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The value of sentinel plants for risk assessment and surveillance to support biosecurity

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Abstract

Effective surveillance for early detection of invasive alien species in natural ecosystems, or on valued plants found in modified areas, could prevent potentially devastating and costly impacts (whether environmental, economic or cultural) of new invasions on the invaded country. Surveillance technologies are often constrained by a range of factors. Determining which species present a significant risk before they reach the border is an effective strategy to minimize the possibility of invasion and/or the impact of invasion. Surveillance of sentinel plants provides an important tool to strengthen biosecurity programs assisting with i) detecting and identifying insect pests, nematodes and plant diseases that could potentially invade uncolonized countries, and ii) developing pest risk analysis profiles to eliminate or mitigate the risk of arrival. This review examines some of the challenges and opportunities provided by sentinel plant research and discusses the factors that could affect the success of their use for biosecurity risk assessment and surveillance in the New Zealand context.

Keywords

Plant biosecurity, expatriate plant sentinels, IPSN, insects, plant pathogens, nematodes, pest surveillance, pest risk analysis

Introduction

Global mass transportation of trade and humans is a significant driver for movement of biota into new regions and ecosystems. Some of these biota thrive in the new environments and become invasive aliens. A key aim of invasion science is to predict which species will become invasive before an invasion occurs. Accurate prediction of potential invasiveness of an organism supports the risk assessment of that organism and the development of effective, targeted biosecurity measures, including surveillance, against it. In practice, the first invasion of a new species is frequently unanticipated because the invader is not a recognized pest in its country of origin (Poland and McCullough 2006; Paap et al. 2017) and/or the invader has jumped to a new host that is not attacked in its country of origin (Vettraino et al. 2017). New Zealand (Aotearoa) is an island nation with a high proportion of endemic plant and animal species (Miller 1971; Dugdale 1988; McGlone et al. 2001). It is heavily reliant on its natural landscapes for tourism, and primary industries for its economic wealth. Both natural ecosystems and primary production are at risk from the negative impacts of exotic invaders including loss of biodiversity, habitat modification, reduced growth or persistence, and cost of controls. So too are some taonga (things of value), in this case flora and fauna of significance for Māori, the indigenous population of New Zealand. Biosecurity strategies developed pre-border, border, and post-border, are New Zealand's defensive screen against invasive alien species that threaten species of cultural, environmental and economic importance. Sentinel plants (as defined below) can be a tool to detect potential plant pests, help indicate the degree of damage they could inflict on valued species and inform pest risk analyses, if there is a potential threat to New Zealand. They can therefore, play a significant role in border biosecurity.

Since the concept was formally proposed as a means of identifying the potential risk of invasive species offshore (Aalders et al. 2006; Fagan et al. 2008; Britton et al. 2010), sentinel plants have developed into an internationally recognized strategy for detecting potential invaders (Groenteman et al. 2015; Barham et al. 2016; Paap et al. 2017; Eschen et al. 2018). However, the sentinel plant concept has been interpreted in several different ways. This review describes the scope of the sentinel plants concept and presents examples of its implementation. We also consider ways in which the use of sentinel plants can be optimized for biosecurity purposes with particular reference to the enhancement of New Zealand's biosecurity.

What is a sentinel plant?

The simplest definition of a sentinel plant is "a plant that is monitored for the presence of species that have the potential to cause damage". Examples of damaging species include herbivorous insects, plant parasitic nematodes and plant pathogens, and these will hereafter be referred to collectively as "pests". Sentinel plants may be broadly classified into two types depending on the primary reason for monitoring, i.e. to identify new pest species of risk to determine their distribution (sentinel plants for risk assessment) or to detect pest species of risk (sentinel plants for surveillance) (Figure 1). While the former is concerned with determining the potential pests of a particular host plant genus or species, which can then inform a pest risk assessment, sentinel plants for surveillance focus on detecting range expansion of particular pests or pest groups.

Sentinel plants for risk assessment

The purpose of sentinel plants for risk assessment is to detect new host associations of particular valued plants with pests with which they have not co-evolved. To do so, we monitor valued plants that have been grown outside their natural home range, i.e. expatriate plants (Britton et al. 2010; Eschen et al. 2018), where they are exposed to a suite of organisms from the country in which they are grown and determine whether any of those organisms feed or cause damage on the sentinel plants (Table 1 summarises recent examples of this approach).

An example of this is New Zealand native plants growing in botanic gardens or arboreta in other countries which provide the opportunity to identify species utilizing those plants and which could become pests if they established themselves in New Zealand (Fagan et al. 2008). Such observations can identify potential invaders and prompt risk analyses for those species to be conducted. Once the degree of invasion risk is estimated, the potentially affected economic sectors can be alerted to it, raising awareness and surveillance for the identified pest and risk managers can, if it is deemed necessary, employ strategies to block the pathways by which an invasion could occur. For instance, soil samples were taken from the root zones of a selection of expatriate New Zealand native plants growing at the Ventnor Botanic Gardens on the Isle of Wight (United Kingdom). Nematodes extracted from the soil revealed that the plant parasitic lesion nematode *Rotylenchus pumilus* (Perry), was associated with *Olearia pachyphylla* Cheeseman (Asterales: Asteraceae). This is a very rare and critically endangered endemic shrub in New Zealand (de Lange et al. 2017). While sampling at Ventnor Botanic Gardens did not ascertain the effect of the nematode on *O. pachyphylla*, the discovery suggests that if a pathway existed for long-distance transfer of *R. pumilus* to New Zealand (e.g. on soil contaminated footwear, McNeill et al. 2011), the few remaining wild populations of *O. pachyphylla* in New Zealand may be at risk.

While established expatriate sentinel plants can be used for monitoring (Scott-Brown et al. 2017), specific plantings of valued plants can also be undertaken. For example, trade in live plants from China to Europe provided a pathway, carrying significant risk, for the introduction of invasive alien species into Europe. As an early warning tool to identify potential impacts, European tree species were grown in China as sentinels to detect possible insect pests and pathogens originating from that region (Roques et al. 2015; Vettraino et al. 2015). An invasion risk identified from this work was the box moth, *Cydalima perspectalis* (Walker) (Roques et al. 2015). Taking a similar strategy, native Asian plants that are commonly traded with Europe, were grown in 'sentinel plant nurseries' in China for the same purpose (Vettraino et al. 2017; Kenis et al. 2018).

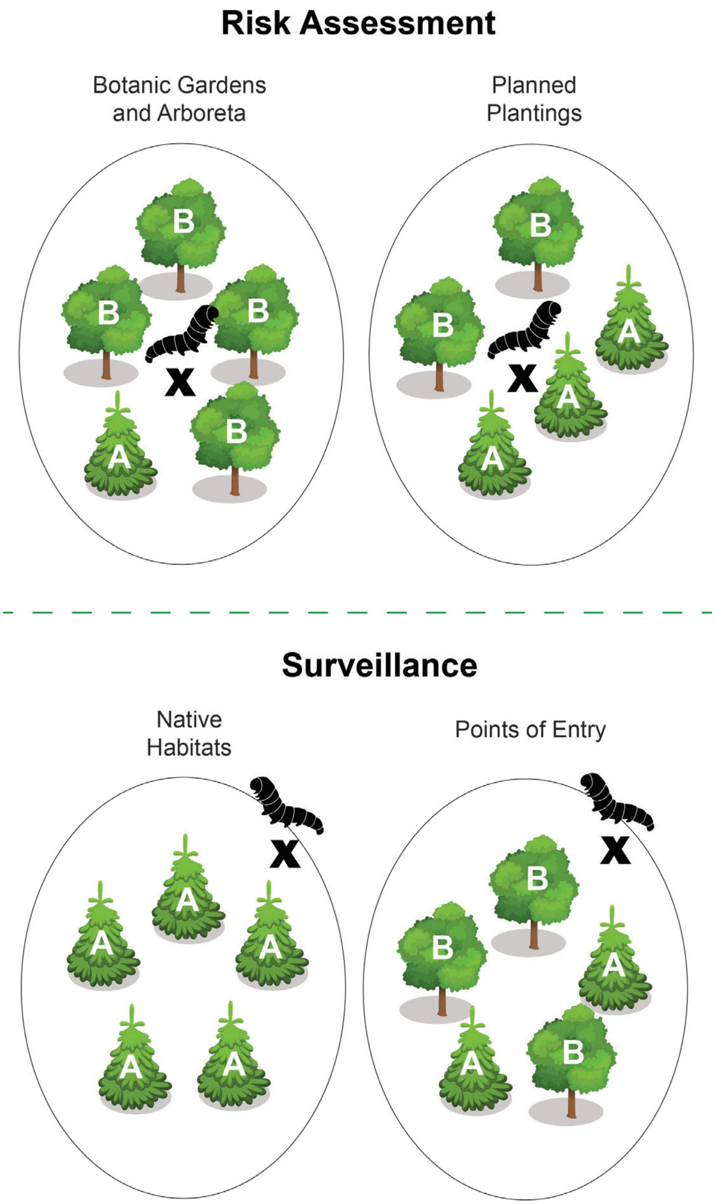

Figure 1. Different types of sentinel plants. **Risk Assessment:** monitoring expatriate plant A (*outside its native range*), can give information on exotic pests (pest X) associated with plant B that might attack Plant A should pest X become established in the home range of plant A. In this case, plant A acts as a sentinel plant for risk assessment. Sentinel plants may be *in situ* within existing botanic gardens and arboreta or planned plantings to record colonization and impacts. Risk assessment sites can be in the native range of plant B or regions outside plant B's native range where pest X is invasive. **Surveillance:** monitoring plant A and/or plant B in *the native range of plant A* may give information on the arrival and spread of pest X into that area. In this case, plants A and B act as sentinel plants for surveillance. Surveillance sites may be in native habitats for plant A or at likely points of entry for pest X.

The concept of growing plant species in exotic environments to detect known associate pests of those plant species, or similarly native species in their home range has been described as "*ex-patria*" and "*in-patria*" plantings respectively (Eschen et al. 2018). As defined by Eschen et al. (2018), *in-patria* plantings consist of young woody plants of species that are commonly exported to identify pests native to the exporting country. *Ex-patria* plantings consist of exotic young or mature woody plants and surveys may provide information about potential impacts of pests if these were to become established in a new country. However, this dichotomy fails to acknowledge that some invasions will not follow the most direct pathway from the country of origin to the invaded country. An invader may enter and colonize one (or more) countries outside its native range through bridgehead invasion (e.g. Lombaert et al. 2010) before reaching the country of concern. Figure 2 illustrates this from the New Zealand perspective: primary invasion represents the most direct route for invasion into New Zealand whereas bridgehead invasion and secondary invasion represent an indirect route via invasion of another country before reaching New Zealand.

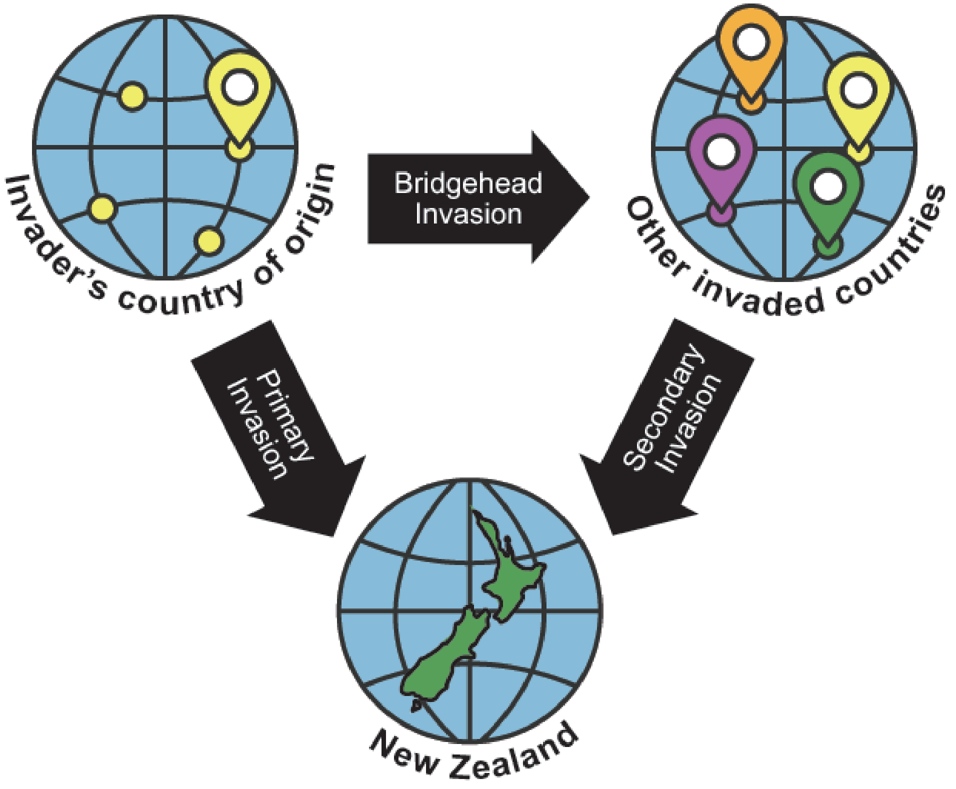

Figure 2. Invasion pathways into New Zealand in relation to the invasive species' country of origin. In a primary invasion, an invader may enter New Zealand directly from its native range, while in a secondary invasion pathway, the pest colonizes one (or more) countries outside its native range through bridgehead invasion, before reaching New Zealand.

Sentinel plants for surveillance

Sentinel plants used for surveillance assume that a risk of pest invasion has been identified and possible entry and dispersal pathways determined. In this case, surveillance sites can be selected based on proximity to trade and tourism entry points, climate matching and other relevant criteria such as potential host-plant associations, historical interception records and logistics of accessing sites. Once the risk of a new host association has been identified, then sentinel plants for surveillance may be used to detect arrival or range expansion of particular pests (Table 1). Whether the host plant is native to the country potentially being invaded or exotic does not matter so long as it is susceptible to attack by the pest of interest. A defining feature of sentinel plants for surveillance is that they are used outside the known range of the target pest.

An obvious application of sentinel plants for surveillance is for detecting the invasion of new species into an area. For example, New Zealand's Ministry for Primary Industries (MPI) High Risk Site Surveillance System (HRSS), oversees the monitoring of arborescent plants near likely points of pest entry, such as airports, seaports and container devanning sites (Stevens 2008). Currently >10,000 inspections are carried out annually, each involving many individual sentinel plants along a predetermined walked transect. In 2005–06, its first year of operation, the HRSS reported 62 significant finds of pests new to New Zealand, new host records and new pest distributions (Stevens 2008). In the period 2013–2018, the system has detected a total of 22 species which are new to New Zealand (Stevens 2018). New Zealand's HRSS is clearly an effective application of the 'sentinel plants for surveillance' concept, though it is monitoring the vegetation as found at site. There may be potential to design sentinel systems for surveillance that include particular plants, not already present among *in situ* vegetation, to target a specific pest, but the authors are not aware of relevant published examples. Any planned planting of sentinel plants for surveillance near points of entry would need to balance the benefits of early detection and rapid response to invasion against the risk that such plants may act as habitat that supports colonization by invasive species.

Biosecurity applications for the use of sentinel plants

The efficacy of a biosecurity program that uses sentinel plants, either for risk assessment or surveillance will be affected by several factors and these need to be considered when designing the program. These include: i) is there a scientific aim for the program; ii) the selection of sentinel plant species; iii) attributes of the potential invasive species/taxa of interest; iv) commonalities and differences between geographic origin/location of the sentinel plants and invaders, including habitat and environmental matches; v) appropriate technologies for detection of invasive species; vi) appropriate frequency of monitoring; and vii) effective communication of results to groups of interest. These factors may interact with each other. For example, the invasive species/taxa of interest will determine the most appropriate

Table 1. Examples of sentinel plant research for risk assessment and surveillance including use of *in situ* plants and planned plantings.

Sentinel type	Sentinel location	Target plants	Target pests	Outcome	Reference
Risk, *in situ*	Ventnor Botanic Garden, Isle of Wight	New Zealand species	Nematodes	New association found between root nematode and rare endemic species	Aalders et al. 2006
Risk, *in situ*	Siberian arboreta and cities	European and Eurasian woody broadleaved species	Fungal pathogens	29 new fungus-host plant associations detected, some with significant damage	Tomoshevich et al. 2013
Risk, *in situ*	Southern California	39 New Zealand perennial species	*Homalodisca vitripennis*, *Xylella fastidiosa*	28 species tested positive for *X. fastidiosa*; 26 out of 102 individual plants showed *H. vitripennis* activity	Groenteman et al. 2015
Risk, *in situ*	Christchurch	62 exotic conifers	Exotic aphids	13 new aphid-plant associations detected	Redlich et al. 2019
Risk, planned	Riverside, California	12 Australian tree species	*H. vitripennis*	8 species supported at least one life stage; 5 species supported adults, nymphs and eggs	Rathe et al. 2014
Risk, planned	Beijing and Fuyang	European trees: 5 broadleaves, 2 conifers	Foliage-feeding insects	> 100 morphospecies including larvae of at least 6 species detected on trees	Roques et al. 2015
Risk, planned	Fuyang	3 *Quercus* species	Fungal pathogens	Four taxa associated with disease symptoms identified	Vettraino et al. 2015
Risk, planned	Beijing and Fuyang	5 ornamental woody plants from Asia	Insects	> 90 new insect-plant associations detected	Kenis et al. 2018
Surveillance, *in situ*	Palm House, Kew Gardens	181 species	*Scirtothrips dorsalis*	73 species had *S. dorsalis* adults, 44 species also had juveniles	Scott-Brown et al. 2017
Surveillance, *in situ*	New Zealand wide	Various native and exotic spp.	Exotic pests	22 exotic species detected 2013–2018	Stevens 2018

sampling methods for detection. Consideration of such factors, and their interactions, in the design phase of the biosecurity program will facilitate its successful implementation and ensure it achieves its purpose.

Scientific aim

A purely protective biosecurity program does not require a scientific goal but there are considerable benefits for such an inclusion, not least being the validation of the program and possible improvements to future programs based on the success, or otherwise, of the current program. Sentinel plants for risk assessment and surveillance can be used not only for the primary purpose of identifying and detecting new potential invaders (e.g. Stevens 2008; Tomoshevich et al. 2013; Vettraino et al. 2017; Kenis et al. 2018), but also to test either general ecological theories about biological invasions (Kirichenko et al. 2013; Kirichenko and Kenis 2016; Burgess and Wingfield 2017) or specific hypotheses about particular invasive species (Thu et al. 2009; Rathe et al. 2014; Kurose et al. 2015). Some sentinel plant programs address both purposes (Roques et al. 2015; Vettraino et al. 2015; Eschen et al. 2018). Programs designed to test theories or hypotheses can require deliberate planting of sentinel species to meet experimental requirements; as was carried out in China using European tree species (Roques et al. 2015; Vettraino et al. 2015) or Chinese species grown for the nursery trade into Europe (Kenis et al. 2018), and Australian tree species domiciled in California (Rathe et al. 2014). Deliberate planting has advantages such as the program design can be more robust than if relying on existing plants, plants can be selected for consistency (e.g., plant age, cultivar type), sample size can be pre-determined, and the investigation sites can be chosen to meet specific conditions (e.g. climate, habitat type, proximity to a source of potential invaders).

If the program's sole purpose is identification of potential new invaders, it is more common to monitor selected plants *in situ* from pre-existing botanic gardens or arboreta. The International Plant Sentinel Network (IPSN) was established to co-ordinate sentinel plant monitoring and data sharing across botanic gardens in multiple countries (described by Barham et al. 2016). The use of *in situ* plants, and long term monitoring, can have advantages where long-lived perennial species, particularly woody plants, are involved because a plant's susceptibility to attack may change during its lifespan (Eschen et al. 2018). Reliance on *in situ* plants, however, does limit the species and cultivars/ecotypes available to sentinel plant programs. Species that are either poorly represented or wholly absent in existing botanic gardens and arboreta will require deliberate planting if they are to be included in a sentinel plant program. Where deliberate planting is used to establish a sentinel plant program, it is essential that the plants themselves do not create a new invasion problem, either by becoming weeds or by inadvertent introduction of new pests. To minimize such risks, local biosecurity concerns need to be considered during selection of sentinel plant species and all plant material subject to screening for unwanted organisms before use in the program and destruction and disposal of plants at the conclusion of the experiment to prevent their establishment as weeds.

Selection of sentinel plant species

Sentinel plant programs choose plants of significant value to humans. That value may be environmental (endangered species, species that perform a valued non-economic service, or species that support key ecosystems); economic (plants grown for food and fibre), or cultural/aesthetic. New Zealand's long geographic isolation has led to a high level of endemism amongst its flora (Wilton and Breitwieser 2000). Of the many indigenous vascular plant taxa, 403 are classified as threatened and 851 as 'at risk' (de Lange et al. 2017), due to habitat loss or environmental changes (de Lange et al. 2010, 2017). For New Zealand's Department of Conservation, many of these species are considered high priority for inclusion in expatriate sentinel plant programs (C Green, Department of Conservation, pers. communication). Several New Zealand plants e.g. kaka beak (*Clianthus puniceus*) (G.Don) Sol. ex Lindl. (Fabales: Fabaceae), are classified as critically endangered in the wild but are grown in several Australian and European botanic gardens.

In New Zealand, the cultural/aesthetic aspect includes a wide range of significant species of value to Māori (Black et al. 2019), and under obligations relating to the

Treaty of Waitangi (a document of central importance to the history and political constitution of New Zealand), this aspect is an important consideration in selection of species for sentinel plant research. Therefore, species such as pōhutukawa (*Metrosideros excelsa* Sol. ex Gaertn.) (Myrtales: Myrtaceae), kauri (*Agathis australis* Salisb.) (Pinales: Araucariaceae) and harakeke (flax) (*Phormium tenax* J.R.Forst. & G.Forst.) (Asparagales: Asphodelaceae), have value for Māori because of their traditional utilisation for food, medicine, weaving, carving and construction.

When plants growing *in situ* are used as sentinels in programs with a research component, availability is an important criterion and can override other factors. If a sentinel plant program intends to test ecological theories about invasive species, as opposed to the empirical risk assessment described above, then the history of different taxa, or individual plants, may affect the results. For example, the rate of accumulation of new species has differed between plant taxa in Europe (Roques 2015), suggesting some plant taxa are more vulnerable to invasive species than others. Kirichenko and Kenis (2016) found residence time, i.e. the year an exotic species was first planted at the study site, influenced the rate of colonization by native leaf miners in a Siberian botanic garden. Such factors need to be considered explicitly during program design and subsequent data analysis because including plant groups with substantially different histories in the same program may create unintended bias. Any prior knowledge regarding the invasive species/taxa of interest to the program should be taken into account when selecting sentinel plant species (see next section), and there may be significant limitations to risk assessment if the invasive species cannot be identified using either morphological or molecular taxonomy (Roques et al. 2015).

Potential invasive species/taxa of interest

Expatriate sentinel plant programs may target particular pest species (e.g. glassy-winged sharpshooter, *Homalodisca vitripennis* (Germar), Groenteman et al. 2015), taxa (e.g. leaf chewers and leaf miners, Kirichenko and Kenis 2016) or insect herbivores and plant pathogens associated with specific plant taxa (e.g. oaks and conifers, Roques et al. 2015). If a potential invasive species is a recognized pest in its place of origin, knowledge of it and previous research on its native host plant range can assist development of expatriate sentinel plant programs.

If the pest of interest has invaded elsewhere, the impact of these invasions on plants in those locations may indicate vulnerable species that should be considered for inclusion in sentinel plant programs for surveillance in the country at risk of invasion. For example, studies of glassy-winged sharpshooter, *H. vitripennis,* on Australian and New Zealand native plant species growing in California, provided information on new insect-plant host associations of biosecurity concern to both countries (Rathe et al. 2014; Groenteman et al. 2015). For example, Groenteman et al. (2015) found 26 of 102 individual plants growing in Californian botanic gardens and arboreta showed signs of *H. vitripennis* activity (eggs, nymphs, adults, or presence of shed exuviae) while the pathogen *Xylella fastidiosa* was present in 51% of the plant samples. Of particular concern to New Zealand, *X. fastidiosa* was detected in the culturally important species pōhutukawa, tītoki (*Alectryon excelsus* Gaertn.) and kauri.

In some cases, investigations are looking for the unknown – apparently harmless species that change hosts or that escape natural enemies in their native range to become significant pests in an invaded country. For example, the emerald ash borer, *Agrilus planipennis* Fairmaire is not a pest within its native range in Asia but became a significant pest after invading North America (Poland and McCullough 2006). These unknown potentially invasive species are the most difficult to recognize prior to invasion. For example, a study carried out in China over a two-year period on five ornamental woody plants (*Acer palmatum* Thunb., *Ilex cornuta* Lindl., *Buxus microphylla* Siebold & Zucc., *Fraxinus chinensis* Roxb. and *Zelkovia schneideriana* Handel-Mazzetti) that are commonly exported from China to Europe, recorded 105 insect species and host associations on these sentinel plants with 90% of these associations not recorded in a previous literature review of insect pests of the five plants (Kenis et al. 2018). An earlier investigation that involved planting seven European tree species in China followed by three years of monitoring, found 38 unanticipated plant-insect associations in which the majority of identified species had switched from agricultural crops and fruit trees rather than from forest trees (Roques et al. 2015).

A possible clue to identifying a non-pest species that has the potential to become a significant risk in another country may be via examination of herbivorous invertebrate communities associated with plants native to that country and that are closely related to sentinel plant species of interest. Any herbivores associated with these closely related plant species, particularly where impacts are severe, should be investigated as risks and potential invaders if pathways, climate suitability, and hitchhiker potential enable long distance dispersal, survival and establishment of that species (e.g. Toy and Newfield 2010; Meurisse et al. 2018). Wylie and Floyd (2002) explored this concept in relation to Australian eucalypts and potential insect invaders from tropical Asia: seven of ten key pest genera or species associated with eucalypts native to Asia were rated as high or medium risk to Australian eucalypts. Conversely, Australian insects were identified as significant risks to eucalypt plantations in Asia, especially those that could occupy unfilled faunal niches should they invade (Wylie and Floyd 2002).

Insect pests and plant diseases generally have received the most attention within the sentinel plant context, in part because the signs and symptoms of damage are generally visible to both specialist researchers and casual observers. By comparison, indications of the presence of nematodes tend to be more cryptic, and their impacts overlooked. Of the nematode taxa, plant parasitic nematodes (PPN) provide the most concern to biosecurity officials and growers, because their effects on plant growth and production can be significant. PPN are small (generally less than 1 mm in length) and found mostly in and around plant roots, while a small number of important genera infect leaves and stems. Plant symptoms of nematode infection can often be mistaken for nutrient deficiency or attributed to other pests or diseases. Due to their small size, identification requires access to specialist equipment and expertise. Few species of PPN are currently recognized as invasive but this is undoubtedly because of insufficient investigation and recognition of their presence (Singh et al. 2013). The importance of potential association of PPN with New Zealand expatriate native plants, and by inference in New Zealand, was shown by a study involving three overseas botanic gardens (Aalders et al. 2006; Aalders et al. 2012; Bell et al. 2013). While PPN impacts were not assessed, 17 plant feeding nematode genera or families were identified from all three sites, including root-knot (*Meloidogyne* spp.) and lesion (*Pratylenchus* and *Rotylenchus* spp.) nematodes (Fagan et al. 2009; Aalders et al. 2012).

Geographic origin, trade patterns and pathways

Central to the concept of sentinel plants is the question of geographic origins of potential invaders and selected sentinel plant species (Figure 2). For New Zealand, Australia (Close et al. 1978, Fox 1978) China and the United States (Paini et al. 2016) represent the greatest potential sources of invasive species. It seems logical, therefore, to deploy sentinel plant programs for risk assessment to these countries. Trade and tourism with all these countries provide invasion pathways that, if unmitigated, could enable invasive species to establish in New Zealand (McCullough et al. 2006; Anderson et al. 2015; Early et al. 2016; Paini et al. 2016; Chapman et al. 2017).

Floral similarities between countries also facilitate invasion by “new” pests. For New Zealand, sentinel pōhutukawa plants for risk assessment that are grown in countries with substantial Myrtaceae flora (e.g. Australia, Pacific Islands, South America) allow the identification of new potential invaders that may enter New Zealand directly (Figure 2, primary invasion). This approach is based on the hypothesis that exotic pests associated with plants closely related to the sentinel plant are an invasion risk (Ridley et al. 2000). For pōhutukawa, the taxonomic focus can be narrowed down from family to the genus *Metrosideros*, which is distributed across the Pacific, South America and South Africa, with its centre of biodiversity located in New Caledonia (Wright et al. 2000; Pillon et al. 2015). This narrowing of investigation from family to genus level could increase the accuracy of predictions that arise from it and is being used to reduce potential risk to pōhutukawa. Myrtle rust *Austropuccinia psidii* (G. Winter) Beenken, a pandemic neotropical rust strain associated with Myrtaceae (Carnegie and Pegg 2018) has recently established in New Zealand (Beresford et al. 2018; Large and Galbraith 2017). Other emerging threats include *Ceratocystis huliohia* and *C. lukuohia*, two recently identified pathogenic strains killing the endemic ōhiʻa tree (*Metrosideros polymorpha*) in Hawaii (Barnes et al. 2018). The obvious concern is that these strains also could have an impact on New Zealand *Metrosideros* species. The probability of *C. huliohia* and *C. lukuohia* reaching New Zealand is open to conjecture. Movement of infected plant material is believed to be the main pathway for introduction and spread of these plant pathogens (Barnes et al. 2018), and as no live plant material is permitted into New Zealand without a phytosanitary certificate and pre-release screening for unwanted organisms, the pathway risk appears minimal.

Nevertheless, in conjunction with the USDA, a follow-up project has been initiated to screen *M. excelsa* for resistance against both *C. huliohia* and *C. lukuohia*.

As noted above, it is possible for potential invaders to switch hosts to unrelated plant species; this type of host shift is very difficult to predict. From New Zealand's perspective, an unexpected host shift may be detected after a 'bridgehead' invasion (Figure 2) that has the potential to act as a source of colonists for future invasions (Lombaert et al. 2010). Detections of possible risk from this pathway is likely to happen through networks like the IPSN that monitor *in situ* plants (Barham et al. 2016). Such a detection would also alert biosecurity scientists to the potential risk of secondary invasion (Figure 2) into New Zealand. Monitoring to detect bridgehead invasions is important because it identifies species that have already demonstrated invasiveness; sentinel plants for risk assessment are ideal for this purpose. It further provides an opportunity to investigate the invader's ecology in both its invaded range and country of origin (if known), before it reaches New Zealand. International research to assess impacts from known invasive species also may detect new associations unexpectedly e.g. *Metrosideros polymorpha* ('ōhiʻa) seedlings sent from Hawaii to Viçosa University in Brazil for testing against multiple strains of myrtle rust fungus (*A. psidii*), became infested with the pathogenic fungus *Calonectria metrosideri* (Alfenas et al. 2013). This new association was described as another fungal pathogen of 'ōhiʻa and listed as an "actionable" species for USDA-APHIS (Farr and Rossman 2016). It seems sensible to consider this fungal pathogen a potential risk to New Zealand's *Metrosideros* species.

Sampling methods, taxonomic identification and frequency of monitoring

The choice of sampling methods used in a sentinel plant program, for either risk assessment or surveillance, should be determined by what is known about the potential invader(s). If the target is a known species or taxon, then specific sampling techniques may be able to be adopted to maximise the probability of pest detection, e.g. Kirichenko and Kenis (2016) used different sampling methods for leaf chewers versus leaf miners. If the sentinel plant program is targeting unknown pests then a variety of sampling methods or techniques validated to detect a wide range of organisms should be used so that the probability of detecting a pest is maximized. For example, different methods are needed to detect insect herbivores to those needed for fungal pathogens.

A key step when dealing with unknown invaders is correct taxonomic identification based on morphological and/or molecular characteristics, at least to genus and preferably to species level (James et al. 2014; Kenis et al. 2018). The more precise the identification, the more accurate the risk predictions can be. The identification process may be particularly challenging for cryptic species, such as PPN and gall-forming insects. An important aim of the IPSN is enhanced early detection of new and emerging invasive species through initiatives to raise awareness of plant health issues, provide tools to aid early detection and identification, train stakeholders to develop their taxonomic skills, and develop electronic reporting systems (Barham et al. 2016, Roques et al. 2017).

Sentinel plants may be subject to a regular monitoring schedule or checks may be conducted intermittently, as time permits. In general, a regular and frequent schedule is likely to be more useful for biosecurity purposes, particularly when consistent sampling methods are used at each check (e.g. detection of *Thaumastocoris peregrinus* in New Zealand, Sopow et al. 2012), as the quality of data collected is likely to be better. However, even intermittent inspections may give early warning of potential new invaders. For example, Fagan et al. (2009) identified 10 potential invaders to New Zealand from 14 visits to overseas botanical gardens by researchers.

Communication of research results

An easily overlooked, but essential, aspect of sentinel plant research is the need to communicate results to the relevant biosecurity authorities and potentially affected stakeholders. These need early warning of both potential and actual new invaders, particularly if significant impacts are expected, so that mitigation can be planned and implemented to minimise pest impact. While publication in peer-reviewed journals is critical for scientific veracity and quality, this does not obviate the need for wider communication of new research findings. Communication must be timely and relevant with the information presented in a way that non-specialists in government and industry organisations can understand, yet it must also acknowledge the inevitable uncertainties in research findings.

In New Zealand's case, rapid communication is best directed to government agencies such as the Ministry for Primary Industries (MPI) (as New Zealand's National Plant Protection Organisation) and the Department of Conservation (DOC) as well as the appropriate Crown Research Institutes, depending on the sectors or environments most likely to be affected by the new invader. The most affected sectors will also determine which industry stakeholders should be involved with a risk assessment or an incursion response. In general, early communication with authorities and stakeholders informs pest risk and pathway analyses, as well as raising awareness and vigilance amongst the affected groups. As part of this process, there needs to be effective channels to share feedback from government authorities and stakeholder organizations with research providers. This is essential to confirm that useful information has been received by all parties, to share information, and to support co-development of important pest risk and pathway analyses.

Gaps in sentinel plant programs

Most research using sentinel plants, whether to detect new invasions or assess risks, involves perennial woody tree species. Plants of environmental and cultural value are more likely to be monitored through botanic gardens and arboreta, which presumably reflects the availability of such species in alien environments. Annual plants, short-lived perennials, and grasses are under-represented in the literature, yet there are valued species within these groups e.g. snow tussock (*Chionochloa rigida*) is an iconic New Zealand species. It is not clear if these under-represented groups are less common in parks and botanic gardens and therefore simply unavailable for monitoring, or if these groups are actively excluded from sentinel plant programs either because the value of this approach is not recognized for such plants or research funding is unavailable.

The other significant group rarely included in sentinel plant programs for risk assessment are plants of economic importance. For example, many non-woody crop plants are grown outside of their native range where they are at risk of attack by local polyphagous pests (Singer et al. 1993). Once the local pest has colonized the novel crop plant within the pest's native range, there is potential for that pest to become invasive if a pathway exists for it to move to new countries. Conceptually, novel crops act as sentinel plants for detection of new pest associations and may provide early warning of new biosecurity risks. For example, Queensland fruit fly, *Bactrocera tryoni* (Froggatt), is a well-known biosecurity risk for New Zealand and other countries both because of its ability to damage a wide range of fruit crops that did not co-evolve with this pest and its history of detections at or post-border (Kean 2016; Haynes and Dominiak 2018). A barrier to the inclusion of economic crops in a sentinel programme may be that, whether expatriate or domestic, they are subject to regular harvesting and pest control; practices that are often incompatible with monitoring programs intended to detect biosecurity threats. In such cases dedicated sentinel crops may be required. Sentinel plant programs for risk assessment that target commercial crops in regions of biosecurity concern may provide useful insights on the diversity of potential invasive species, their associated impacts and biological control agents (as shown by Roques et al. 2015 and Kenis et al. 2018). For New Zealand, sentinel plant programs for risk assessment that target forage or horticultural crops in regions of biosecurity concern (e.g. Australia, China or USA, Paini et al. 2016), may provide useful insights on pest biodiversity, impacts and biological control agents from sowing to maturity. This would be augmented by research literature identifying specific pests to include in sentinel plant programs. In this respect, it is important to be able to access foreign language literature, as this can expand information on pest species and impacts (e.g. Xu et al. 2016).

Outside of programs focused strictly on biosecurity, but in many cases aligned to real or potential biosecurity breaches, sentinel plant programs for risk assessment can be used to develop pest control strategies, particularly where biological control of invasive plant species is considered. Sentinel plants may be used to identify potential biological control agents and/or to assess their efficacy (e.g. Groenteman et al. 2015) although such work is conducted more often in response to a successful invasion (e.g. Kurose et al. 2015), rather than before invasion occurs. Along similar lines, expatriate plants may be used to test for non-target impacts from potential weed biological control agents prior to introduction to the affected country. This approach is important to protecting commercial forestry from invasive pests (Showalter et al. 2018) and has been used previously to test the susceptibility of New Zealand's endemic *Sophora microphylla* Aiton (kowhai) to *Pirapion immune* Kirby, a phytophagous biological control agent of broom (*Cytisus scoparius*, (L.) Link) in the UK (Syrett and Harman 1995). The ability of *P. immune* to develop successfully on *S. microphylla* under field conditions in the UK, led to the rejection of the weevil as a biological control agent for *C. scoparius* in New Zealand (Syrett and Harman 1995). More recently, the same approach was used to test susceptibility of the native passion vine, *Passiflora tetrandra* Banks ex DC., to biological control agents of the invasive weed, banana passionfruit (*Passiflora* spp.) in Colombia (Q. Paynter, Landcare Research, pers. comm.).

Sentinel plants and New Zealand's biosecurity

Ideally, both *in situ* plants (in botanic gardens and arboreta) and planned plantings (research plantings) should be incorporated in target sentinel plant programs, because no single approach can cover all potential invaders, particularly plant pathogens (Desprez-Loustau et al. 2007; Webber 2010). In this respect, home gardens near ports also provide another avenue for early detection of invasive pests (e.g. Barratt et al. 2015). The engagement of citizen scientists to support detection and reporting of new incursions may prove valuable to the overall aims of biosecurity (Thomas et al. 2017).

Regular monitoring of established specimens of plant species that are valuable to New Zealand, particularly expatriate specimens of endemic species, is the most practical strategy because it contributes information about recognized pests in their country of origin, new pests that emerge through bridgehead invasions into other countries, and potential new invasions into New Zealand (Figure 2, Table 2) while at the same time requiring relatively low monetary and capital resources. Alongside such monitoring, participation in the IPSN and similar collaborative networks can potentially leverage knowledge held by local staff in botanic gardens and arboreta, while increasing the number of 'eyes on the ground' (Britton et al. 2010, Barham et al. 2016). The report that pōhutukawa is susceptible to *X. fastidiosa* subsp. *multiplex* originated through this network (Anon. 2016). Participation also provides the opportunity to identify overseas locations of key plant species for *a posteriori* study to measure impacts from invasive species following their establishment in New Zealand (e.g. Marroni et al. 2018).

Planned planting programs of sentinel plants for risk assessment are best used to address specific questions that cannot be answered using *in situ* plants in the invader's country of origin and/or its invaded range or where robust data collection is required. The cost and logistics of sentinel plant programs will increase with complexity and inevitably there will be trade-offs between optimal data collection and manageability. However, such programs will be particularly important for plant taxa that are poorly represented in botanic gardens and arboreta, such as grasses, annuals and short-lived perennials and may also be justified in the case of economic crops. For example, ryegrasses (*Lolium* spp.) are New Zealand's most valuable crop (Nixon 2016) and its economic worth would justify planned plantings and extensive monitoring in countries where potential invaders occur, particularly as relatively few pests in New Zealand attack it. Plant selection can be strategic to assess impacts of selected invasive pests or pathogens not yet in New Zealand (e.g. exposing *Metrosideros* spp. to *C. huliohia* and *C. lukuohia*

Table 2. Strategies for use of sentinel plants to enhance New Zealand's (NZ) biosecurity.

Geographic location	*In situ* sentinel plants	Planned sentinel plantings
Invader's country of origin (sentinel plants for risk assessment)	Monitor 1) any plants damaged in country of origin that are valuable to NZ and 2) any valuable NZ species that are taxonomic relatives of plants damaged in country of origin.	Establish planned plantings of any potentially vulnerable species not already represented among *in situ* plants in the invader's native geographic range.
Other countries subject to a bridgehead invasion	Monitor 1) any plants damaged in the invaded range that are valuable to NZ and 2) any valuable NZ species that are taxonomic relatives of plants damaged in the invaded range. If the invader's country of origin can be identified, follow recommended sentinel plant strategy within the invader's native geographic range.	Establish planned plantings of any potentially vulnerable species not already represented among *in situ* plants in the invaded range and, if possible, the invader's native geographic range.
New Zealand (sentinel plants for surveillance)	Monitor 1) local specimens of any plant species damaged in the invader's country of origin (if known), 2) local specimens of any species valuable to NZ that are damaged in other invaded countries, and 3) any valuable NZ species that are taxonomic relatives of plants that are either damaged in the invader's country of origin (if known) or damaged in other invaded countries. Monitoring should include air and sea ports, botanical gardens, forestry plantations, home gardens etc., whose geographic location increases their likelihood of exposure to invaders.	Planned plantings may be less relevant in this context because rapid detection of a new invasion is best achieved through *in situ* plants occurring across a wider geographic landscape. At sites where biosecurity scientists can have input into long-term landscaping choices, it may be feasible to plant valuable species that augment *in situ* plants.

in Hawaii), or structured in order to assess colonization and impact from a range of pest taxa on selected valuable species (e.g. Rathe et al. 2014; Roques et al. 2015). The selection of plant species to be assessed faces differing requirements depending on their status. In New Zealand, assessment of commercial crop species requires little if any public approval but the use of native plant species requires consultation and agreement from Māori, particularly where seed is sourced from regions within hapū boundaries.

Challenges to implementation of planned sentinel plant programs include freedom to carry out research in overseas jurisdictions, remote management and monitoring of overseas field trials and data ownership as well as biosecurity, commercial and cultural considerations. Another significant challenge is that an 'absence of evidence is not evidence of absence', i.e., sentinel plants can provide positive evidence of a pest-plant interaction, but the lack of such interaction does not prove conclusively that the interaction will never occur. This is particularly important for plant pathogens, where the conditions supporting infection may be highly specific (Cleary et al. 2016). There is also no guarantee that a pest-plant host association that shows little impact in one environment or region will have a similar impact in another environment or region, because host generality and trophic position (Romanuk et al. 2009), natural enemy release (Colautti et al. 2004; Jeschke et al. 2012); new host plant-pathogen associations (Cleary et al. 2016), or a range of other variables determine the impact of invasive species (Desprez-Loustau et al. 2007; Tylianakis and Romo 2010; Enders et al. 2018).

Over and above these is the challenge of identifying the specimens collected in the studies, especially if they are undescribed, and the cost of carrying out the research. However, this approach may provide a better platform to assess impacts from invaders, as it allows for experimental replication, site selection, and may give some control over the degree of exposure to the invasive species. Many crop and pasture species are grown worldwide so sentinel plant projects with such species may be easier to implement than for native or endemic species, due to fewer biosecurity and cultural concerns around planned planting of the chosen species at the experiment sites. For these economically important species, the cost of sentinel plant programs that enable pre-emptive mitigation of potential pest impact would undoubtedly result in a positive cost benefit analysis, where the cost of investigation is far exceeded by the economic savings gained from preventing an invasion.

As financial and logistic constraints are likely to limit the scope of sentinel plant programs, so collaboration and information sharing between countries is essential, as the IPSN demonstrates. Regular monitoring of valuable New Zealand species that are present in botanic gardens and arboreta is an important strategy for New Zealand's biosecurity; but particularly for commercial species and those with high cultural value, there is also a case for planned sentinel plant programs whereby these species are grown overseas and regularly monitored for evidence of colonization by exotic invertebrate pests and plant pathogens.

Closing remarks

Botanic gardens can act as early warnings of exotic pests and diseases as well as increasing knowledge of exotic species presence/absence (Barham et al. 2016). Through the IPSN there has been a concerted effort amongst botanic gardens and arboreta to improve expertise in identifying exotic species (Roques et al. 2017), raise awareness, and improve networking amongst botanic gardens and arboreta on a global scale.

Expatriate sentinel plant research using deliberate plantings has shown the potential to identify new insect-plant host associations, while also demonstrating that there can be significant challenges to identifying key phytophagous taxa when taxonomic databases or resources are lacking (Roques et al. 2015; Kenis et al. 2018). Expatriate sentinel plants can take a targeted approach for particular insect taxa (Groenteman et al. 2015) or potentially can target specific plant species or taxa, such as the project to screen *M. excelsa* against the pathogens *C. huliohia* and *C. lukuohia* in Hawaii.

As a working sentinel plants framework, Fagan et al. (2008) investigated various scenarios for selecting and monitoring overseas gardens including a ranking system based on climate matching, local site criteria, plant collection and pest parameters along with the willingness for collaboration. Planned visits by New Zealand biosecurity scientists to survey important plant species for potential invaders will complement participation in such networks, although the frequency and timing of visits should be managed to maximize their value for our national biosecurity goals. Such visits are also necessary to maintain reciprocal biosecurity networks and to identify new research opportunities. Fagan et al. (2008) developed a good template for operational research that may warrant greater investment, although refinements in site selection need to take into account major trading partners, the dynamics of invasion into new regions as well as climate change scenarios.

As a biosecurity pre-border strategy, expatriate sentinel plants provide the advantage of early warning of pest and disease attack, but selection criteria and desired outcomes need to be carefully planned as does a mechanism to prioritize risk. For New Zealand, an area that is lacking from the sentinel plant approach to border biosecurity is their use for commercial crops, particularly for the agricultural sector. The sentinel plant approach can be a component of New Zealand's biosecurity platform, but the global examples presented in this review demonstrate its potential to contribute to New Zealand's biosecurity preparedness. Continued monitoring of plants near likely invasion sites within New Zealand through the HRSS program (Stevens 2008) completes the chain of sentinel plant data, from country of origin to other invaded countries then to New Zealand (Table 2).

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Author contributions

MRM and SM carried out the literature search and wrote the paper, BIPB contributed to writing of the manuscript, and along with LA and NB contributed to collection of specimens and interpretation of data for the project; DT, KBW and JK contributed to the development of the project and review.

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