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

	the garden or transport invasive species established in the garden to the external environment		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	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

			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.

Declaration

Funding: This work was supported by the South African Department of Forestry, Fisheries and the Environment (DFFE).

Conflict of interest/competing interests: The authors have no conflict of interest to declare that are relevant of the content of this article.

Availability of data and material: Data sharing is not applicable to this article as no datasets were generated or analysed during the current study

Code availability (software application or custom code): Not applicable

Ethics approval: Not applicable

Consent to participate: Not applicable

Consent for publication: All the authors have given their consent for the submission and publication of this article**.**

References

Alpert P (2006) The advantages and disadvantages of being introduced. Biol Invasions 8: 1523-1534. https://doi.org/10.1007/s10530-005-5844-z

Aukema JE, Leung B, Kovacs K, Chivers C, Britton KO, Englin J, Frankel SJ, Haight RG, Holmes TP, Liebhold AM (2011) Economic impacts of non-native forest insects in the continental United States. PLoS ONE 6: e24587. https://doi.org/10.1371/journal.pone.0024587

Aukema JE, McCullough DG, Von Holle B, Liebhold AM, Britton K, Frankel SJ (2010) Historical accumulation of nonindigenous forest pests in the continental United States. Bioscience 60: 886-897. http://dx.doi.org/10.1525/bio.2010.60.11.5

Baker EG (1966) Inadvertent distribution of fungi. Can J Microbiol 12: 109.112. DOI: 10.1139/m66-016

Barham E, Sharrock S, Lane C, Baker R (2016) The International Plant Sentinel Network: a tool for Regional and National Plant Protection Organizations. Bulletin OEPP/EPPO Bulletin 46: 156-162.

Borsch T, Löhne C (2014) Botanic gardens for the future. Integrating research, conservation, environmental education and public recreation. Ethiop J Biol Sci 13: 115-133.

Boyd IL, Freer-Smith PH, Gilligan CA, Godfray HCJ (2013) The consequence of tree pests and diseases for ecosystem services. Science 342: 1235773.

Brasier CM (2000) Intercontinental spread and continuing evolution of the Dutch elm disease pathogens. In: Dunne CP (ed) The elms: breeding, conservation and disease management. Kluwer Academic Publishers, Boston, pp 61-72.

Britton K, White P, Kramer A, Hudler G (2010) A new approach to stopping the spread of invasive insects and pathogens: early detection and rapid response via a global network of sentinel plantings. New Zeal J Sci 40: 109-114.

Brockway LH (1979) Science and Colonial Expansion: The Role of the British Royal Botanic Gardens. Academic Press, New York.

Bullock J, Beale S, Chapman D, Schafer S, Roy D, Girardello M, Haynes T, Beal S, Wheeler B, Dickie I, Phang Z, Tinch R, Čivić K, Delbaere B, Jones-Walters L, Hilbert A, Schrauwen A, Prank M, Sofiev M, Niemelä S, Räisänen P, Lees B, Skinner M, Finch S, Brough C (2012) Assessing and controlling the spread and the effects of common ragweed in Europe (ENV.B.2/ETU/2010/0037). European Commission, Final report.

Burdon JJ, Thrall PH (2009) Coevolution of plants and their pathogens in natural habitats. Science 324: 755-756. DOI: 10.1126/science.1171663.

CABI (2020) *Xylella fastidiosa* (Pierce's disease of grapevines). Invasive Species Compendium. https://www.cabi.org/isc/datasheet/57195. Accessed 20 August 2020.

Carrillo D, Amalin D, Hosein F, Roda A, Duncan RE, Pen˜a JE (2012) Host plant range of *Raoiella indica* (Acari: Tenuipalpidae) in areas of invasion of the New World. Exp Appl Acarol 57: 271-289. https://doi.org/10.1007/s10493-011-9487-8.

Carter PCS (1989) Risk assessment and pest detection surveys for exotic pests and diseases which threaten commercial forestry in New Zealand. New Zeal J For Sci 19: 353-374.

Chen G and Sun W (2018) The role of botanic gardens in scientific research, conservation, and citizen science. Plant Divers 40: 181-188. https://doi.org/10.1016/j.pld.2018.07.006.

Chen J, Cannon CH, Hu H (2009) Tropical botanical gardens: at the in situ ecosystem management frontier. Trends Plant Sci 14: 584-589. DOI: 10.1016/j.tplants.2009.08.010.

Coetzee MPA, Wingfield BD, Harrington TC, Steimel J, Coutinho TA, Wingfiled MJ (2001) The root rot fungus *Armillaria mellea* introduced into South Africa by early Dutch settlers. Mol Ecol 10: 387-396. DOI: 10.1046/j.1365-294X.2001.01187.x.

Coetzee MPA, Wingfield BD, Roux J, Crous JPW, Denman S, Wingfield MJ (2003) Discovery of two northern hemisphere *Armillaria* species on Proteaceae in South Africa. Plant Pathol 52: 604-612. https://doi.org/10.1046/j.1365-3059.2003.00879.x

Coetzee MPA, Musasira NY, Roux J, Roets F, van der Merwe NA, Wingfield MJ (2018) *Armillaria* root rot spreading into a natural woody ecosystem in South Africa. Plant Pathol 67: 883-891. https://doi.org/10.1111/ppa.12804.

Daehler CC (2009) Short lag times for invasive tropical plants: evidence from experimental plantings in Hawai'i. PLoS ONE 4: e4462. DOI: 10.1371/journal.pone.0004462.

Dawson W, Mndolwa AS, Burslem D, Hulme PE (2008) Assessing the risks of plant invasions arising from collections in tropical botanical gardens. Biodivers and Conserv17: 1979-1995. DOI: 10.1007/s10531-008-9345-0.

Dodd A, Stoeckl N, Baumgartner J, Kompas T (2020) Key result summary: Valuing Australia's biosecurity system. Centre of Excellence for Biosecurity Risk Analysis (CEBRA) Report.

Eschen R, Hanlon RO, Santini A, Vannini A, Roques A , Kirichenko N, Kenis M (2019) Safeguarding global plant health: the rise of sentinels. J Pest Sci 92: 29-36. https://doi.org/10.1007/s10340-018-1041-6.

Eskalen A, Stouthamer R, Lynch SC, Twizeyimana M, Gonzalez A, Thibault T (2013) Host range of *Fusarium* dieback and its ambrosia beetle (Coleoptera: Scolytinae) vector in southern California. Plant Dis 97: 938-951. http://dx.doi.org/10.1094 / PDIS-11-12-1026-RE.

Gadgil PD, Flint TN (1983) Assessment of the risk of introduction of exotic forest insects and diseases with imported tents. New Zeal J For 28: 58-67.

Global Invasive Species Database. http://www.iucngisd.org/gisd/. Accessed on 15 November 2020.

Groenteman R, Forgie SA, Hoddle MS, Ward DF, Goeke DF, Anand N (2015) Assessing invasion threats: novel insect-pathogen-natural enemy associations with native New Zealand plants in southern California. Biol Invasions 17: 1299-1305. Doi:10.1007/s10530-014-0804-0.

Groom Q, Desmet P, Reyserhove L, Adriaens T, Oldoni D, Vanderhoeven S, Baskauf SJ, Chapman A, McGeoch M, Walls R, Wieczorek J, Wilson JRU, Zermoglio PFF, Simpson A (2019) Improving Darwin Core for research and management of alien species. Biodiversity Information Science and Standards 3: e38084. doi:10.3897/biss.3.38084

Harrower CA, Scalera R, Pagad S, Schönrogge K, Roy HE (2018) Guidance for interpretation of CBD categories on introduction pathways. Technical note prepared by IUCN for the European Commission.

Hayden K (2020) Botanic gardens and plant pathogens: a risk-based approach at the Royal Botanic Garden Edinburgh. Sibbaldia: The International Journal of Botanic Garden Horticulture 18: 127-139. DOI: https://doi.org/10.24823/Sibbaldia.2020.293.

Herms DA, McCullough DG (2014) Emerald ash borer invasion of North America: history, biology, ecology, impacts, and management. Annu Rev Entomol 59: 13-30. doi: 10.1146/annurev-ento-011613-162051.

Heywood VH (2011) The role of botanic gardens as resource and introduction centres in the face of global change. Biodivers Conserv 20: 221-239. DOI 10.1007/. s10531-010-9781-5.

Holmes T, Aukema J, Von Holl B, Liebhold A, Sills E. 2009. Economic impacts of invasive species in forests. Annals of the New York Academy of Science 1162:18-38.

Hulbert JM, Paap T, Burgess TI, Roets F, Wingfield MJ (2019) Botanical gardens provide valuable baseline Phytophthora diversity data. Urban For and Urban Gree 46: 126461. DOI: 10.1016/j.ufug.2019.126461.

Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalization. J Appl Ecol 46: 10-18. https://doi.org/10.1111/j.1365-2664.2008.01600.x.

Hulme PE (2011) Addressing the threat to biodiversity from botanic gardens. Trends Ecol Evol 26: 168-174. doi:10.1016/j.tree.2011.01.005.

Hurley BP, Garnas J, Wingfield MJ, Branco M, Richardson DM, Slippers B (2016) Increasing numbers and intercontinental spread of invasive insects on eucalypts. Biol Invasions 18 921–933. https ://doi.org/10.1007/s10530-016-1081-x

Jock S, Rodoni B, Gillings M, Kim WS, Copes C, Merriman P, Geider K (2000) Screening of ornamental plants from the Botanic Gardens of Melbourne and Adelaide for the occurrence of *Erwinia amylovora*. Australas Plant Path 29: 120-128. DOI: 10.1071/AP00020.

Kenis M, Hurley BP, Colombari F, Lawson S, Sun J, Wilcken C, Weeks R, Sathyapala S (2019) Guide to the classical biological control of insect pests in planted and natural forests. FAO Forestry Paper No. 182, Rome.

Klapwijk MJ, Hopkins AJM, Eriksson L, Pettersson M, Schroeder M, Lindelow A, Ronnberg J, Keskitalo ECH, Kenis M (2016) Reducing the risk of invasive forest pests and pathogens: Combining legislation, targeted management and public awareness. Ambio 45: 223-234. doi:10.1579/0044-7447-38.3.135.

Krishnan S, Novy A. 2016. The role of botanic gardens in the twenty-first century. CAB Reviews 11, No. 023.

Liebhold A, Brockerhoff E, Garrett L, Parke J, Britton K (2012) Live plant imports: the major pathway for the forest insect and pathogen invasions of the US. Front Ecol Environ 10:135-143. https://doi.org/10.1890/110198.

Liebhold AM, Kean JM (2019) Eradication and containment of non-native forest insects: successes and failures. J Pest Sci 92: 83-91. https://doi.org/10.1007/s10340-018-1056-z.

Liebhold AM, Griffin RL (2016) The legacy of Charles Marlatt and efforts to limit plant pest invasions. Am Entomol 62: 218-227. https://doi.org/10.1093/ae/tmw072.

Liu HP, Bauer LS, Gao R, Zhao T, Petrice TR, Haack RA (2003) Exploratory survey for the emerald ash borer, Agrilus planipennis (Coleoptera: Buprestidae), and its natural enemies in China. Great Lakes Entomol 36:191–204.

Lovett GM, Weiss M, Liebhold AM, Holmes TP, Leung B, Lambert KF, Orwig DA, Campbell FT, Rosenthal J, McCullough DG, Wildova R, Ayres MP, Canham CD, Foster DR, Ladeau SL, Weldy T (2016) Nonnative forest insects and pathogens in the United States: Impacts and policy options. Ecol Appl 26: 1437–1455. https ://doi.org/10.1890/15-1176.

Lowe S, Browne M, Boudjelas S, De Poorter M (2000) 100 of the world's Worst Invasive Alien Species. A selection from the Global Invasive Species Database, The Invasive Species Specialist Group, a specialist group of the Species Survival Commission (SSC) of the World Conservation Union (IUCN), p 12.

Mansfield S, McNeill MR, Aalders LT, Bell NL, Kean JM, Barratt BIP, Boyd-Wilson K, Teulon DAJ (2019) The value of sentinel plants for risk assessment and surveillance to support biosecurity. NeoBiota 48: 1-24. https://doi.org/10.3897/neobiota.48.34205.

Maunder M, Culham A, Alden B, Zizka G, Orliac C, Lobin W, Bordeu A, Ramirez JM, Glissmann-Gough S. (2000). Conservation of the Toromiro tree: Case study in the management of a plant extinct in the wild. Conserv Biol 14: 1341-1350. https://doi.org/10.1046/j.1523-1739.2000.98520.x.

Mehta SV, Robeert G, Haight FR, Homans S, Polasky, RC, Venette (2007) Optimal detection and control strategies for invasive species management. Ecol Econ 61: 237-245. DOI: 10.1016/j.ecolecon.2006.10.024.

Mendel Z, Protosav A, Sharon M, Zveibil A, Ben Yahuda S, O'Donnell K, Rabaglia R, Wysoki, M, Freeman S. (2012) An Asian ambrosia beetle *Euwallacea fornicatus* and its novel symbiotic fungus *Fusarium* sp. pose a serious threat to Israeli avocado industry. Phytoparasitica 40: 235-238. https://doi.org/10.1007/s12600-012-0223-7.

Miller A J, Novy A, Glover J, Kellogg EA, Maul JE, Raven P, Jackson PW (2015) Expanding the role of botanical gardens in the future of food. Nature Plant. Article Number 15078. Doi: 10.1038/nplants.2015.78.

Morales-Rodríguez C, Anslan S, Auger-Rozenberg M-A, Augustin S, Baranchikov Y, Bellahirech A, Burokienė D, Čepukoit D, Çota E, Davydenko K, Doğmuş Lehtijärvi HT, Drenkhan R, Drenkhan T, Eschen R, Franić I, Glavendekić M, de Groot M, Kacprzyk M, Kenis M, Kirichenko N, Matsiakh I, Musolin DL, Nowakowska JA, O'Hanlon R, Prospero S, Roques A, Santini A, Talgø V, Tedersoo L, Uimari A, Vannini A, Witzell J, Woodward S, Zambounis A, Cleary M (2019) Forewarned is forearmed: harmonized approaches for early detection of potentially invasive pests and pathogens in sentinel plantings. NeoBiota 47: 95-123. https://doi.org/10.1016/j.biocontrol.2017.07.009.

Oldfield S (2007) Great Botanic Gardens of the World. New Holland, London.

Paap T, Burgess T, Wingfield MJ (2017) Urban trees: bridge-heads for forest pest invasions and sentinels for early detection. Biol Invasions 19: 3515-3526. https://doi.org/10.1007/s10530-017-1595-x.

Paap T, de Beer ZW, Migliorini D, Nel WJ, Wingfield MJ (2018) The polyphagous shot hole borer (PSHB) and its fungal symbiont *Fusarium euwallaceae*: a new invasion in South Africa. Australas Plant Path 47: 231-237. https://doi.org/10.1007/s13313-018-0545-0.

Paap T, Wingfield MJ, Burgess TI, Hulbert JM, Santini A (2020) Harmonising the fields of invasion science and forest pathology. NeoBiota 62: 301-3032. https://doi.org/10.1016/j.tree.2004.07.021.

Pilkington LJ, Irvin NA, Hoddle MS, Triapitsyn SV, Carey BG, Jones WA, Morgan DJW (2005) Introduced parasitic wasps could control glassy-winged sharpshooter. Calif Agr 59: 223–228. https://**doi**.org/10.3733/ca.v059n04p223.

Pimentel D, Zuniga R, Morrison D. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol Econ 52: 273-288. DOI: 10.1016/j.ecolecon.2004.10.002.

Pluess T, Jarosik V, Pysek P, Cannon R, Pergl J, Breukers A, Bacher S (2012) Which factors affect the success or failure of eradication campaigns against alien species? PLoS ONE 7: 826 e48157. https://doi.org/10.1371/journal.pone.0048157.

Powledge F (2011) The evolving role of botanical gardens. BioScience 61: 743-749. DOI: 10.1525/bio.2011.61.10.3.

Pratt CF, Constantine KL, Murphy ST (2017) Economic impacts of invasive alien species on African smallholder livelihoods. Glob Food Sec 14:31-37. http://dx.doi.org/10.1016/j.gfs.2017.01.011.

Rigling D, Prospero S (2018) Cryphonectria parasitica, the causal agent of chestnut blight: Invasion history, population biology and disease control. Mol Plant Pathology 19: 7-20. https://doi.org/10.1111/mpp.12542.

Rodoni B, Gardner R, Giles R, Cole M, Wimalajeewa S (2002) National surveys did not detect *Erwinia amylovora* on host plants in Australia. Acta Hortic 590: 39-45. DOI: 10.17660/ActaHortic.2002.590.3.

Roques A, Fan J, Courtial B, Zhang Y, Yart A, Auger-ozenberg M, Denux O, Kenis M, Baker R, Sun J (2015) Planting Sentinel European Trees in Eastern Asia as a Novel Method to Identify Potential Insect Pest Invaders. PLOS ONE. https://doi.org/10.1371/journal.pone.0120864.

Roques A, Rabitsch W, Rasplus J-Y, Lopez-Vaamonde C, Nentwig W, Kenis M (2009) Alien terrestrial invertebrates of Europe. Pages 63-79 in DAISIE editor. Handbook of alien species in Europe. Springer, Berlin.

Salisbury A, Malumphy C, Halstead AJ (2011) First incursion of *Aloe australis* (Hemiptera: Miridae) and *Pulvinaria delottoi* (Hemiptera: Coccidae) in Europe, and three other Hemipteran insects imported from South Africa. Br J Ent Nat Hist 24: 217-220.

Santini A, Ghelardini L, De Pace C, Desprez-Loustau M-L, Capretti P, Chandelier A, Cech T, Chira D, Diamandis S, Gaitniekis T, Hantula J, Holdenrieder O, Jankovsky L, Jung T, Jurc D, Kirisits T, Kunca A, Lygis V, Malecka M, Marcais B, Schmitz S, Schumacher J, Solheim H, Solla A, Szabo I, Tsopelas P, Vannini A, Vettraino A, Webber J, Woodward S, Stenlid J (2013) Biogeographical patterns and determinants of invasion by forest pathogens in Europe. New Phytol 197: 238-250. Doi: 10.1111/j.1469-8137.2012.04364.x.

Santini A, Liebhold A, Migliorini D, Woodward S (2018) Tracing the role of human civilization in the globalization of plant pathogens. ISME J 12: 647-652. http://dx.doi.org/10.1098/rsos.150370.

Scalera R, De Man D, Klausen B, Dickie L, Genovesi P (2012) European code of conduct on zoological gardens and aquaria and invasive alien species. Council of Europe, New edition November 2016, p 40.

Scott-Brown AS, Hodgetts J, Simmonds MSJ & Collins DW (2018) Potential role of botanic garden collections in predicting hosts at risk globally from invasive pests: a case study using *Scirtothrips dorsalis*. J Pest Sci 91: 60-611. https://doi.org/10.2307/2261425.

Sharrock SL, Blackmore S, Cheney J, Dunn C, Husby C, Jebb M, Kennedy K, Kiehn M, Kramer A, Kueffer C, Raven P, Reichard S, Rejmanek M, Oldfield S, Wyse Jackson P (2011) The biodiversity benefits of botanic gardens. Trends Ecol Evol 26: 433. Doi: 10.1016/j.tree.2011.05.008.

Sheridan JE (1989) Quarantine risks imposed by overseas passengers. New Zeal J For Sci 19: 338.346.

Smith P (2019) The challenge for botanic garden science. Plants People Planet **1**: 38-43.

Sweeney J, Anderson RS, Webster RP, Nevill R (2012) First records of *Orchestes fagi* (L.) (Coleoptera: Curculionidae: Curculioninae) in North America, with a checklist of the North American Ramphini. Coleopts Bull 66: 297-304. https://doi.org/10.1649/072.066.0401.

Tchotet Tchoumi JM, Coetzee MPA, Rajchenberg M, Roux J (2019) Taxonomy and species diversity of *Ganoderma* species in the Garden Route National Park of South Africa inferred from morphology and multilocus phylogenies. Mycologia 11: 730-747. https://doi.org/10.1080/00275514.2019.1635387.

Thakur MP, van der Putten WH, Cobben MMP, van Kleunen M, Geisen S (2019) Microbial invasions in terrestrial ecosystems. Nat Rev Microbiol 17: 621- 631. https://doi.org/10.1038/s41579-019-0236-z.

Walter R (2012) Economic relations between Europe and the world: Dependence and Interdependence. European History Online (EGO), published by the Leibniz Institute of European History (IEG). http://ieg-ego.eu/en/threads/europe-and-the-world/economic-relations. Accessed 21 August 2020.

Wingfield MJ, Brockerhoff EG, Wingfield BD, Slippers B (2015) Planted forest health: The need for a global strategy. Science 349: 832–836. https ://doi.org/10.1126/scien ce.aac6674.

Wylie FR, Griffiths M, King J (2008) Development of hazard site surveillance programs for forest invasive species: a case study from Brisbane, Australia. Austral For 71: 229-235. https://doi.org/10.1080/00049158.2008.10675040.