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Citizen science can enhance strategies to detect and manage invasive forest pests and pathogens

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Incorporating a citizen science approach into biological invasion management strategies can enhance biosecurity. Many citizen science projects exist to strengthen the management of forest pest and pathogen invasions within both pre- and post-border scenarios. Besides the value of citizen science initiatives for early detection and monitoring, they also contribute widely to raising awareness, informing decisions about eradication and containment efforts to minimize pest and pathogen spread, and even finding resistant plant material for restoration of landscapes degraded by disease. Overall, many projects actively engage citizens in the different stages of forest pest and pathogen invasions, but it is unclear how they work together across all stages of the entire biological invasion process to enhance biosecurity. Here we provide examples of citizen science projects for each stage of the biological invasion process, discuss options for developing a citizen science program to enhance biosecurity, and suggest approaches for integrating citizen science into biosecurity measures to help safeguard forest resources in the future.

KEYWORDS

citizen science, invasive species, forest health, biosecurity, public engagement

1. Introduction

Forest ecosystems are threatened by the anthropogenic dispersal of tree pests and pathogens, climate change and the synergies between parasites and novel environments. For example, the introduction and spread of forest pathogens such as *Cryphonectria parasitica* (causing chestnut blight) and *Hymenoscyphus fraxineus* (causing ash dieback) and insects such as *Agrilus planipennis* (emerald ash borer) and *Anoplophora glabripennis* (Asian longhorned beetle) have devastated tree populations in forests and urban areas worldwide (Haack et al., 2010; Herms and McCullough, 2014; Prospero and Cleary, 2017; Rigling and Prospero, 2018) and in some cases caused irreversible ecological impacts (Loo, 2008; Flower et al., 2013; Mitchell et al., 2014; Klooster et al., 2018; Hultberg et al., 2020). Although these organisms, and indeed more generally forest pests and pathogens, are highly diverse, the management strategies for these biological invasions have generally followed the same pattern.

The options for managing forest pest and pathogen invasions can be categorized into opportunities of pre-border and post-border mitigation (Cunniffe et al., 2016; Epanchin-Niell, 2017; Tovar et al., 2017; Nahrung et al., 2023). Before an non-native species is introduced to a new area (pre-border), preventative measures can be informed by horizon scanning, pathway action planning and risk assessments (Brasier, 2008b; Roy H. E. et al., 2014), coupled with implementation of surveillance and monitoring, including the establishment of sentinel plantings for early warning and rapid detection (Vettraino et al., 2015; Eschen et al., 2019; Morales-Rodríguez et al., 2019). Additionally, pathway action planning can underpin trade restrictions (Leung et al., 2002; Hulme, 2009; Roy B. A. et al., 2014) and pathway regulations (e.g., ISPM-15 or ISPM-36) (Haack et al., 2014). However, once the non-native species has been introduced (post-border), options to minimize the impact include implementing measures for detection, and assessing the feasibility to eradicate founding populations, contain the spread, and ultimately restoration (Pyšek and Richardson, 2010; Hulbert et al., 2017; Carnegie and Nahrung, 2019). Inherently, the efficiency of these post-border approaches and the feasibility of reducing the impacts are largely dependent on early detection and rapid response (Lodge et al., 2006; Westbrooks et al., 2014; Liebhold et al., 2016). Therefore, preventative strategies, that is pre-border approaches, are considered to give the best return on investment when considering the costs in terms of damage and control efforts following incursion (Leung et al., 2002; Hansen, 2008). However, despite increased awareness of the benefits of preventative strategies as opposed to post-border management, the number and extent of forest pest and pathogen incursions continue to increase (Seebens et al., 2017).

Recent examples of the emergence and continued spread of plant pathogens such as *Austropuccinia psidii* (myrtle rust) in Australia and New Zealand, *Phytophthora ramorum* (ramorum blight and sudden oak death) in the United Kingdom and USA, or the insect pest *Euwallacea fornicatus* (polyphagous shot hole borer) in South Africa, California, and Israel demonstrate the need to consider the gaps in protecting forests in current biosecurity frameworks (Brasier, 2008a; Carnegie and Pegg, 2018; Paap et al., 2018, 2020). For example, pre-border options to prevent plant pathogen invasions or conduct horizon scanning and risk assessments are challenged by the vast number of unknown species, potential for host shifts (Desprez-Loustau et al., 2007; Burgess et al., 2016; Burgess and Wingfield, 2016; Roy et al., 2017), complexities in genetic diversity and the possible exchange of genetic material within or between species (McTaggart et al., 2016; Wingfield et al., 2017), including interspecific hybridization (Brasier, 2001; Stukenbrock, 2016). Roy et al. (2017) noted this pronounced unpredictability of pathogen invasions as the greatest challenge to managing their threat. In addition, the quantities of live plants in trade is beyond the capacity to monitor and inspect at the border (Liebhold et al., 2012; Nahrung et al., 2023) and the global online market has increased the number of sources to monitor (Humair et al., 2015). Moreover, lack of stakeholder awareness about the risks and threats of invasive non-native pathogens is also low (Marzano et al., 2015, 2016) and in some cases pathogens may fall through regulatory frameworks, barring coordinated action (Roy et al., 2017). Furthermore, incursions of non-native species affecting trees in forests and urban environments have increased exponentially in recent years (Santini et al., 2013; Roques et al., 2016) and non-native species accumulation worldwide is continuing to increase and predicted to continue to do so (Seebens et al., 2017). These challenges suggest current biosecurity capacities are insufficient to deal with this growing global problem and additional methods and initiatives are needed to enhance capacity in managing invasive non-native species throughout all stages of the biological invasion process.

Although the options and challenges with managing biological invasions are thoroughly considered in many of the original and revised biological invasion frameworks (e.g., Blackburn et al., 2011; Wingfield et al., 2017; Bonello et al., 2020), the potential for public participation has not been incorporated. Recognition of public engagement, especially citizen science, as an effective tool for biosurveillance and monitoring is growing (Poland and Rassati, 2018; Johnson et al., 2020; Encarnação et al., 2021), and its inclusion in biosurveillance and biological invasion management strategies has been suggested as an important area for further research (Caley et al., 2020; van Rees et al., 2022). Here we consider the value citizen science projects, generally defined as projects with public participation in knowledge production (Fraisl et al., 2022), could add within the context of invasive non-native pest and pathogen management strategies.

Citizen science programs can enhance biosecurity, especially in post-border situations where the early detection of a new incursion is critical to enable any chance at successful eradication where the founding population is localized. The value of directly engaging volunteers or incorporating passive data (e.g., iNaturalist observations) in surveillance of plant pests has been widely demonstrated. In Australia, personnel working on Barrow Island voluntarily detected eighteen non-native invertebrate species new to the island over 5 years (Thomas et al., 2017) and hundreds of Acute Oak Decline observations have been recorded by citizen scientists in the United Kingdom (Baker et al., 2018). Brown et al. (2017) demonstrated the value of incorporating citizen scientist observations into a statutory monitoring program for Acute Oak Decline by using citizen reports to delineate and focus monitoring on the boundaries of the affected areas. Similarly, Meentemeyer et al. (2015) used samples collected by citizens to predict hotspots of disease incidence of *Phytophthora ramorum* to inform stakeholders about areas to focus detection and management efforts. Together these examples demonstrate how incorporating broader participation in biosecurity frameworks can add to the capacity and efficiency of monitoring and management of invasive non-native pests and pathogens.

Many citizen science projects exist within the field of forest health. For example, twenty-nine projects are listed on the Forest Health Citizen Science community webpage (**Supplementary Table 1**; Hulbert et al., 2019a). The projects cover the entire spectrum of biological invasion stages, with most engaging participants in monitoring approaches, although some contribute to pre-border strategies, containment strategies or protection and restoration of threatened species. The objectives of this manuscript are therefore to review examples of active programs within the context of biological invasions by forest pests and pathogens and provide recommendations for integrating citizen science projects to enhance forest biosecurity.

2. Citizen science applications in the forest pest invasion detection and management process

2.1. Pre-border scenarios

Citizen science programs can enhance pre-border biosecurity initiatives by raising awareness of biosecurity approaches and concerns amongst diverse stakeholders while engaging citizen scientists to recognize the symptoms and signs of invasive non-native species prior to their arrival, collect baseline data, or monitor sentinel plantings. Below we highlight approaches and provide examples of programs that engage the public with these pre-border objectives.

2.1.1. Raising awareness

Many invasive non-native pest and pathogens are introduced unintentionally *via* pathways driven by consumers such as the trade of ornamental plants for planting (Brasier, 2008b; Liebhold et al., 2012). However, many of the stakeholders involved in the "plants-for-planting" pathway are generally unaware of the risk and their possible roles in the introduction and spread of these organisms (Marzano et al., 2015). Therefore, methods that raise awareness of the risks associated with the trade of living plants, for example, could be effective at preventing the introduction of invasive non-native species.

Citizen science programs can increase participant knowledge and awareness. For example, reviews of citizen science projects active in biodiversity and environmental monitoring reported knowledge gain and increased community awareness as main participant learning outcomes (Stepenuck and Green, 2015; Peter et al., 2019; Gardiner and Roy, 2022). However, studies about the learning outcomes of participating, in terms of knowledge or behavior change, in citizen science projects aimed at monitoring invasive non-native species are limited and generally inconclusive (Crall et al., 2013; Bela et al., 2016), although it is assumed that participation increases awareness (Gallo and Waitt, 2011; Bates et al., 2015). Incorporating mechanisms for participant feedback and evaluation within more citizen science initiatives can help inform future citizen science initiatives.

Raising public awareness can increase support for invasive non-native species management (Klapwijk et al., 2016; Novoa et al., 2017) and citizen science can complement these programs (Pocock et al., 2020). For example, resources from dontmovefirewood.org are routinely referenced during training activities in the Forest Health Watch[1] citizen science program, and these resources have increased awareness of firewood as the pathway of invasive non-native species (Solano et al., 2020). Indeed, increasing awareness of the signs and symptoms of biological ivnasions before they arrive can be an effective method to promote early detections. For example, members of the public were responsible for locating and sharing observations and signs of *Anoplophora glabripennis* (Asian longhorned beetle) infestations in multiple locations of North America (Meng et al., 2015). Therefore, projects that incorporate resources from other awareness campaigns or highlight general signs or symptoms can be an effective pre-border strategy promote the early detection of biological invasions.

2.1.2. Promoting effective horizon scanning

Citizen science programs can also contribute to enhanced biosecurity in pre-border situations by providing relevant information on biological invasion history of pests and pathogens that can be used within horizon scanning or risk assessments. For example, Hulbert et al. (2019b) engaged staff in Cape Citizen Science to detect and sample plant pathogens affecting exotic and native plants in botanical gardens. These surveys identified novel plant-microbe interactions and detected pathogen species outside of their previously known distributions. Botanical gardens and arboreta are hubs of non-native plant species that provide a unique opportunity to integrate citizen science (Martellos et al., 2016) with initiatives aimed at monitoring sentinel trees such as the International Plant Sentinel Network (Barham et al., 2016). Planting non-native species can serve as a source entry point for non-native pests or pathogens (Kirichenko and Kenis, 2016; Eschen et al., 2019). For example, the quarantine pathogen *Lecanosticta acicola* which causes brown spot needle blight was recently detected on exotic *Pinus mugo* planted at an arboreta in southern Sweden and represents a new risk for commercially important Scots pine (Cleary et al., 2019). Therefore, conducting citizen science to monitor tree species planted outside of their native range can generate information pertinent for horizon scanning and risk assessment.

Urban forests and urban green spaces also provide important opportunities for collecting data useful to horizon scanning (Paap et al., 2017) and there are many citizen science initiatives and tools that have been designed to monitor street trees (Hawthorne et al., 2015; Roman et al., 2017). For example, the Healthy Trees Healthy Cities program was initiated to engage citizen scientists to establish and monitor urban trees (TNC, 2020). Urban forests are also recognized as places to connect people to nature (Gulsrud et al., 2018) and programs such as the Urban Forest Visual program in Melbourne (City of Melbourne, 2017) have generated and engaged citizens in extensive datasets of urban forest health with novel forms of engagement such as giving individual trees email addresses. The extensive potential to incorporate public engagement and surveillance of tree health in urban settings is widely recognized (Meentemeyer et al., 2015; Hulbert et al., 2017; Hallet and Hallett, 2018).

2.1.3. Advancing baseline species inventory and distribution data

Citizen science programs can also contribute important baseline data on the distribution, and host range, of invasive non-native pests and diseases. For example, the discovery and subsequent description of two *Phytophthora* species was possible because of the Cape Citizen Science program (Bose et al., 2021). Such information is critical for local post-border management, but also for informing pre-border biosecurity within uninvaded regions. The general requirement within current regulatory frameworks for a non-native species to have been previously identified based on taxonomic information can be a major pitfall because only a small proportion of microbes have been found or adequately described (McTaggart et al., 2016; Roy et al., 2017). Therefore, projects that aim to explore the distribution and diversity of pests or pathogens, such as the *Phytophthora* Citizen Science project in Sweden, Cape Citizen Science in South Africa[2] or the Backyard Bark Beetles program in the USA,[3] are important because of the potential to discover and describe novel species. Taken together, there are many citizen science projects generating data about potential forest pests and pathogen species that could emerge as major threats within different environments or hosts. Sharing data rapidly, openly and widely (e.g., Findability, Accessibility, Interoperability, and Reusability (FAIR) Principles;

1 https://foresthealth.org/

2 https://citsci.co.za/

3 https://www.citizenscience.gov/catalog/397/

Wilkinson et al., 2016) is critical to maximize the benefits of such information.

Programs that provide baseline distribution data, host susceptibility, and environmental/climate suitability with respect to imported commodities and potential diseases are critical for understanding the potential risks associated with imports (Hulme, 2009; Webber, 2010). For example, once an invasive non-native species is known to occur in an exporting country, the importing country can include it in risk assessments or specifically screen imported material for the organism during inspections. However, distribution data is often limited because the origins for most pathogens are unknown (Stukenbrock and McDonald, 2008) and the increasing connectivity of previously separated biogeographical areas and phenomena such as "the bridgehead effect" (Lombaert et al., 2010) are increasing the spread of forest pests and pathogens (Hulme, 2009; Wingfield et al., 2015; Hulbert et al., 2017; Prospero and Cleary, 2017). Indeed, efforts to improve understanding of the distribution of potential threats are critical because invasion risk is strongly linked with the distribution of non-native species within a country's trade network (Chapman et al., 2017). Thus, citizen science programs that increase information about the distribution of potential pests and pathogens provide important data that can enhance pre-border biosecurity measures in other parts of the world.

Datasets derived from citizen science platforms like iNaturalist can also contribute to the passive surveillance for invasive non-native species. For example, citizen scientists may add observations of *Thaumetopoea processionea* (oak processionary moth) out of curiosity or simply to document the biodiversity. This passive surveillance can lead to the first detection of an invasive non-native pest in a new area (Brown et al., 2020) and provides a potential long-term and widescale dataset at a relatively low cost (Pocock, 2013). These datasets can also be actively monitored for priority pests.[4] However, these occurrence datasets are usually derived from opportunistic data collection which can result in ambiguity of whether the organism is truly absent from an area without recorded presence data (Pocock et al., 2017). These challenges can be overcome through active recruitment and training of citizen scientists for structured monitoring that records failure to detect the target organism (Cooper et al., 2012), but this design depends on the resources and objectives of the project.

2.1.4. First detector training

Immense value can be realized in training citizen scientists to recognize specific symptoms and signs of damaging agents on trees to effectively inform and implement control measures. For example, several "first detector" programs include training *via* the National Plant Diagnostic Workshop[5] or state and country specific programs such as the Oregon Forest Pest Detector training[6] or Observatree[7] in the United Kingdom. These projects raise awareness by offering training sessions, materials, and online courses to first detectors.

4 https://www.inaturalist.org/projects/usda-aphis-priority-forest-pests
5 https://firstdetector.org
6 https://extension.oregonstate.edu/ofpd/
7 https://www.observatree.org.uk

2.2. Post-border scenarios

Citizen science programs can add capacity to post-border strategies by promoting early detection and rapid response to biological invasions, helping to eradicate founding populations or contain the spread, and assisting with efforts aimed at long-term management and possible restoration of impacted areas. Below we highlight programs that exist within each stage of the biological invasion process following introduction of an invasive forest pest or pathogen.

2.2.1. Increased capacity for early detection

Human activities drive biological invasions (Santini et al., 2018), and consequently involving citizens in surveillance efforts increases the chance of detecting an outbreak or epidemic sufficiently early to ensure effective response. Detecting a new incursion shortly after introduction is critical to limiting subsequent impacts because eradication and containment have higher levels of success for biological invasions which are locally established (Liebhold et al., 2016; Hansen et al., 2019; de Groot, 2020). In many cases, biological invasions are first detected by landowners or homeowners making initial reports to local officials that are then amplified. For example, sudden oak death was first detected by a California homeowner and then amplified by an extension specialist (Garbelotto et al., 2001; Hulbert et al., 2017). Training citizens as first detectors can be key to making early detections for responding rapidly and reducing the impacts of biological invasions.

There are many examples of programs actively engaging the public in surveillance in addition to the first detector programs mentioned previously. Observatree (see text footnote 7) trains volunteers to monitor for priority pests and diseases in the United Kingdom. The UK also has a Tree-Alert system[8] for untrained volunteers to report concerns or sightings of pests and diseases. Similarly, New Zealand has developed the Find-A-Pest[9] program and the USA has an initiative called Forest Health Watch (see text footnote 1). Collectively, these projects emphasize the possibility to raise awareness and empower citizens as first detectors.

Citizen science programs are also known to increase the number of observations and their distributions at relatively low costs (Bonney et al., 2009) while also increasing information from private lands (Meentemeyer et al., 2015) because of the inclusion of volunteers. Citizen participation in many of the forest health focused programs led to many first reports or findings. For example, a citizen scientist in the Observatree program found the second site for the oriental chestnut gall wasp outbreak in the UK (Observatree, 2015; Brown et al., 2020), quickly stimulating the response of officials. Similarly, the first report of *Phytophthora ramorum* from a county connecting the epidemics in California and Oregon was made during a Sudden Oak Death (SOD) Blitz (COMTF, 2019). The SOD Blitz program is a long-standing citizen science program to monitor the spread of *P. ramorum* throughout the state of California (Garbelotto et al., 2014). Results of the initiative have also contributed to the understanding of the epidemiology of the pathogen (Meentemeyer et al., 2015; Lione et al., 2017). In the Cape Citizen Science program in South Africa, nine *Phytophthora* species were recovered

8 https://forestresearch.gov.uk/tools-and-resources/tree-alert/
9 http://www.findapest.nz/

for the first time that would not have been possible without citizen participation (Hulbert, 2020). Together, these examples demonstrate the merit of engaging the public in detection efforts and the value of having "many eyes" in nature to enhance biosecurity in the post-border stages of an biological invasion framework.

2.2.2. Eradication

Citizen science programs can increase the chances of successful eradication through early detection and possibly, through direct action to remove invasive non-native pests or pathogens. Early detection of a pest or pathogen from citizen scientists can on occasion directly enable successful eradication in local environments. The report of the oriental chestnut gall wasp by a trained Observatree participant led to rapid intervention measures to eradicate the pest around St. Albans, UK (Brown et al., 2020). Eradication of forest pests and pathogens before they spread is often difficult because of the long lag phase between when the introduction occurred and the first detection, but citizen science programs can increase capacity of early warning systems and reduce the lag phase (Crow and de Groot, 2020). In another example from the Sudden Oak Death (SOD) Blitz program, local citizens took it upon themselves to remove trees in their community confirmed infected with *P. ramorum* (Pers. Comm. Garbelotto, 2017). Together these examples demonstrate that citizen scientists can increase the success of rapid responses and be empowered to act to reduce the spread of invasive non-native pests and pathogens.

2.2.3. Containment

Citizen science programs can also benefit management strategies focused on containment rather than eradication or detection. For example, the SOD Blitz program has provided accurate and up-to-date information about the distribution and epidemiology of *P. ramorum* in California to be able to predict hotspots of disease emergence (Meentemeyer et al., 2015) and detect relationships between climatic data and the epidemiology of the pathogen (Lione et al., 2017). This information is invaluable for prioritizing targeted areas for intervention and for adaptive management under anticipated changes to the climate. Similarly, Oregon has also adopted a strategy to involve citizens in monitoring for sudden oak death (Kline et al., 2019). The program involves citizens in sampling streams with bait leaves, a method used for early detection of infestations in entire watersheds (Sutton et al., 2009), and provides valuable data for their active containment and site-based eradication strategies (Hansen et al., 2019).

Citizen science has also been used in conjunction with statutory surveys to map the distribution of disease epidemics. Brown et al. (2017) evaluated the value of incorporating pre-existing citizen reports (e.g., TreeAlert) to increase the efficiency of statutory surveys of acute oak decline in England; the study indicated that incorporating citizen reports maximized the use of available resources to focus on defining boundaries of the affected area. Crow and de Groot (2020) also highlight how Observatree and LIFE ARTEMIS have been integrated in official monitoring systems in the UK and Slovenia, respectively. Therefore, citizen observations can provide important distribution information that can be further used to amplify ongoing regulatory surveys to determine boundaries of biological invasions. These data can then be used to inform interventions in areas near the boundaries similarly to the strategy used to manage the sudden oak death epidemic in Oregon (Hansen et al., 2019).

A final example of a citizen science project actively engaging citizens in the containment stage of a forest epidemic is the Kauri Rescue Program in New Zealand.[10] The program invites citizens to test treatments of varying phosphite stem-injection doses to reduce the impacts of a root disease caused by *Phytophthora agathidicida* on the culturally important kauri (*Agathis australis*) tree (Bradshaw et al., 2020). As of 2019, about seventy citizens had treated more than a thousand trees using treatment kits provided by the program and many were on private lands (Kauri Rescue, 2019). This program therefore demonstrates the possible engagement of citizens in strategies to reduce impacts and contain the expansion of forest disease epidemics.

2.2.4. Documenting impacts

Citizen scientists can also play a role in documenting the spread and impacts of invasive non-native species and contributing to understanding of biological invasions or measuring the success of management approaches. Indeed, forest pests or pathogens provide an opportunity to convey the ecological complexity of biological invasions and specifically the importance of documenting interactions amongst species to contribute to assessment of impacts on biodiversity and ecosystems (Groom et al., 2021).

2.2.5. Restoration

Options to restore ecosystems back to a resilient state after an invasive non-native forest pest or pathogen has been contained or eradicated are limited. Re-planting non-host species is often a strategy used in urban environments (Liu, 2018), but efforts to breed resistant varieties may be the best solution to restore natural ecosystems (Sniezko, 2006). However, the availability of genetic material with potential for resistance and suitable for breeding can be difficult to find.

Citizen science can aid restoration efforts with increased numbers of people searching for naturally resistant material and providing a low-cost means to maximize search efforts (Ingwell and Preisser, 2011). The Save the Ash Citizen Science program[11] in Sweden aimed to encourage citizens to help locate rare "vital" ash trees within landscapes devastated by ash dieback. European ash populations have been significantly reduced following the introduction of the non-native fungus *Hymenoscyphus fraxineus*, and in Sweden the tree species is endangered (Hultberg et al., 2020), though a small proportion of the natural population shows high resistance to the disease (Cleary et al., 2017; Liziniewicz et al., 2022). Citizen participation was ideal for identifying resistant phenotypes for breeding because ash in Sweden is found at very low proportions within forests (<1% of the forest inventory stock), usually mixed with other temperate broadleaved tree species, and is sparsely distributed across the country (Cleary et al., 2017). Widespread publicizing of the project in media (radio, TV, newspapers, nature/forestry magazines, social media, and the website) and instruction on specific criteria for identifying healthy trees, generated hundreds of responses from the public and informed subsequent surveys. Consequently, more than 900 ash genotypes are now included in the resistant inventory

10 www.kaurirescue.org.nz/

11 https://raddaasken.nu/

database and currently undergoing screening by established field trials to identify tolerant or resistant ash populations suitable for restoration. The initiative provided a low-cost means of maximizing search efforts across wide geographic areas, raised awareness of the concern regarding the loss of this important keystone species and risk to other associated biodiversity, and has even resulted in wider spreading of awareness regarding ex-situ conservation of ash by the citizens themselves, through online blogs which they themselves manage.

Similar citizen science approaches are underway with a number of tree species in the United States using a mobile application called TreeSnap.[12] The application was created for citizen scientists to contribute to research by locating seemingly resistant trees (Crocker et al., 2019). The application invites citizens to contribute observations of nine focal tree species, including tanoak, one of the species critically threatened by *Phytophthora ramorum* (Cobb et al., 2012). The application has received more than 2500 observations from at least 1600 users (Crocker et al., 2019), demonstrating the value that citizens can contribute to research and improvements for restoration through breeding with naturally resistant genotypes.

2.3. Summary

Forests are under threat globally because of introductions of invasive non-native pests and diseases and changes in climate (Ramsfield et al., 2016). Invasive non-native forest pests and pathogens continue to emerge and challenge biosecurity because of the complexity of their biology (McTaggart et al., 2016; Wingfield et al., 2017), the overwhelming amount of plant material traded (Liebhold et al., 2012), insufficient awareness (Marzano et al., 2015), and gaps within regulations and coordination (Roy et al., 2017). The historical and continued accumulation of forest pests and pathogens demonstrates the need for new approaches to reduce the impacts. The examples presented here demonstrate the merits of citizen science to add capacity for biosecurity and management through each stage of the biological invasion process.

Many projects are actively engaging citizen scientists to reduce the effects of both insect pests and pathogens. Some programs provide value in the context of pre-border scenarios, but the citizen science approach is more broadly applied in post-border scenarios (i.e., after an invasion has been detected). While we discussed projects in the context of either pre-border or post-border stages of invasions, many projects contribute to both scenarios. For example, all of citizen science projects discussed above likely increase the awareness of the threats and consequences of non-native forest pest and pathogen invasions. Therefore, while each citizen science initiative may have substantial merit for adding capacity at a certain stage in the biological invasion process (e.g., monitoring an ongoing biological invasion), the programs also have far-reaching impacts, allowing for capacity building in society, fostered learning, networking among public stakeholders, and exchange of information between the public and the scientific community. Furthermore, while a program may exist within a single stage of the biological invasion process, it may be beneficial to include another project within the program focused on another stage. For example, programs that are monitoring the spread of a forest disease could simultaneously launch a project to survey stands for evidence of genetic resistance within the infestation area.

In summary, there are many citizen science programs adding to the capacity of management strategies across all stages of biological invasions. These programs enhance biosecurity by raising awareness, generating important data for horizon scanning, advancing knowledge about the distribution and diversity of potential threats, and adding capacity for containment and restoration.

3. Precautions for future projects

Data quality is widely scrutinized in citizen science projects (Dickinson et al., 2010; Crall et al., 2011; Welvaert and Caley, 2016; Roman et al., 2017; Baker et al., 2018; Hallet and Hallett, 2018) and methods to validate findings are critical in biosecurity research. For example, a false-positive result for the internationally regulated and nationally quarantined pathogen, *Phytophthora ramorum*, could have substantial effects on the local economy through consequential trade restrictions. In this sense, a false positive could reduce trust in citizen science as a tool for biosecurity related to quarantined organisms (Pers. Comm. Garbelotto, 2019). However, projects can alleviate this risk by working closely with regulating agencies to verify findings. For example, the SOD Blitz program has overcome this risk through close collaboration with state and federal agencies and developed protocols for validating early warning information from citizen scientists. These relationships are critical and demonstrate the need for support from regulating agencies to incorporate citizen science in biosurveillance systems as has been done in the UK and Slovenia (Crow and de Groot, 2020). On the other hand, avoiding false-negatives may also be difficult and negatives in general are ambiguous because it may not necessarily represent the absence of a species (Cooper et al., 2012; Pocock et al., 2017).

Evaluating the programs discussed herein more closely can also provide insight for overcoming data quality challenges. For example, some of the projects (e.g., TreeAlert) incorporate professionals in the validation methods and Brown et al. (2017) recommend re-visiting sites for validation. Such validation is especially critical for the efficiency of projects that rely on citizens to share observations rather than collections. For example, all citizen-fed tips for the location of vital ash trees in Sweden are followed up with field surveys to verify the criteria and quality traits needed for selecting genotypes for clonal propagation and testing. However, some tools such as iNaturalist incorporate confirmations from the wider community as a form of validation (Nugent, 2018). Mass participation and collection-based projects such as the SOD Blitz program may be less prone to data quality issues because the collections are evaluated within a central lab. However, the program also relies on validation of positive samples from new locations through coordination with state and federal officials because of the focus on a quarantine organism. Other attempts to increase data quality might include qualifying the relative capability of the citizen scientist by asking about their background (e.g., Meentemeyer et al., 2015), limiting participation to artisans or professionals, or incorporating an assessment of recorder effort (Pocock et al., 2017). Alternatively, many of the programs, especially the "first detector" programs, provide substantial training and resources to participants. Offering training to citizens and

12 https://treesnap.org/

Pre-border			Post-border			
Raising Awareness	**Horizon Scanning**	**First Detector Training**	**Early Detection**	**Eradication**	**Containment**	**Restoration**
Citizen scientists become more aware of the process and consequences of biological invasions	Citizen scientists collect baseline valuable data (distributions or discovery of novel species) for horizon scanning in other parts of the world.	Citizen scientists are empowered to recognize signs and symptoms of priority forest pests and pathogens and learn how to make reports	Citizen scientists share observations of pests or pathogens after introductions.	Citizen scientists report detections leading to interventions from officials Citizen scientists actively remove infected trees from their communities	Citizen scientists share observations to provide realtime distribution data. Citizen scientist observations are used to predict hotspots of pest and disease emergence Citizen scientist observations are used to refine statutory monitoring efforts Citizen scientists test treatment options.	Citizen scientists find resistant or 'lingering' trees in invaded populations.

FIGURE 1
Summary of the fit of the citizen science approach before and after the start of a biological invasion.

providing targeted areas for sampling that are randomized can also overcome some of the challenges to data quality (Gardiner et al., 2012; Meentemeyer et al., 2015; Hulbert et al., 2019c). It is also critical that volunteers have sufficient understanding to ensure appropriate responses (Pocock et al., 2014); there is a risk of unintended consequences if volunteers do not adhere to best practice in managing biological invasions, including the potential to increase the rate of spread of some non-native species if on-site biosecurity protocols are inadequate. For example, training for boot and equipment washing may be an important management practice for citizens actively searching for *Phytophthora ramorum* or other plant pathogens that can be spread *via* infested soil or water.

Citizen science approaches may not work equally well for all forest pest and pathogens. For example, Caley et al. (2020) noted citizen reporting probabilities was highly dependent on the morphological characteristics of insects, suggesting citizen science initiatives were less likely to be valuable for small or uncharismatic insects. In this case, effective public engagement may require innovative methods of collection such as the DIY traps used in the Barkyard Bark Beetles program (Steininger et al., 2015). Furthermore, while there are abundance of projects focused on microscopic organisms that cause disease, particularly for *Phytophthora*, for which there are at least seven projects (Hulbert et al., 2019a), the value or number of citizen contributions may depend on the invasion stage of the taxa. For example, participation is likely to be higher to accommodate research surrounding the active invasion of *Phytophthora ramorum*, compared to the general *Phytophthora* biodiversity projects led in South Africa and Sweden. In summary, while citizen science has merit to enhance biosecurity throughout the invasion framework, not every forest pest or pathogen invasion may be appropriate for citizen science.

4. Recommendations

This review provides the first attempt to categorize citizen science projects within the biosecurity strategy for invasive non-native forest pests and pathogens. Citizen scientists can add capacity in each stage of managing biological invasions (**Figure 1**). Understanding how citizens contribute in each project can inform the development of future projects. For example, there is considerable potential to increase the role of citizen science in the monitoring of sentinel plantings and field guides have already been designed to aid the efforts in classifying potential damaging agents on woody sentinels (Roques et al., 2017). One idea could be to adapt methods from the Mildew Mania project (e.g., Rennie, 2015) to provide citizens with exotic species that are locally propagated as "baits" for potential pests to inform horizon scanning in other countries. Such an initiative would also provide opportunities for parallel projects and foster global collaboration and coordination because many forest pests and pathogens have global impacts (Ramsfield et al., 2016).

Engaging citizens and designing citizen science projects to fit within biosecurity strategies is not mutually exclusive and unlikely to detract from other efforts of surveillance or control. In this review, we highlight many benefits of integrating such projects alongside other efforts and do not see a downside to engaging citizen scientists. Indeed, programs involving high-consequence invasive species may need to be carefully designed to incorporate or streamline professional verification. Even still, incorporating some element of citizen science in surveillance and management strategies is likely to enhance biosecurity.

Citizen science projects aimed at enhancing biosecurity will need to consider implementing extra precautions for confirming detections and first reports accurately. Indeed, data quality is a common theme when citizen science projects are examined (Cox et al., 2012; Kosmala et al., 2016; Lukyanenko et al., 2016; Roman et al., 2017). Once the purpose of a citizen science project moves beyond citizen engagement, environmental awareness, and education, basic scientific principles apply with respect to data quality assurance and understanding the limitations. Quantifying error is important regardless of whether experts or non-experts are engaged in data collection. Once error is quantified this informs how the data may be used. For citizen science projects that aspire to enhance biosecurity we recommend implementing QA/QC procedures that provide reliability statistics for the data set. In addition, new detections and decreases in tree health can be verified by experts.

One objective of this review was to provide a list of active projects to serve as examples and advance the application of the citizen science approach within the field of forest health. Reviewing these projects and adopting training protocols and procedures aimed at improved data quality is pivotal to further demonstrate and advance the rigor and value of future projects. We encourage further review of the possible methods to increase data quality and error assessment of citizen science within biological invasion management strategies.

While the data collected and generated by citizen science programs have already contributed important information pertinent to biosecurity (Meentemeyer et al., 2015; Thomas et al., 2017; Baker et al., 2018; Caley et al., 2020) and most projects assume participation is increasing awareness, little research has evaluated the educational outcomes for participants or empirically demonstrated participation increases awareness of forest pests or pathogens. Biosecurity is a shared responsibility and raising awareness is an important component to "safeguarding the land" as noted in the programs discussed from New Zealand. Many polices dealing with invasive species stress the importance of raising public awareness and commitment to take responsibility such that it will encourage private efforts and voluntary compliance, and influence behavioral changes in stakeholders, decision makers (politicians) and citizens (consumers) who play a role in the movement of non-native species. A vulnerability assessment to identify potential areas of security risk could be done to find opportunities where citizen science can strengthen support within invasion frameworks.

As a final note, we recommend engagement with the broader community through communities of practices such as the Forest Health Citizen Science Community.[13] Each of the projects described herein fits into one or more parts of the invasion framework and the purpose of the community is to enhance coordination between countries, programs, and projects. For example, the abundance of citizen science projects focused on *Phytophthora* demonstrates there is immense potential for parallel studies or at least comparisons of methods of public engagement. Therefore, while each program discussed herein is likely contributing to enhance biosecurity in its respective country, the community provides an opportunity to enhance biosecurity globally.

5. Conclusion

Citizen science programs can play key roles in surveillance and biosecurity at many levels and across the biological invasion spectrum. Countries aiming to strengthen the detection and management of invasive forest pests and pathogens should integrate citizen science programs because of the enhanced protection and inherent benefits of community engagement. To our knowledge, there are no downsides of involving citizen scientists and their contributions to biosecurity can only be improved through intentional training, targeted survey designs, and explicit QA/QC procedures. Robustly designed citizen science programs can strengthen biosecurity when integrated in biological invasion strategies or early warning systems.

13 https://fhcs.page/

Author contributions

All authors contributed equally in writing and synthesis of literature to compile this review manuscript and contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2023.1113978/full#supplementary-material

SUPPLEMENTARY TABLE 1
Citizen science projects listed on Forest Health Citizen Science Community webpage (https://fhcs.page).

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