taxonomists. However, problems arise when individuals of unknown species or immature stages are found (Wu et al. 2017). Larval identification, for example, requires very specific expertise and may be impossible due to the lack of identification keys; therefore, rearing adults is necessary to determine species. In such cases, laboratory-based DNA barcoding provides a powerful tool for identification (Armstrong and Ball 2005; Darling and Blum 2007; Hodgetts et al. 2016; Wu et al. 2017), although the lack of matching reference barcodes or the presence of errors in the databases can be limiting (Boykin et al. 2012). In *specific surveillance* programs, identifiers must determine whether the specimen collected is the target species and rapid identification is required because management decisions must be made quickly (Boonham 2014). Several tools are now available for rapid identification (Mumford et al. 2016). Progress on loop-mediated isothermal amplification (LAMP) technology, in particular, has overcome many limitations of PCR-based methods (Tomlinson and Boonham 2008). These two technologies are similar in terms of sensitivity and specificity, but LAMP does not require costly equipment, amplification is carried out at constant temperature, and the process is less sensitive to irrelevant DNA (Tomlinson and Boonham 2008). Furthermore, the availability of battery-powered portable platforms allows inspectors to identify pests and pathogens directly in the field or high-risk sites in about 20 min with little training (Boonham 2014). LAMP-based genetic identification has been shown useful for quickly identifying insects intercepted at airports (Blaser et al. 2018), insects detected in traps (Chinellato et al. 2013), and even for identifying insects from traces (i.e., fecal pellets or frass) found on wood packaging (Ide et al. 2016a, b). The main disadvantages are the costs of portable platforms and the need for primers that are specific to the species of interest and which must be developed a priori.

Remote sensing and hyperspectral imagery

Remote sensing instruments have been investigated as a potential *post-border surveillance* tool. Detection of rapid changes in spectral, structural, and temporal characteristics of vegetation may indicate the presence of non-native species (Asner et al. 2008). For example, Olsson et al. (2012) used satellite imagery to accurately map damage of Norway spruce, *Picea abies*, caused by the invasive Hungarian spruce scale, *Physokermes inopinatus* Danzig and Kozar (Hemiptera: Coccidae), and the associated sooty mold before any damage was detected in the field. Olsson et al. (2016) demonstrated that remotely sensed data can be used for real-time monitoring of insect defoliation. Although useful for large-scale surveys, remote sensing and hyperspectral imagery have some main limitations. They can be applied only to insects that cause obvious damage to their hosts, which is a small percentage of all forest insects introduced worldwide. In addition, spectral changes often do not become apparent until several years after initial infestation and they can be caused by native species or other disturbances, raising false alarms (Rocchini et al. 2015; Senf et al. 2017; Table 1). Rather than a surveillance tool, remote sensing can prove more useful for modeling non-native species distribution and spread (Rocchini et al. 2015; Juanes 2018). For example, Zhang et al. (2014) combined high-spatial-resolution aerial imagery, commercial ground and airborne hyperspectral data, and Google Earth imagery along with current distribution data and spread rates to develop a prediction function for emerald ash borer spread, which was about 63% accurate.

Citizen science

Citizen science is the participation of non-scientists in data collection for scientific investigations and can be particularly useful for *post-border surveillance* and *containment* (Thomas et al. 2017). For example, the highly invasive longhorned beetles *A. glabripennis* and *A. chinensis* (Coleoptera: Cerambycidae) in Europe and North America (Haack et al. 2010), as well as numerous infestations of emerald ash borer in several US states (Simisky 2017), were first found by the general public. Citizen science is relatively inexpensive (Conrad and Hilchey 2011), has wide application (Conrad and Hilchey 2011), has broad educational benefits (Bonney et al. 2009), and can be conducted over large areas (Whitelaw et al. 2003) (Table 1). The main limitation of citizen science is the acquisition of low-quality data, especially when target organisms are identified by untrained people (Froud et al. 2008) (Table 1). Consequently, there is often a need for specimen identifications to be validated by taxonomic experts, especially for small insects (Gardiner et al. 2012). Nonetheless, many regulatory agencies have educational and reporting tools (e.g., hot lines, Web sites, mobile phone applications) that allow citizens to report potential sightings of non-native species. For example, reporting tools for emerald ash borer are available in at least 39 US states and Canada (EAB info 2017). Furthermore, citizen science may become more widely used with the growing availability of smartphone and Internet applications that allow for easier species identification (Graham et al. 2011; Goczał et al. 2017), real-time reporting of the record location (Pimm et al. 2015), and generation of near real-time distribution maps (EDDMapS 2017). One good example of successful citizen science is the Backyard Bark Beetle project, which was initiated to monitor bark and ambrosia beetles, and engages interested citizens who install simple trapping systems in their gardens, collect captured beetles, and send them to the researchers to identify (Steininger et al. 2015).

Integrating available tools into a comprehensive biosecurity surveillance program

The tools and techniques described above are important resources to port inspectors, phytosanitary personnel, and regulatory agencies that can aid biosecurity at regional, national, or even international levels if used in a complementary way. Here, we provide an example of how this could be done, using wood-boring beetles as the target group, Europe as the importing region and China and the USA as primary trade partners (Fig. 1). Regarding the choice of the insect group, we selected wood-boring beetles both because they are known as one of the most successful groups of non-native species worldwide and because they include some of the most important invasive pests in recent decades (Kovacs et al. 2011; Haack 2017). Regarding the choice of the countries, we selected China and the USA as trade partners because they represent, respectively, the first and the second countries in terms of value of goods exported to the EU (Eurostat 2018) and because they represent the source of several non-native wood-boring beetles that are established in the EU (Rassati et al. 2016b). Nonetheless, the described approach can be applied to any other insect group or any other country.

Border surveillance should focus at the sites identified as most at risk of arrival of non-native wood-boring beetles including seaports and nearby forests (Rassati et al. 2015a), wood-waste landfills (Rassati et al. 2015b), airports (Tatem 2009), timber importers (Skarpaas and Økland 2009), tree nurseries (Liebhold et al. 2012; Eschen et al. 2015a), as well as industrial parks and warehouse districts of large urban areas (Colunga-Garcia et al. 2010). At such sites, visual inspections of imports (Saccaggi et al. 2016) and traps baited with either specific or generic lures (Brockerhoff et al. 2006b; Rassati et al. 2015a, b) should represent the first approaches to be exploited, as efficient and cheap (Fig. 1). For quarantine species that are easy to identify and for which specific attractants exist, camera-integrated traps could be used, but only in areas with good security to avoid damage from people (Rassati et al. 2016a). These can then be complemented with sniffer dogs (Hoyer-Tomiczek et al. 2016), portable E-noses, laser vibrometer and bioacoustic

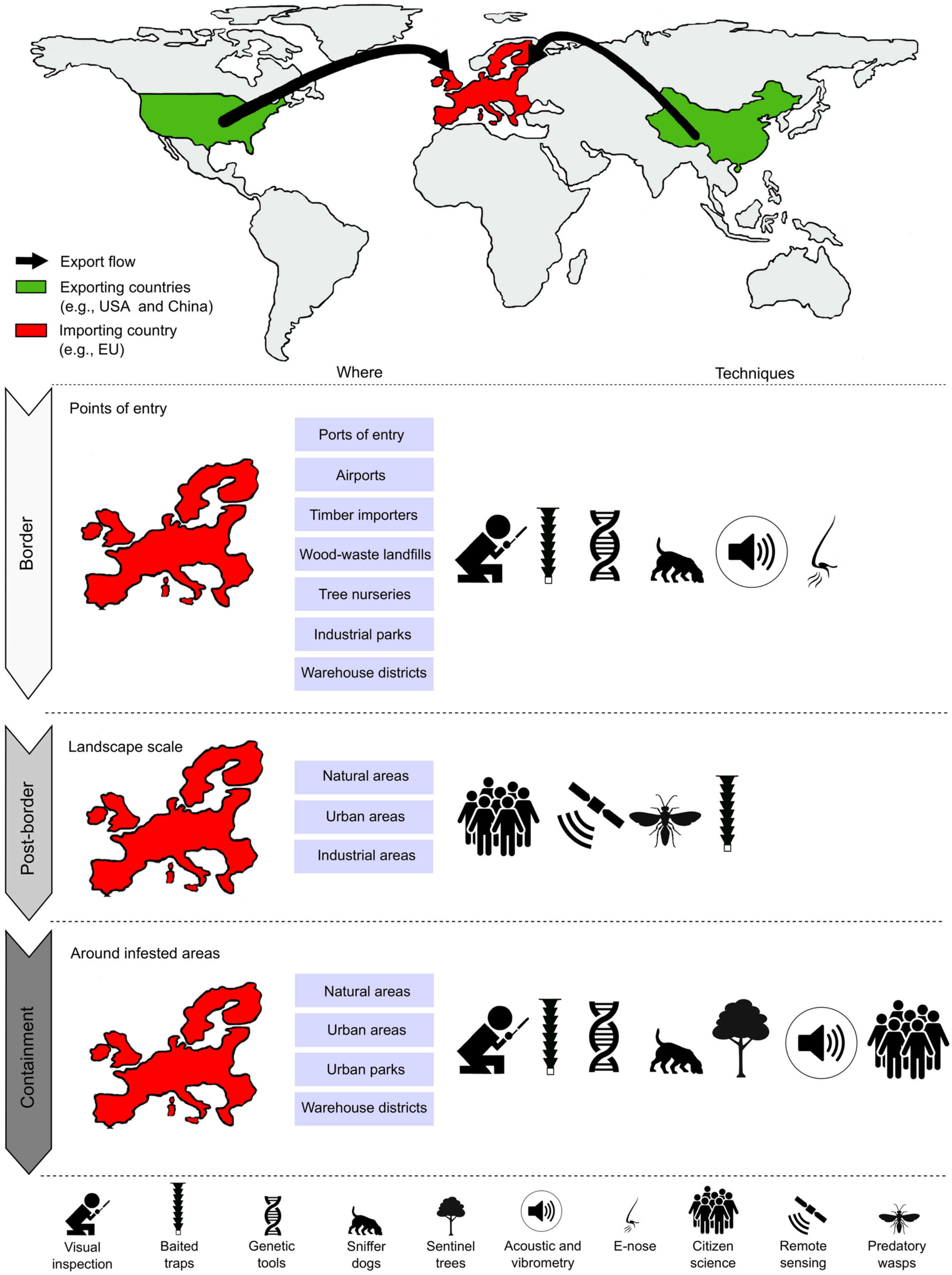

Fig. 1 Example of how to integrate available tools into a comprehensive biosecurity surveillance program. Here, we use wood-boring beetles as the target non-native species group, the European Union as the importing country, and the USA and China as major trade partners. Nonetheless, this approach can be applied to any other insect group or any other country

sensors (Zorovic and Cokl 2015) for detecting insects within imported wood products or plants, and genetic tools, i.e., barcoding and portable LAMP, for identifying unknown insects captured in traps or confirming the presence of target species, respectively (Chinellato et al. 2013; Wu et al. 2017). This integrated approach could allow interception of insects emerging from uninspected wood products or cargo possibly preventing establishment in natural areas surrounding points-of-entry, and detection of quarantine pests triggering rapid responses such as cargo rejection.

Post-border surveillance is aimed at detecting non-native species that were not intercepted at points-of-entry and may have naturally dispersed or been transported to surrounding forests or distant locations, and it is usually carried out at a landscape scale. *Active surveillance* can be conducted using generic traps deployed across the territory (Rabaglia et al. 2008), as well as with remote sensing using aerial surveys and hyperspectral imagery to detect possible non-native species damage (Juanes 2018), and biosurveillance to monitor beetle communities captured by predatory wasps (Nalepa et al. 2015). These activities can be integrated with simple trapping techniques in the context of citizen science programs (e.g., Steininger et al. 2015). *Passive surveillance* through reporting by the general public or industries should be encouraged and enhanced through outreach and educational campaigns as well as online reporting networks.

Containment surveillance activities are implemented surrounding known infestations to delimit the infested area and detect new infestations beyond the current distribution. Determining the leading edge and locating isolated new infestations allows implementation of management tactics to reduce spread and contain the infestation. When a target species is known to occur in a limited area, visual inspections integrated with sampling of potentially infested plant parts on symptomatic (Bullas-Appleton et al. 2014) or asymptomatic trees (Hérard et al. 2009; Ryall et al. 2011), sniffer dogs (Suma et al. 2014), acoustic detection, and laser vibrometry (Zorović and Čokl 2015) can be exploited to detect the presence of immature stages (i.e., larvae) within the trunk or branches and thus identify infested trees. Portable genetic tools can be used for quick on-site identification of the detected specimens. Single-lure traps, if specific lures are available, and sentinel trees (Hérard et al. 2009) can be used to intercept active beetles. Finally, the general public (i.e., citizen science) can be engaged to report trees showing signs of infestation.

Concluding remarks and further steps

In addition to the methods described above, many additional steps should be undertaken to further improve biosecurity programs worldwide. A key step is harmonization of regulations (Eschen et al. 2015b; Allen et al. 2017) and inspection efforts (Eyre et al. 2018), as both vary considerably among countries. It is also necessary to deploy existing tools and resources more effectively (Ormsby and Brenton-Rule 2017). Cost-effective surveillance strategies are needed for efficient responses to biological invasions and must account for the trade-offs between surveillance effort and management costs. Mechanistic models are being developed to determine optimal deployment of surveillance, assuming that the probability of detecting a population depends on population size, surveillance effort, and sample sensitivity (Epanchin-Niell et al. 2012, 2014). For instance, greater surveillance effort is warranted for non-native species that have higher establishment rates, cause higher damages, that are more costly to eradicate, or for which sampling is less costly. Prompt sharing of interception and new establishment data among countries will also facilitate global surveillance efforts (Simpson et al. 2009). In this regard, more attention should be given to native species found at domestic ports or nearby forests, as this information could alert inspectors in other countries as to which species could arrive with that country's exports (Rassati et al. 2018b). Efforts should focus not only on insects, but also on microorganisms they can vector, which can be done exploiting genetic tools similar to those available for insects (Okabe et al. 2017; Malacrinò et al. 2017). More attention should also be given to the social perceptions of insect invasions and related biosecurity strategies, as prompt and accurate communication of these issues can have several implications at different management levels and affect both policy and stakeholders (Marzano et al. 2017).

Author contributions

TMP and DR contributed equally to reviewing the literature and writing the manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights This article does not contain any studies with human participants or animals performed by any of the authors.

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