Botanical gardens as key resources and hazards for biosecurity

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Abstract

Biodiversity and economic losses resulting from invasive plant pests and pathogens are increasing globally. For these impacts and threats to be managed effectively, appropriate methods of surveillance, detection and identification are required. Botanical gardens provide a unique opportunity for biosecurity as they accommodate diverse collections of exotic and native plant species. These gardens are also often located close to high-risk sites of accidental invasions such as ports and urban areas. This, coupled with routine activities such as the movement of plants and plant material, and visits by millions of people each year, place botanical gardens at risk to the arrival and establishment of pests and pathogens. Consequently, botanical gardens can pose substantial biosecurity risks to the environment, by acting as bridgeheads for pest and pathogen invasions. Here we review the role of botanical gardens in biosecurity on a global scale. The role of botanical gardens has changed over time. Initially, they were established as physic gardens (gardens with medicinal plants), and their links with academic institutions led to their crucial role in the accumulation and dissemination of botanical knowledge. During the second half of the 20th century, botanical gardens developed a strong focus on plant conservation, and in recent years there has been a growing acknowledgement of their value in biosecurity research as sentinel sites to identify pest and pathogen risks (novel pest-host associations); for early detection and eradication of pests and pathogens; and for host range studies. We identify eight specific biosecurity hazards associated with botanical gardens and note potential management interventions and the opportunities these provide for improving biosecurity. We highlight the value of botanical gardens for biosecurity and plant health research in general, and the need for strategic thinking, resources, and capacity development to make them models for best practices in plant health.

Keywords: invasive pests, invasive pathogens, early detection, early warning, sentinel plants, invasive alien species

Introduction

Invasive alien pests and pathogens pose major threats to plant health globally, resulting in significant ecological and economic damage (Holmes et al. 2009; Aukema et al. 2011; Boyd et al. 2013; Lovett et al. 2016). Huge economic losses in the agricultural and forestry sector have been attributed to the damage caused by invasive alien pests, for example up to $39 billion per year in the United States alone (Pimentel et al. 2005; Holmes et al. 2009; Pratt et al. 2017). Over the last few decades, there has been a rapid surge in the number of alien arthropod pests, microbial pathogens and parasitic nematodes (hereafter referred to as pests) of plants in many countries (Aukema et al. 2010; Liebhold et al. 2012; Santini et al. 2013; Wingfield et al. 2015; Hurley et al. 2016). This recent surge is commonly attributed to the increasing global network of trade, travel and, in particular, the movement of live plants (Hulme 2009; Roques et al. 2009; Santini et al. 2013).

Regulatory measures that are taken against alien pests include the listing of quarantine pests [as supported by Pest Risk Analyses (PRAs)] and plant passports/quarantine inspections i.e. visual inspections/lab analyses (Klapwijk et al. 2016). However, such interventions are severely hampered by a lack of knowledge on potential pests and novel pest-host associations (Eschen et al. 2019). Co-evolution between plant pests and their hosts, as well as pressures from competition, predation and parasitism, contribute to the complexity and stability of natural ecosystems. Outbreaks of native pests under natural environmental conditions, are therefore rare (Alpert 2006; Burdon and Thrall 2009). Consequently, many damaging invasive alien plant pests were unknown to science, or at least unknown to cause severe damage, prior to their arrival and establishment in a novel environment. Examples include Dutch elm disease, *Ophiostoma ulmi sensu lato* (Ophiostomatales: Ophiostomataceae) and chestnut blight, *Cryphonectria parasitica* (Diaporthales: Cryphonectriaceae) in Europe and America (Brasier 2000; Rigling and Prospero 2018); and the polyphagous shot hole borer (PSHB), *Euwallacea fornicatus* (Coleoptera: Curculionidae) and its fungal symbiont *Fusarium euwallaceae* (Hypocreales: Nectriaceae) in California, Israel and South Africa (Mendel et al. 2012; Eskalen et al. 2013; Paap et al. 2018). Once established in a novel environment, these and many other pests have caused devastating economic and environmental impacts.

Early detection of pest incursions after their arrival is essential for control and management interventions to achieve eradication or containment, and for impacts and risks to be managed cost-effectively (Mehta et al. 2007; Liebhold and Kean 2019). In Australia, it has been estimated that their biosecurity system (by detecting and responding to introductions of pests and thereby reducing the future impacts) will result in a net national benefit of AUS$314 billion (an equivalent of US$210 billion) over the next 50 years (Dodd et al. 2020). However, the detection of pests at the early stages of an incursion is challenging (Klapwijk et al. 2016; Thakur et al. 2019; Paap et al. 2020). Detection is often impossible before signs and symptoms develop on the host plants, and visible impacts are observed in the recipient environment (Thakur et al. 2019). By this point in time, the pest may already be well established. In addition, the diagnostic processes required to identify the organism(s) responsible for the damage further add to the long lag time between arrival, detection and identification of alien species. This is further exacerbated by the limited resources available to monitor large areas, particularly in countries with minimal budgets for plant health surveillance.

One strategy to improve the detection rate of incursions and identification of pest risks is to monitor sentinel plants i.e., plants already present in the vicinity of high-risk sites or in urban areas and used for regular inspection of pests (Britton et al. 2010; Eschen et al. 2019; Mansfield et al. 2019). A similar approach is to use sentinel plantings - plantings in the country of origin of the pests used to identify organisms in their native range that are likely to be harmful if introduced and establish elsewhere (Roques et al. 2015; Eschen et al. 2019). Sentinel plantings could be existing collections of plants in botanical gardens or plants planted for this purpose. Sentinel plants and sentinel plantings help to detect and identify pest risks effectively and are useful for early warning (Wylie et al. 2008; Sweeney et al. 2012; Paap et al., 2017; Morales-Rodríguez et al. 2019). An example of the potential role of sentinel plantings is the emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae), one of the devastating invasive insect pests in the United States (Herms and McCullough 2014). The emerald ash borer was detected on North American ash species planted in the beetle's native range in China long before its introduction in North America (Liu et al. 2003).

Botanical gardens provide a unique resource of sentinel plants and sentinel plantings to identify recently introduced alien pests and novel pest-host associations. There are thousands of botanical gardens widely distributed across the world with diverse collections of native and exotic plants (Miller et al. 2015; Barham et al. 2016). The high diversity of plant species in botanical gardens and their proximity to high-risk sites of introduction makes them suitable sites for post-border surveillance and monitoring of alien pests. Staff in these gardens work amongst the plant collections on a daily basis. Therefore, raising awareness and building the capacity of garden staff in surveillance and detection of pests can provide increased opportunities for detection of pests. This is especially useful for countries with limited plant health surveillance and biosecurity budgets. On the other hand, botanical gardens pose various biosecurity hazards through their regular activities such as collection, cultivation, sharing and the sale of plant materials; the use of machineries, vehicles and equipment; outsourcing of organic material; and tourism. These activities could lead to the introduction, establishment and spread of invasive species (Coetzee et al. 2001, Dawson et al. 2008; Scalera et al. 2012; Harrower et al. 2018; Rigling and Prospero 2018).

In this review we consider the changing role of botanical gardens, identify the associated hazards and highlight the recent recognition of their value for biosecurity. We discuss their potential role as bridgeheads and conduits of pest invasions, but also their recent role as key resources for identifying pest risks and new pest-host associations, as well as their potential to aid in early pest detection and eradication.

Changing attitudes to biosecurity in botanical gardens as their functions and roles evolve

The functions and the roles of botanical gardens have evolved significantly over time (Powledge 2011; Krishnan and Novy 2016). Initially (mid-16th century), botanical gardens were established to study medicinal plants (Oldfield 2007). However, during the European expansion and exploration of the rest of the world (17th to 19th century), botanical gardens such as the Royal Botanical Garden Kew in Britain and the Hortus Botanicus Leiden in the Netherlands were engaged in economic botany and cultivation of attractive plants (Brockway 1979). This led to the movement of plants at unprecedented levels and enhanced the collection and documentation of exotic and previously unknown plant specimens (Brockway 1979; Borsch and Lohne 2014; Krishnan and Novy 2016). During the second half of the 20th century, botanical gardens around the world developed a strong focus on the conservation of rare and threatened plant species and the sustainable use of biodiversity to mitigate the impacts of climate change, habitat loss, and many other factors (Maunder et al. 2000; Borsch and Lohne 2014). In the 21st century, the focus of botanical gardens has moved towards maintaining relevance to communities and meeting their needs, locally and globally. Along with their role in *ex situ* conservation of biodiversity, botanical gardens have increased their focus on impactful education, research, and ecological restoration (Krishnan and Novy 2016; Smith 2019). Furthermore, the expertise of botanical gardens is being used in *in situ* conservation of plant biodiversity and ecological restoration (Chen et al. 2009; Krishnan and Novy 2016; Chen and Sun 2018).

Despite the general evolving roles and functions of botanical gardens overtime, their role in relation to biosecurity issues has remained largely unappreciated until recently. During the early days of the establishment of botanical gardens (mid-16th century), the concept of native and alien pests was not recognized. Yet, there was a significant level of economic exchange between Europe and the rest of the world, and the resultant exchange of goods could have enhanced the movement of pests (Walter 2012). Likewise, during the 17th to 19th century, biosecurity was not acknowledged nor considered important, despite the unprecedented level of movement of plants across the world for various purposes (Brockway 1979). It was only in 1878 that the first attempt to regulate the international movement of plants was made in response to the significant damage caused by the insect Grape

Phylloxera, *Phylloxera vastatrix* (Hemiptera: Phylloxeridae) (now *Daktulosphaira vitifolia*), to the viticulture industry (Santini et al. 2018).

A growing awareness of the importance of biosecurity was observed among botanical gardens as their focus shifted from economic botany and they began to acknowledge their role in science and plant conservation. However, much of this focus was on plant invasions (Lowe et al. 2000; Heywood 2011; Hulme 2011; Sharrock et al. 2011), and little attention was given to the movement of harmful plant pests. In the United States, voluntary codes of conduct and ethics such as the 'Chapel Hill Challenge' and the 'St Louis Declaration' were launched for botanical gardens, arboreta and the horticultural industry in 1999 and 2002, respectively (Hulme 2011). These codes of conduct set recommendations for the removal of invasive plants from living collections and plant sales, and for the control of invasive plants in botanical gardens. They also set recommendations for undertaking risk assessments on new collections. As a result, botanical gardens had begun to take action to combat the risk of plant invasions associated with their conservation efforts. For example, the European Botanical Gardens Consortium established an initiative to identify potential invasive taxa from botanical collections in various gardens. The consortium also alerted collectors of potential invasion threat posed by their plant collections. Botanical gardens in the United States have instituted similar initiatives for the identification of invasive horticultural species (Heywood 2011; Sharrock et al. 2011).

In the last two decades, scientists have recognized the role that botanical gardens can play in plant health and biosecurity and tried to align this role with the conservation role of gardens to minimize the introduction and spread of pests (Barham et al. 2016; Eschen et al. 2019). To this end, the International Plant Sentinel Network (IPSN) (https://www.plantsentinel.org/) was launched in 2013 with the aim of providing support and resources needed by botanical gardens and arboreta to conduct research on plant health (Barham et al. 2016). The IPSN is an initiative developed by Botanic Gardens Conservation International (BGCI), to facilitate collaboration among botanical gardens and arboreta, National Plant Protection Organizations (NPPOs) and plant health scientists. In this regard, botanical gardens such as the Royal Botanic Garden Edinburgh in the United Kingdom (UK) have taken important steps to reduce opportunities for pests to develop in their *ex situ* conservation collections. They have made substantial efforts to develop protocols for quarantine and horticultural practices, and expanded visitor engagement and public education on plant pests. They have also implemented precautionary approaches for plant distribution in order to minimize the introduction of pests into the gardens and to halt their subsequent dispersal (Hayden 2020). The Royal Botanic Gardens, Kew in the UK and the Botanic Gardens Biosecurity Network and Botanic Gardens Surveillance Network in Australia have formed important links with government plant health departments to enhance biosecurity through inspection and structured plant pest surveillance (https://extensionaus.com.au/botanicgardensbiosecurity/structured-plant-pest-surveillance-by-botanic-gardens-staff/, https://www.kew.org/read-and-watch/behind-the-scenes-plant-quarantine-unit).

Recently, botanical gardens have been used as sentinel sites for the detection of introduced alien pests (Paap et al. 2017; Eschen et al. 2019). Botanical gardens can also be viewed as *ex-patria* sentinel plantings or sentinel plantations, as proposed by Eschen et al. (2019). In this case, woody plants native to the importing country, which are growing in botanical gardens in the exporting country, can be used to monitor and identify pest risks. The identification of native pest–exotic host associations in the exporting country could provide valuable information of potential future invasion risks to the country of origin of the host plant (Britton et al. 2010; Barham et al. 2016; Paap et al. 2017; Eschen et al. 2019; Morales-Rodríguez et al. 2019).

The role of botanical gardens in biosecurity

The key elements and features that lend botanical gardens special importance in biosecurity, particularly in the study, detection and management of pests, are illustrated in Fig. 1 and the accompanying Table 1. Eight specific hazards were identified and are discussed, noting that the threats also provide opportunities for improved management and communication. In this section, we highlight these hazards and the opportunities botanical gardens present, i.e. botanical gardens as:- bridgeheads and conduits for invasions; sentinel sites for the detection and eradication of pest incursions; important resources for research (focussing on the opportunities they provide to identify new pest-host association and thereby determine pest host range); and great opportunities for meaningful public engagement on biosecurity issues.

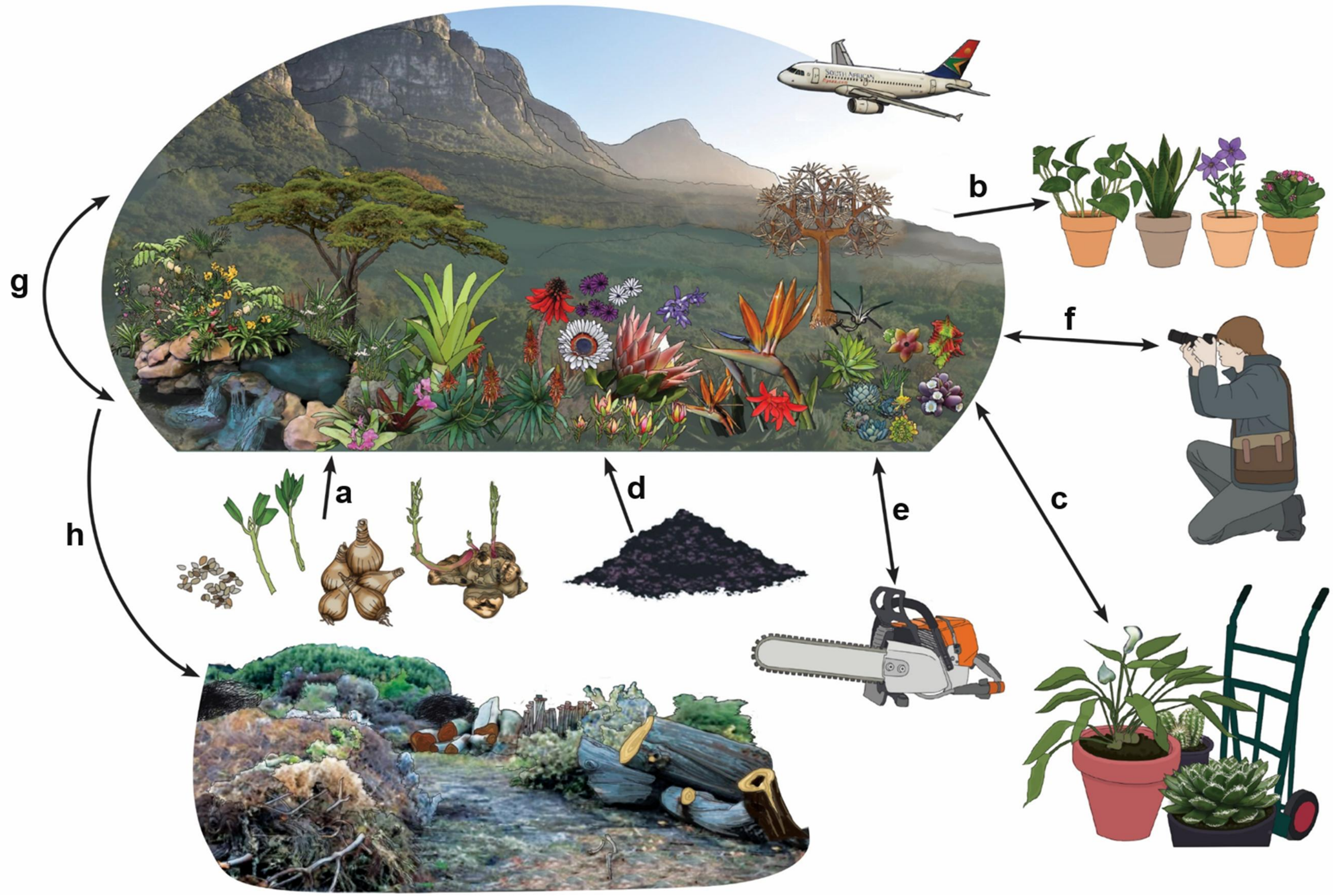

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Fig.1 Eight biosecurity hazards presented by botanical gardens and the opportunities they provide to improve management and communication. Details on the hazards, pathways of movement, real-world examples, management measures, and the corresponding opportunities are outlined in Table 1. The letters in the figures correspond to the letters in the table. The high diversity of native and exotic plant species in the gardens and their proximity to high risk sites such as ports and urban areas provides a unique opportunity for the detection and identification pest risks. Materials going into the gardens such as seeds, tubers, cuttings, mulch, compost and soil could potentially transport and introduce pests to the gardens (a, d). On the other hand, materials leaving the gardens such as sold plants, prunings and dead plants can potentially transport pests established in the gardens to the external environment (b, h). Other activities of the gardens, including visits by local and international visitors (f), the use of machinery and equipment (e), and plant exchange between botanical gardens (c) may also serve as pathways of movement of pests to- and from the gardens. Additionally, pests may naturally disperse between managed estates of the gardens and the adjacent natural vegetation (g)

Table 1 Key biosecurity hazards and opportunities presented by botanical gardens, and potential management options. The hazards are linked to the relevant invasion pathway as they would operate for botanical gardens using terminology adopted by the Convention on Biological Diversity with proposed revisions by Harrower et al. (2018) and as recently included in the Darwin Core (dwc: pathway, see https://dwc.tdwg.org/pw/#dwcpw accessed 29 March 2021; Groom et al. 2019; the Darwin Core terms is given in the brackets, multiple pathways are separated by a pipe delimiter). Examples of how the hazards have led to invasions or potential invasions are given either specifically for botanical gardens, or for systems that would be expected to be analogous to botanical gardens, noting that in the latter case a different pathway might be involved from that specified here.

	Hazard	**Pathway**	**Examples**	**Management and opportunities**
a	Plant materials are brought into the garden for cultivation and either the plants themselves or something associated with the plants or the soil material becomes invasive	Escape: Botanical gardens & Zoos (publicGardenZooAquaria)|Contaminant: Contaminants of plants (contaminantOnPlants) |Contaminant: Nursery material contaminant (contaminantNursery) | Contaminant: Parasites of plants (parasiteOnPlant) | Contaminant: Seed contaminant (seedContaminant)	• In Cameroon, the trumpet tree (*Cecropia peltata*) was spread from a plantation in Limbe Botanical Garden into the forests of Mount Cameroon by fruit-eating bats and birds, where this tree outcompeted the native pioneer trees. • A genetically altered tropical alga (*Caulerpa taxifolia*) escaped from a public aquarium in Monaco into the	• Importers of alien species must comply with the phytosanitary regulations and demonstrate that the risk of escape is minimised, or the consequences of escape are not significant. It is also important to engage with various stakeholders including industries and the general public to create awareness about invasive species and the threats they pose.

			Mediterranean Sea possibly with aquarium overflow (Scalera et al. 2012). • At the Amani Botanical Garden (ABG), Tanzania, of 214 alien plant species found extant 38 had established and 16 had spread widely in the botanical garden (Dawson et al. 2008). • The invasive root rot fungus, *Armillaria mellea* was introduced from Europe to the Company's Garden in Cape Town, South Africa, possibly on potted plants planted in the garden (Coetzee et al. 2001). • In the US, *Cryphonectria parasitica*, the causal agent of chestnut blight was first reported from the Zoological Park of New York City in	• The presence of invasive species that has escaped collections provide an opportunity to increase awareness of invasive plants in the region in a controlled setting. • Annual reports describing escape from plantings can be used to calculate the lag time between initial planting and earliest record of successful spread and thereby help to determine invasiveness of a species (e.g. Daehler 2009). This would enable an assessment of the risk of plant invasion from collections in botanical gardens. • Introduction of invasive species via contaminant pathway is closely linked to international trade. Thus, international

			1904. The fungus was likely introduced via nursery stock imported from Asia (Rigling and Prospero 2018, Global Invasive Species Database). • A container survey in New Zealand found eggs of brown marmorated stink bug (*Halyomorpha halys)* on leaves and foliage of imported plants (Harrower et al. 2018). • *Hymenoscyphus fraxineus*, the causal agent of Chalara ash dieback has been introduced to many countries through movement of diseased ash plants (Harrower et al. 2018). • Two hundred cherry trees were sent in 1911 as a gift from the people of Japan to be planted in Washington	regulations and phytosanitory measures/standards play very important role in reducing the problem. The exporting country should apply the sanitary and phytosanitory standards required while the importing country practices border controls and quarantine procedures. Harmonization of phytosanitory measures among countries is required, as is a stricter follow up on the enforcement of the enacted regulations and Acts. • Technological advancement provides immense opportunities to unravel cryptic species, divergent lineages and endophytic organisms which are difficult to

			DC. Upon their arrival found infested with crown gall disease and various insect pests (Liebhold and Griffin 2016).	detect and identify using classical approaches. Many pests are unknown prior to their arrival in a new environment. Identification of novel pest-host associations through sentinel plant research and early warning systems provide valuable information and aids the detection and identification process.
b	Plant material is propagated in the botanical garden (in a nursery) and sold to the general public, taken elsewhere, and that process leads to the spread of invasive plant species and organisms	Escape: Horticulture (horticulture) |Escape: Ornamental (ornamentalNonHorticulture)| Contaminant: Nursery material contaminant (contaminantNursery)|Contaminant: Parasites of plants (parasitesOnPlants) |Contaminant: Seed contaminant (seedContaminant)	• Garden lupin (*Lupinus polyphyllus*) and has been introduced to Europe, Australia and New Zealand for various purposes, including for ornamentation, soil stabilisation and cultivation. • Water hyacinth (*Pontederia crassipes*) has been introduced to	• The risk of spread of invasive species through plant sale can be minimised by focusing the sale on less risky plant species and following good phytosanitory practices within the nursery. Compliance with local regulations on plant movement is also equally important in reducing the risks.

	(contaminants) associated with the plants.		different parts of the world as an ornamental plant. • *Phytophthora ramorum*, the causal agent of Ramorum disease in many plant species appears to be transported with infected nursery plants and soil (Global Invasive Species Database).	• Opportunities exist to create public awareness on invasive species on special occasions such as annual plant sale days. This can be done through oral presentations, posters and distribution of written information about invasive species, their pathways of movement, the impact and management measures.
c	Plant material is shared with other gardens or used for display purposes, and the process leads to the introduction and spread of invasive pest species	Contaminant: Nursery material (contaminantNursery)| Contaminant: Parasite of plants (contaminantOnPlants) | Contaminant: Seed contaminant (seedContaminant) |	• Plant donation from Kirstenbosch National Botanical Garden in South Africa to London for the 2011 Royal Horticultural Society Chelsea Flower Show resulted in the accidental introduction of five sap-sucking hemipteran pests to the UK. Fortunately, all the infested plants	• The donor should inspect plants for pests and issue a plant passport for the donated plants. • Upon arrival, the recipient should keep the plants in a quarantine facility and regularly inspect for pests and diseases. It is only after this process that the use of plants should be allowed.

			were destroyed before the spread of insects (Salisbury et al. 2011).	
d	Organic materials such as mulch, wood chips and soil can transport invasive species into the gardens	Contaminant: Habitat material contaminant (transportationHabitatMaterial)	• Dispersal of the fungus *Phellinus noxius*, the causal agent of brown rot disease of trees is possible through transport of infested soil (Global Invasive Species Database). • Common ragweed, *Ambrosia artemisiifolia* is common in construction sites suggesting its dispersal through transport of soil and gravel (Bullock et al. 2012). • *Phytophthora cinnamomi*, an oomycete that causes root rot and dieback in various plant species can also be spread through soil and organic matter.	• Obtaining organic materials from trusted sources is very important. A trusted source should avoid making mulches and wood chips from infested plant parts. Fine chipping and composting is recommended to kill the contaminants. Allow mulch and wood chip to dry before use as fresh material would spread pests. • Soil solarisation is recommended to minimise the risk of introduction or spread of invasive species.
e	Plant propagules and pests can be imported or	Stowaway: Machinery & equipment (machineryEquipment)	• There are many examples of invasive plant species	• Machinery, equipment and vehicles should be carefully

	exported or spread within the garden on vehicles, machinery or equipment		transported/dispersed by machineries, equipment and vehicles [CABI Invasive Species Compendium: Machinery and equipment (Pathway vector)]. E.g. Seeds of the alien invasive Common ragweed (*Ambrosia artemisiifolia* L.) have been transported in litter and soil by agricultural machinery from infested areas across Europe (Bullock et al. 2012). • Plant pathogens such as *Phytophthora cinnamomi* and *Austropuccinia psidii*, the causal agent of myrtle rust spread by machinery, equipment and vehicles.	washed/cleaned before entry or exit of the gardens. • It is equally important to limit the use of machinery and equipment to specific parts of the garden. If there is a need to use them in multiple sites, cleaning/washing is recommended between sites. • Limit the number of entry and exit points (gates) to reduce free movement of machinery, equipment and vehicles. • Display biosecurity signs at vehicle access points.
f	Garden visitors accidentally either bring an invasive species into	Stowaway: People & luggage (people)	• 65 fungal species were cultured from shoes of air travellers in a study	• Creating public awareness about invasive species, the threats and pathways of movement is

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<td>the garden or transport invasive species established in the garden to the external environment</td>
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<td>conducted at Honolulu, the US (Baker 1966).
• Spores of pathogenic fungi were detected from clothing of passengers in a study conducted at Wellington Airport in 1980 and 1982 (Sheridan 1989).
• The harlequin ladybird (Harmonia axyridis) has been reported arriving in new regions in suitcases.
• Organic and inorganic debris and live insects were found on tents brought by air passengers at Auckland International Airport during December 1981 (Gadgil and Flint 1983).
• Plant pathogens such as P. cinnamomi and A. psidii can easily be transported via contaminated</td>
<td>important. The principle of “arrive clean, leave clean” should be encouraged and implemented. Teach the public and garden workers to ensure all clothing, hats, footwear, tools, equipment, machinery and vehicles are free of weed seeds, mud, soil and organic matter before entering and exiting botanical gardens. This can be encouraged through signage, newsletters, social medias such as Twitter, Facebook and other media outlets, school teaching and citizen science.
• The use of baths to clean shoes and air current to remove contaminants form hair, clothing and luggage of visitors would minimise the</td>
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			clothing, hats, footwear, equipment or vehicles.	introduction and spread of invasive species.
g	Invasive species naturally spread from the gardens to neighbouring areas or from neighbouring areas to the gardens	Natural dispersal (naturalDispersal)	• The root rot fungus, *Armillaria mellea* which was initially reported from the Company's Garden and subsequently from Kirstenbosch National Botanical Garden in South Africa, has gradually moved to the neighbouring Table Mountain National Park. • Similarly, *Cryphonectria parasitica*, the causal agent of chestnut blight which was initially reported on American chestnut in the Zoological Park of New York City has subsequently spread to the surrounding environment and devastated native American chestnut trees.	• Botanical gardens are important sentinel plantings and sentinel sites. It is therefore important to conduct regular surveillance and monitoring to detect and identify invasive species spreading from the neighbouring environment to the botanical gardens. • Similarly, regular surveillance is recommended in the natural vegetation neighbouring botanical gardens to monitor the spread of invasive species established in botanical gardens and take the necessary management measures.

h	Invasive species can spread from botanical gardens to the surrounding environment via disposal/dumping of plant waste.	Contaminant: Transportation of habitat material (transportationHabitatMaterial)	• In Java, the invasive aquatic plant water hyacinth (*Eichhornia crassipes*) became widely spread as a result of dumping of excessive weed from Bogor Botanical Garden into the Ciliwung River during the early 20th century (Hulme 2011).	• Plant waste disposal is one of the regular activities of botanical gardens. However, care should be taken not to dispose severely infected plants or plant parts in regular dumping sites as these will aid the spread of invasive species. Infested plants or plant parts should preferably be burnt in the gardens rather than disposing them out. • Disposal/dumping site should be far from natural vegetation and high human traffic areas to minimise the risk of dispersal of invasive species.

Botanical gardens as bridgeheads and conduits for invasions

Despite their clear role in biodiversity conservation, botanical gardens have historically acted as conduits for the introduction of invasive plants. For example, of the 34 plants listed by the IUCN as among 100 of the worst invasive species worldwide (Lowe et al. 2000), there is published evidence implicating botanical gardens as the most probable source of introduction for over half of these species (Hulme 2011).

There is no doubt that *ex-situ* plant conservation plays a vital role in the conservation of plants, but it also poses high risk of pest introduction (Liebhold et al. 2012). Therefore, botanical gardens can also serve as pathways of introduction for invasive pests. It is possible for alien pests established in botanical gardens to spread further into the surrounding environment through various garden activities. Examples include invasion by chestnut blight, *C. parasitica* in the United States (Rigling and Prospero 2018) and the root rot fungus, *Armillaria mellea* (Agaricales: Physalacriaceae) in South Africa (Coetzee et al. 2001, 2003). In the United Sates, the first report of *C. parasitica* was on American chestnut in the Zoological Park of New York City in 1904 (Rigling and Prospero 2018). Subsequently, this pathogen spread to the surrounding environment and devastated native American chestnut trees. Similarly, *A. mellea* was initially detected in Company's Garden and Kirstenbosch National Botanical Garden in South Africa (Coetzee et al. 2001, 2003). It has recently been reported from the surrounding natural vegetation of Table Mountain National Park, a declared UNESCO world heritage site (Coetzee et al. 2018).

Plant donation from the Kirstenbosch National Botanical Garden in South Africa resulted in the accidental introduction of five sap-sucking hemipteran pests to London, UK (Salisbury et al. 2011). Several pot-grown *Aloe* species together with a *Cheiridopsis glomerata* (Cryophyllales: Aizoaceae) were sent to London for the 2011 Royal Horticultural Society Chelsea Flower Show. At the end of the show, the plants were donated to the Royal Society of Chelsea. No pests were found on the plants despite assessments being made before and after the show. The donated plants were placed in the propagation department's quarantine facility. Within a month, it was clear that the plants were infested with several sap-sucking insects, which were later identified as five different insect species. Two of these species, the small mirid bug, *Aloea australis* (Hemiptera: Myridae) and the iceplant scale, *Pulvinaria delottoi* (Hemiptera: Coccidae), were the first detections of these pests in Europe. Dried specimens of these pests were deposited in different insect reference collections and all the infested plants were destroyed. During the initial inspections, the pests may be at their immature stages and less visible, suggesting the need for continues inspection of plant materials.

Botanical gardens as sentinel sites for the detection and eradication of pest incursions

A recent move towards sentinel plant research has facilitated the detection and identification of emerging pest risks. Initiatives such the IPSN, COST Action Global Warning (https://www.cost.eu/actions/FP1401/#tabs|Name:overview), and the European Union Horizon 2020 HOMED (Holistic Management of Emerging Forest Pests and Diseases) project (http://homed-project.eu/), are coordinating sentinel plant research globally. These projects serve to highlight the many first reports of pests from botanical gardens and arboreta (Jock et al. 2000; Salisbury et al. 2011; Paap et al. 2018; Hulbert et al. 2019; Tchotet Tchoumi et al. 2019). In South Africa alone, 67 pest species (including fungi, oomycetes, insects, and mites) were detected and identified from various botanical gardens over the past 23 years (1996-2019), 20 of which were first reports for the country (Wondafrash et al., in prep). In a recent review article, Mansfield et al. (2019) reported several cases of novel pest-host associations identified from sentinel plants, including plants grown in botanical gardens. These novel associations involved insects, fungi, bacteria and nematodes. Timely detection and identification of such pests aids eradication and containment of new incursions, thereby reducing the risks to natural vegetation and commercial and agricultural systems (Jock et al. 2000; Kenis et al. 2019).

Globally, thousands of eradication programmes have been implemented for alien forest insects since 1970. These include many cases of successes and failures (Liebhold and Kean 2019). Historical examples of eradication include many successful localized gypsy moth, *Lymantria dispar* (Lepidoptera: Erebidae) eradication programs in the United States and the Asian long-horn beetle, *Anoplophora glabripennis* from Chicago, the United States; Toronto, Canada and Braunau, Austria (Liebhold and Kean 2019). Recently (April 2020), *E. fornicatus* was detected on plants growing in greenhouse in the botanical gardens of Trauttmansdorff Castle in Italy and eradication is underway (https://gd.eppo.int/reporting/article-6772).

Eradication of plant pathogens once established in natural ecosystems presents a huge challenge (Paap et al. 2020). Yet, there are numerous examples of successful eradication of alien plant pathogens from controlled environments (Pluess et al. 2012). For example, inspection of known host plants of fire blight caused by the bacterium *Erwinia amylovora* (Enterobacterales: Erwiniaceae) in botanical gardens of Melbourne and Adelaide in Australia, resulted in its early detection in Royal Botanic Gardens, Melbourne (Jock et al. 2000). This is a pathogen endemic to North America and a causal agent of a serious disease of apple and pear trees and other rosaceous plants. Wide-ranging surveys and an intense host eradication program resulted in the removal of hundreds of trees, and protected Australia's pome fruit industry (Rodoni et al. 2002), valued at US$560 million for the year 2014-15 (https://apal.org.au/). This demonstrates that the early recognition of new disease symptoms, coupled with rapid and accurate diagnostics, can lead to the successful eradication of damaging organisms. Early detection and identification of pests is more easily achieved in botanical gardens than other sites.

Botanical gardens provide opportunities to determine pest host range

The diverse collection of exotic and native plant species in botanical gardens are valuable resources to investigate and determine host ranges of pests (Groenteman et al. 2015; Scott-Brown et al. 2018). Host range studies are not only valuable to the invaded region. Where exotic hosts are present, these studies can also inform other countries regarding possible future threats to their plant health, by contributing information on pests that are of regulatory interest (based on observed susceptibility in invaded ranges). These observations can be useful for early warning as they inform PRAs and assist with categorisation (quarantine status) of pests. Three examples of host range studies conducted in botanical gardens are presented below.

Example 1. *Euwallacea fornicatus* - *F. euwallaceae* complex. The host range of *E. fornicatus* and its fungal symbiont, *F. euwallaceae*, was studied at the Los Angeles Arboretum and the Huntington Botanical Garden in its invasive range in California (Eskalen et al. 2013). Of the 335 tree species present in the gardens, 207 species (62 %), from 58 plant families, showed signs and symptoms of *E. fornicatus* infestation. *Fusarium euwallaceae* was isolated from 54 % of the *E. fornicatus* infested plant species. Trees infested by *E. fornicatus* and its fungal symbiont included native and agriculturally important species, and common street trees. This study showed the potential of the beetle and its fungal symbiont to establish in diverse plant communities in the United States and beyond. The techniques used in this study and the results have aided the study of the beetle and its fungal symbiont in its recent introduced range in South Africa.

Example 2. *Xylella fastidiosa* (Xanthomonadales: Xanthomonadaceae). This is a xylem-dwelling bacterium known to cause disease in a variety of plant species. The symptoms range from leaf scorch, chlorosis or browning to stunted growth, branch dieback and death of infected plants (CABI 2020). It is vectored by the glassy-winged sharpshooter (GWSS), *Homalodisca vitripennis* (Hemiptera: Cicadellidae). The combination of the vector and the bacterium causes severe damage in plants of agricultural, ornamental and biodiversity importance (Pilkington et al. 2005). The host range of *X. fastidiosa* and its vector GWSS and the biocontrol potential of egg parasitoids against GWSS was studied on New Zealand plants in four botanical gardens and arboreta and public spaces in southern California (Groenteman et al. 2015). Signs of GWSS activity were observed on 26 of the 102 plants (25 %) examined, while the bacterium was recovered at all the locations sampled and in 51 % of the samples. This showed that several of New Zealand’s indigenous plant species are susceptible to the bacterium.

Example 3. Red palm mite, *Raoiella indica* (Trombidiformes: Tenuipalpidae). Since its detection in Martinique and St. Lucia in 2004, this polyphagous mite species has spread rapidly through the Neotropical region and has caused significant damage to a diverse range of plant species (Carrillo et al. 2012). The host range of *R. indica* was investigated through periodic surveys in the Fairchild Tropical Botanical Garden in Florida, the United States and the Royal Botanical Gardens in Trinidad and Tobago. This has helped to produce an updated list of 91 reproductive host species of *R. indica*. This study also confirmed 27 new reproductive hosts, representing a 30 % increase of the previously recorded host range (Carrillo et al. 2012).

Public engagement in botanical gardens

Opportunities exist for public engagement in plant protection via the gardens, leading to citizen science and better understanding of threats posed by pests, their pathways of movement and biosecurity measures. Botanical gardens are visited by many people on a daily basis. Biosecurity teams of the botanical gardens can use this opportunity to create awareness regarding pest and pathogen risks, pathways of movement and the recommended measures as per operational biosecurity guidelines. This could be achieved in various ways, including presentations, practical demonstrations of pests and pathogens in the gardens, group discussions and by posting biosecurity signage (see Hayden 2020).

Conclusions

Botanical gardens pose a variety of biosecurity threats — here we characterize eight specific threats (Figure 1, Table 1). However, botanical gardens also provide great opportunities to study invasive pests/plants and native pests that damage exotic plants. They are important sentinel sites for the detection and discovery of pest species, and are valuable resources for host range studies and the identification of novel pest-host associations. We believe some botanical gardens are already champions of biosecurity, and argue that others can expand their role from sentinel sites for biosecurity research to become models for best practices in plant heath, in the global effort to limit the spread and impact of pests. This will require strategic thinking, resources, and capacity development. Yet, we strongly believe that such an approach would increase the value of the botanical gardens and the contribution that they make to biosecurity. *Ex situ* conservation is central to the role of many botanical gardens because of the increasing impacts of climate change, habitat loss, fragmentation, degradation, pollution and over-exploitation on plant biodiversity. This conservation role of botanical gardens needs to be aligned with biosecurity efforts in order to minimize the introduction of invasive pests to the gardens, and thus to halt their subsequent spread to the surrounding environment.

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