Addressing the threat to biodiversity from botanic gardens

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Increasing evidence highlights the role that botanic gardens might have in plant invasions across the globe. Botanic gardens, often in global biodiversity hotspots, have been implicated in the early cultivation and/or introduction of most environmental weeds listed by IUCN as among the worst invasive species worldwide. Furthermore, most of the popular ornamental species in living collections around the globe have records as alien weeds. Voluntary codes of conduct to prevent the dissemination of invasive plants from botanic gardens have had limited uptake, with few risk assessments undertaken of individual living collections. A stronger global networking of botanic gardens to tackle biological invasions involving public outreach, information sharing and capacity building is a priority to prevent the problems of the past occurring in the future.

Sowing the seeds of conflict

Botanic gardens (see Glossary) are increasingly recognized as key players in global plant conservation through their living collections of endangered species, long-term archiving of seeds, taxonomic training and public outreach [1–3]. Much less widely acknowledged is the role that they might have in both the deliberate and accidental introduction of invasive alien plants across the globe [4–6]. Yet an increasing body of evidence highlights the possible role of botanic gardens in facilitating plant invasions worldwide, which conflicts with an otherwise high conservation profile. For example, botanic gardens have been implicated in the early cultivation, local dissemination and/or introduction into one or more global biodiversity hotspots of half the environmental weeds listed by IUCN as among the worst invasive species worldwide (Box 1). This proportion is even greater if only tropical or subtropical ornamental species are considered. Although historical records only provide circumstantial evidence of an association between living collections and plant invasions, many of the first records in herbaria of naturalized aliens are from sites close to arboreta, botanical gardens, nurseries, or experimental plantings [7].

Better documented examples illustrate the diversity of pathways through which botanic gardens might facilitate the introduction and spread of alien species (Box 1). Species have been deliberately introduced to new regions for acclimatization, stimulation of local horticulture or commercial gain. In South Africa, several botanical gardens were actively involved in the cultivation and dissemination of black wattle (*Acacia mearnsii*) saplings that contributed to subsequent invasion across 2.5 million ha of unique vegetation communities in the Eastern Cape [6]. During the late 19th century, the Royal Botanic Gardens at Kew, London, was the driving force behind the spread of the quinine tree (*Cinchona* spp.) across the British Empire. Kew was responsible for the widespread planting of quinine tree on St Helena as a cash crop, where it still forms a major component of the vegetation [8]. Less deliberate has been the accidental escape of species through natural dispersal out of botanic gardens and into the natural environment. This accounts for the spread of the trumpet tree (*Cecropia peltata*) by fruit-eating bats and birds from plantations in Limbe Botanical Garden into the forests of Mt Cameroon, where the invader outcompetes native pioneer trees. Humans might also have an important role in the inadvertent escape of species from botanic gardens. The dumping of excess water hyacinth (*Eichhornia crassipes*) from Bogor Botanical Garden into the Ciliwung River during the early 20th century resulted in the spread of this species in Java, where it now encroaches on many waterways and reservoirs, with subsequent environmental and economic problems. Finally, botanical gardens might also inadvertently introduce alien plants as contaminants in imported soils, plants or seed lots and this probably

Glossary

Alien: an organism occurring outside its natural past or present range and dispersal potential, whose presence and dispersal is to the result of intentional or unintentional human action.
Arboretum: a botanic garden containing living collections of woody plants intended, at least partly, for scientific study.
Botanic garden: an institution holding documented collections of living plants for the purposes of scientific research, conservation, display and education.
Index Seminum: a list of seeds harvested at a botanical garden that is offered to other botanical gardens or institutions usually on the condition that the seeds are used solely for scientific research, conservation of species and the development of recognized collections.
Introduction (introduced): direct or indirect movement, by human agency, of an organism outside its past or present natural range.
Invasion (invasive): refers to established alien organisms that are rapidly extending their range in the new region, usually causing significant harm to biological diversity, ecosystem functioning, socio-economic values and human health in invaded regions.
Native: species that have evolved in a given geographical location and were not introduced by humans.
Naturalization: refers to aliens that form free-living, self-sustaining (reproducing) and durable populations that persist in the wild.
Nursery: a place where plants are propagated and grown to usable size. This includes: retail nurseries, which sell to the general public; wholesale nurseries, which sell only to commercial gardeners; and private nurseries, which supply the needs of institutions or private estates. Botanic gardens increasingly have a retail nursery component to their activities.

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 0169-5347/$ – see front matter doi:10.1016/j.tree.2011.01.005 Trends in Ecology and Evolution, April 2011, Vol. 26, No. 4

Box 1. Assessment of the alleged threat of plant invasion posed by botanic garden collections

No comprehensive assessment has yet been undertaken of the role of botanic gardens in the introduction of invasive plant species, owing to the highly dispersed and often anecdotal nature of information. A simple compilation of evidence of introductions will not present a balanced perspective of the risks posed by living collections. To achieve such a balance, the 34 plants listed by the IUCN as among the 100 worst invasive species worldwide [28] were used as a reference to assess the role of botanic gardens in the introduction or early cultivation of invasive alien plants. Published evidence was found implicating botanic gardens as the most probable source of introduction in over half (19) of these species (Table I). However, at least two species in the reference group do not appear to be grown in botanic gardens [e.g. English cordgrass (*Spartina anglica*) and kudzu (*Pueraria montana*)].

Of the 34 plant species listed by the IUCN among the worst global invasive species, the risks appear greater for ornamental species in tropical regions than for species used primarily for erosion control or forage or those in temperate regions. The IUCN plant list is strongly biased towards tropical species but botanic gardens have been implicated as important sources of alien plants invading other global biodiversity hotspots, such as the Chilean Valdivian forest [32] and the Mediterranean basin [33].

Table I. Botanic garden collections inferred as sources for the introduction, early cultivation or dissemination of 19 out of 34 plants listed to be among the world's worst invasive species[a]. Species nomenclature follows [17]

Botanic garden	Hotspot[b]	Date	Species invading	Refs
Pamplemousses, Mauritius	MIOI	1810	*Psidium cattleianum*	[34]
		1785	*Hiptage benghalensis*	
		1837	*Lantana camara*	
		1863	*Schinus terebinthifolius*	
Curepipe, Mauritius	MIOI	1890	*Ligustrum robustum*	[35]
Peradeniya, Sri Lanka	WGSL	1894	*Clidemia hirta*	[5]
		1905	*Eichhornia crassipes*	
		1926	*L. camara*	
		1888	*Miconia calvescens*	
		1888	*Ulex europaeus*	
Calcutta, India	-	1840	*Chromolaena odorata*	[5]
		1809	*L. camara*	
Darwin, Australia	-	1890	*Mimosa pigra*	[5]
Brisbane, Australia	-	1932	*H. benghalensis*	[36]
		1924	*S. terebinthifolius*	[37]
Singapore, Singapore	S	1903	*E. crassipes*	[38]
		1910	*Spathodea campanulata*	
Bogor, Indonesia	S	1894	*E. crassipes*	[39]
		1949	*Mikania micrantha*	
		1920	*Cecropia peltata*	
Wahiawa, Hawaii	PM	1941	*C. hirta*	[5]
Harold L. Lyon Arboretum, Hawaii	PM	1920	*Ardisia elliptica*	[40]
		1920	*P. cattleianum*	
Harrison Smith, Tahiti	PM	1937	*M. calvescens*	[5]
Yahoué, New Caledonia	NC	1870	*L. camara*	[41]
Amani, Tanzania	EAM	1930	*C. hirta*	[5]
		1930	*L. camara*	
		1930	*S. campanulata*	
Limbe, Cameroon	GFWA	1910	*C. peltata*	[5]
Kisantu, Zaire	GFWA	1900	*C. odorata*	[5]
Cape Town, South Africa	CFR	1830	*Acacia mearnsii*	[6]
Mayaguez. Puerto Rico	CI	1930	*Melaleuca quinquenervia*	[5]
Cinchona, Jamaica	CI	1883	*Hedychium gardnerianum*	[42]
		1883	*Cinchona pubescens*	

[a]Data are also provided regarding the putative date of introduction and the location of the site within a biodiversity hotspot.

[b]Global biodiversity hotspot codes: CFR, Cape floristic region; CI, Caribbean islands; EAM, Eastern Afro-montane; GFWA, Guinean forest of West Africa; MIOI, Madagascar and Indian Ocean islands; NC, New Caledonia; PM, Polynesia and Micronesia; S, Sundaland; WGSL, Western Ghats and Sri Lanka.

explains the widespread occurrence of Koster's curse (*Clidemia hirta*) in the tropical regions of Asia, Africa and the Pacific. Even with a progressive shift away from acclimatization and deliberate introduction, the variety of unintentional pathways suggests that botanic gardens face significant challenges in managing their living collections to prevent plant invasions.

Many of these examples stem from the 19th and early 20th centuries and, although this suggests that there were unlikely to be many other potential sources of these plants in a particular region, the specific origins of the invasions are usually only indirectly inferred to be botanic gardens. However, how much of a threat do botanic garden collections pose today? With more than half of the 2600 major botanic gardens worldwide having been created since 1950 [9], an appraisal of the role of these institutions in plant invasions and the measures in place to mitigate this threat is long overdue.

Box 2. Are living collections biased towards potentially invasive species?

Botanic Gardens Conservation International is the leading network of botanic gardens in the world, with a mission to ensure the worldwide conservation of threatened plants. The organization hosts the most comprehensive information on both the locations of botanic gardens across the globe and the composition of their plant collections. Although it might not capture the entire composition of living collections worldwide, the database presently includes over 575 000 records encompassing data from over 2600 collections and is arguably the most robust source for any examination of living collections. These data can be used to assess the representation of known invasive plants species in global living collections.

As a basis for comparison, a random sample of 574 species (excluding cultivars or varieties) that had received an Award of Garden Merit (AGM) from the Royal Horticultural Society [43] were cross-referenced against the Global Compendium of Weeds [44] to assess the prevalence in botanic garden collections of species with a history of becoming alien weeds. Over 56% of AGM species are known to be invasive somewhere in the world and, across all species, those with known invasion history are significantly better represented in botanic gardens worldwide. With the exception of orchids, this trend is observed for each individual life-form grouping, but is especially significant for bulbs, corms and tubers; herbaceous perennials; as well as trees and shrubs (Table I). The criteria for AGM classification are that a plant must be of outstanding excellence for ordinary garden use, be of good constitution, not require specialist growing conditions or be particularly susceptible to pests and diseases [43]. Not surprisingly, these traits will also be important in the naturalization of the species outside of living collections.

Table I. The representation and frequency of AGM ornamental species in living collections classified by life-form and known occurrence as an alien weed

	Not a weed[a]		Weed[b]		
Life-form/taxon group	Total species[c]	Mean ± SE collections[c]	Total species[c]	Mean ± SE collections[c]	P^d
Annuals	0	-	4	34.5 ± 13.5	
Bamboos	1	24.0	6	25.2 ± 8.3	
Bulbs, corms and tubers	38	32.4 ± 3.9	50	53.4 ± 3.8	***
Cacti and other succulents	27	47.1 ± 6.4	7	63.7 ± 8.0	
Climbers	10	28.6 ± 9.2	29	46.5 ± 4.3	
Conifers	10	71.0 ± 12.7	14	103.9 ± 14.0	
Ferns	4	40.0 ± 17.2	12	78.1 ± 7.5	*
Herbaceous perennials	80	32.0 ± 2.2	88	58.8 ± 2.8	***
Orchids	10	24.4 ± 6.4	0	-	
Perennials grown as annuals	0	-	6	23.3 ± 5.3	
Roses	0	-	1	-	
Trees and shrubs	69	47.7 ± 4.2	108	57.5 ± 7.1	***
Total	249	39.3 ± 1.9	325	62.4 ± 2.0	***

[a]Not listed in the Global Compendium of Weeds [44].

[b]Occurrence as an alien weed from the Global Compendium of Weeds [44].

[c]Results of a plant search at http://www.bgci.org on 20/09/10.

[d]t-test: * $P < 0.05$, ** $P < 0.01$; *** $P < 0.001$

Current botanic gardens collections host many known invasive plant species

It could be argued that many of the documented examples of plant invasions (Box 1) stem from a less enlightened, bygone era, when botanic gardens spearheaded colonial development of agriculture and paid scant attention to the consequences of the natural environment. Yet over the same period, European botanic gardens also facilitated the introduction and spread of alien plants within Europe [10–12], although perhaps with less obvious consequences for native biodiversity. Recent decades have certainly seen a progressive shift in botanic gardens towards conservation activities and an increased focus on native flora in their living collections. Yet plant introductions still remain an important activity for some, and the post-Cold War era has seen a renaissance in modern plant hunting [13]. In Europe and North America, this has often focused on plants of horticultural merit, whereas crops and crop relatives are an important focus for botanic gardens in Russia and China [6]. Nevertheless, even in the absence of introducing new, potentially invasive taxa to botanic gardens, existing living collections still pose a risk for plant escape. For example, in Germany, a significant correlate of an alien species becoming naturalized is how widely it has been cultivated in botanic gardens [14]. Concern has also been expressed regarding living collections acting as repositories for species liable to respond favourably to climate change and thus being pre-adapted to escape as the environment warms [15]. Such threats might be exacerbated as botanic gardens experiment with plants adapted to future climates with a view to their later introduction into gardening [6]. Thus, even though the broader aims of botanic gardens might have changed over recent decades, complacency regarding the potential threat that their living collections pose as sources of invasive plants does not appear warranted.

The scale and distribution of botanic gardens worldwide is staggering, with over 4 million living plant collections representing more than 80 000 species, almost a third of the known flora worldwide [16]. Cross-referencing a major database on the composition of living collections (http://www.bgci.org/plant_search.php) against a representative sample of 450 invasive plants species that pose environmental threats [17] reveals 96% to be found in botanic gardens. This is not too surprising, given that most environmental weeds have origins as garden ornamentals [17]. Indeed, of these 450 major invasive plant species, those absent from botanic gardens include several perennial grasses with limited decorative value but that are important as forage species; for example, creeping river grass (*Echinochloa polystachya*), perennial veldtgrass (*Ehrharta calycina*) and West Indian marsh grass (*Hymenachne amplexicaulis*). Of greater concern is the relatively high frequency of intractable weeds, such as lantana (*Lantana camara*) and kahili ginger (*Hedychium gardnerianum*), which are both found in over 50 living collections. Botanic gardens have been implicated in facilitating the invasion of lantana in Mauritius, Sri Lanka, India, New Caledonia and Tanzania (Box 1). A comparison of the number of regions in which each of these 450 species is recorded as invasive [17] with their frequency in botanic garden collections reveals a significant positive relationship ($r = 0.190$, $df = 448$, $P < 0.01$).

However, it cannot be inferred from these results that living collections are over-represented by invasive plant species; rather, independently of their role in the conservation of threatened species, botanic gardens still have a major role in the cultivation of ornamental plants worldwide and these species tend to be over-represented in invasive plant floras. Examining the ornamental flora in botanic gardens in more detail reveals that most of the popular ornamental species in botanic gardens have records as alien weeds and that those with a history of being an alien weed are found in more living collections than are those with no such history (Box 2). Given that the more frequently a species occurs in living collections across the world, the greater the likelihood that it will be recorded as invasive in at least one region, the greater representation of potential invasive species in living collections worldwide could be of concern. Yet how strong is the link between botanic gardens and plant invasions?

Living collections: identifying the steps from ornamental to detrimental

The occurrence of a potentially invasive alien species in a living collection is not in itself evidence of a threat. Such species might actually be native to the region concerned or, if alien, only survive under glasshouse conditions, lack essential pollination or seed-dispersal mutualists, consist of too few individuals for significant reproductive output and/or occur a considerable distance from locations suitable for natural establishment. For example, in Amani Botanical Garden (Tanzania), the likelihood of a species naturalizing was a significant function of the original planting effort, although some species were able to naturalize even when planted in relatively few numbers [18]. Even where an individual species might be planted in few numbers, if it proves popular with botanic gardens then widespread distribution among many living collections increases the likelihood of its escape from one or more of them. Thus, if as is likely, a proportion of most living collections comprises alien ornamental species,

Box 3. Socioeconomy, botanic gardens and alien plant richness

A positive relationship between the number of botanic gardens in a region and alien plant richness might be indicative of a causal effect, but interpretation is confounded by the numerous other variables that might determine the number of alien plant species in a particular region. A growing consensus is that anthropogenic factors, such as economic activity and human population density, are strongly associated with the number of alien plant species found in large administrative units, such as states, counties or countries [45–48]. Such socioeconomic factors might have a direct effect on alien plant richness through trade facilitating introductions as well as by increasing disturbance, eutrophication, habitat fragmentation and urbanization that can encourage plant naturalization. These factors might also influence the extent to which botanic gardens are established in a particular region (Figure I).

Path analysis can quantify such confounded causal processes separately and, thus, can produce a clearer view of the influences of socioeconomy and botanic gardens on alien plant richness. For a sample of 26 regions representative of islands and continents in both the northern and southern hemispheres [45], the major direct influence on alien plant species richness was human population density, yet there was also a discernible significant effect attributable to botanic garden density. Together, these two variables explained 57% of the variation in alien plant species richness, with botanic garden density accounting for 12%. Human variables also had direct positive effects on botanic garden density. Thus, increases in per capita GDP or population density result in an indirect effect on alien species richness through increases in the number of botanic gardens in a region. However, these variables only explained 27% of the variation in botanic garden density, indicating that other unmeasured factors might be more important in determining this variable.

Tentative conclusions from this analysis are that the number of botanic gardens appears to influence alien plant species richness in a region and, although this effect is small relative to the direct effect of human population density, it is significant. Further research is needed to understand the processes that link botanic gardens to alien plant species richness as well as the factors that determine the number of botanic gardens in a region.

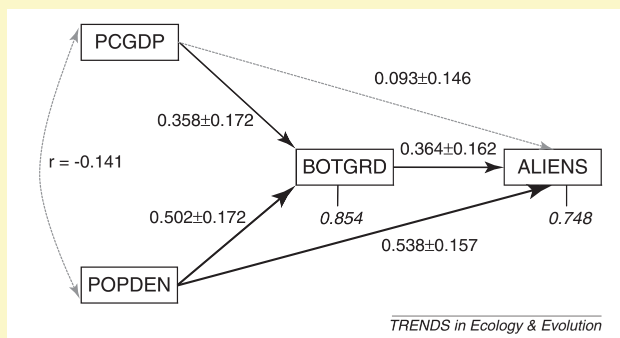

Figure I. Path model of hypothesized causal relationships between alien plant species richness and number of botanic gardens, human population density, and per capita GDP across 26 global regions. Published values for per capita GDP, human population density and alien plant species richness per area [45] for 26 regions across the world were logarithmically transformed before analysis, whereas data on the number of botanic gardens were taken from the BGCI Plant Search database (http://www.bgci.org/plant_search.php) and scaled per unit area. Numbers on arrows are standardized OLS partial-regression coefficients and their associated standard errors, with the width of the arrow reflecting statistical significance (dotted arrow, non-significant; thin arrow $P < 0.05$; thick arrow $P < 0.01$). Each single-headed arrow represents a hypothesized direct causal relationship in the direction of the arrow, and indirect causal relationships occur if one variable is linked to another via another, intermediate variable. A double-headed arrow infers correlation rather than causation, and the correlation coefficient is provided. Values in italics are the path coefficients for the residual variables that reflect all unmeasured variables that affect the dependent variable. Path analysis was robust to assumptions of low co-linearity among predictor variables (variance inflation factors all <1.5 and tolerance scores >0.6) and the sample size per estimated coefficient was greater than the minimum (5) required for reliable results [49,50]. Abbreviations: ALIENS, number of alien plant species/km^2 (log-transformed); BOTGRD, number of botanic gardens/km^2; PCGDP, per capita GDP (log-transformed); POPDEN, human population/km^2 (log-transformed).

the invasion risk posed by botanic gardens should not be underestimated (Box 2). One way to assess this risk is to examine whether, across regions, alien plant species richness is related to the number of botanic gardens. Preliminary evidence indicates that, when other important correlates of alien plant richness are taken into account, a significant effect of botanic gardens on alien plant species richness is found (Box 3). The variation explained by botanic gardens is a little over 10%, which is consistent with these institutions being only one source of alien plants, with other sources of alien plant introduction, such as the use of species in erosion control, landscaping, and horticulture as well as feral crops and grain contaminants, also contributing to alien plant species richness [19]. Furthermore, these results highlight that the establishment of botanic gardens is strongly related to socioeconomic factors, such as population density and per capita gross domestic product (GDP). This is supported by the highly significant correlation across the 216 nations of the world between the number of botanic gardens and GDP ($r = 0.914$, $df = 214$, $P < 0.001$). Thus, the rapid increase in numbers of botanic gardens worldwide since 1950 probably reflects the growing global economy [20]. Yet, if past trends continue, the rapid increase in the numbers of botanic gardens portends a greater risk of plant invasions.

Awareness but inertia shapes the botanic garden response

The potential risks posed by their living collections have not escaped the attention of botanic gardens. In 1999, the 'Chapel Hill Challenge' was launched as a voluntary code of ethics for botanic gardens and arboreta in the USA that included requirements to perform risk assessments on new plant material, remove invasive plants from collections as well as plant sales, control invasive plants in botanic gardens and develop alternatives to alien plant species in collections [4]. In 2002, a similar set of voluntary guidelines, the 'St Louis Declaration', was launched that, although having specific goals for botanic gardens, targeted the entire horticultural industry [21]. The effectiveness of these voluntary codes of practice do not appear particularly strong, with only ten out 461 botanic gardens in the USA having endorsed the St Louis Declaration (http://www.centerforplantconservation.org/invasives/endorsementN.html). Unfortunately, the situation is similar in the horticulture industry in the USA, with only 7% of horticulture professionals in California having heard of the Declaration [22]. The International Agenda for Botanic Gardens in Plant Conservation makes no mention of the Chapel Hill Challenge, but requires botanic gardens to develop and implement control measures for invasive alien plants that pose great threats to biodiversity (http://www.bgci.org/ourwork/2010_bgtargets/). This aim was further aligned to the Global Strategy on Plant Conservation (GSPC) in 2002 with the expectation that, by 2010, all botanic gardens would have carried out invasive species risk assessments of their collections and together they would have contributed to best practice for control programmes for at least 100 major invasive species that threaten plants, plant communities, and associated habitats and ecosystems [23]. To date, there is only limited support for systematic risk assessments having been undertaken in botanic gardens, with examples only from the USA [24], Tanzania [25] and Australia [26]. The only evidence for meeting the GSPC invasive management goal [27] is drawn from the IUCN *World's Worst Invasive Species* publication [28]. Given that this evidence was published before these targets were actually agreed and includes species outside the direct responsibilities of botanic gardens (e.g. marine invertebrates and animal pathogens), it provides little verification for proactive action by these institutions against invasive species. In addition, the International Plant Exchange Network, which supports exchange of material among botanic gardens, places no restrictions on whether a species might be invasive (http://www.botgart.uni–bonn.de/ipen/criteria.html). The foregoing highlights that botanic gardens are aware of the threat that their living collections might pose as sources for the introduction of invasive plants species and have attempted to provide guidance both nationally and internationally [29], but that global uptake and engagement have been poor. What then does the future hold?

Resolving the conflict: recommendations for a way forward

Botanic gardens are only one potential source of alien plant introductions, commercial plant nurseries, amenity and landscape planting and the horticulture industry also have a significant, if not greater, role. Why focus on botanic gardens? In essence because the conservation community should be seen as acting in a concerted way and that the umbrella of plant conservation under which many botanic gardens sit is not compatible with a lax attitude towards biological invasions. Furthermore, the increasing importance of retail activity in the balance sheets of many botanic gardens highlights a potential role to influence attitudes throughout the horticulture industry.

In an ideal world, a botanic garden would adopt a strategy along the lines of the St Louis Declaration, consult with stakeholders over its implementation, subsequently identify known and potentially invasive species, put in place management to reduce or remove risks posed by alien species, ensure commercial sales and further plant introductions are of low risk species, and use the resources of the garden to educate the public regarding biological invasions. Is this wishful thinking? In fact, this ideal describes the strategy currently adopted by the Chicago Botanic Garden [29], a leading example of what can and should be done to address the spread of alien plants from living collections. Why are there so few examples of such best practice among the 2600 botanic gardens worldwide? Three major stumbling blocks and their potential solutions are outlined below:

The fundamental elements for a sustainable botanic garden strategy that balances the risk posed by alien species against the educational, commercial and aesthetic benefits of diverse living collections are already espoused in the St Louis Declaration. These elements can also be found in voluntary codes of conduct on horticulture published by the Council of Europe, yet in what is probably an important oversight, these codes do not specifically address the activities of botanic gardens [30]. The wider adoption of voluntary codes of conduct specifically for botanic gardens would be strongly facilitated if embraced by an international body with oversight of the activities of botanic gardens. One such candidate is Botanic Gardens Conservation International (BGCI), which developed the International Agenda for Botanic Gardens in Conservation. At present, BGCI membership only encompasses approximately a quarter of all botanic gardens, but these appear to be the more conservation-enlightened institutions. For example, although only 17% of botanic gardens in the USA are BGCI members, they include the majority of those that have endorsed the St Louis Declaration. The BGCI should make explicit codes of conduct along the lines of the St Louis Declaration the cornerstone of its invasive plant species policy, while actively encouraging, monitoring and reporting rates of endorsement across its membership. These codes of conduct should be supported by the Convention on Biological Diversity, perhaps to the extent of uptake being a specific indicator of invasive species management. Therefore, such codes of conduct need to have a much higher profile in the future Global Strategy for Plant Conservation (2011–2020).

Risk assessments of existing living collections are of paramount importance to prevent potentially invasive species spreading from botanic gardens. Simply cataloguing species with known invasion histories in living collections is not sufficient (http://www.plantnetwork.org/aliens/). The Australian Weed Risk Assessment protocol has been successfully applied to assess the risks of living collections in the USA, Tanzania and Australia [24–26]. However, risk scores should be moderated using information of the number and performance of individual plants in living collections, as well as the likelihood of escape and the vulnerability of the surrounding environment to invasion. Risk management options to limit spread could then be implemented, which might include removal of the species from collections. However, if an invasive species present in living collections is already widespread in a country, local management will only be relevant if part of a national strategy. Given the potential complexity of these tasks, the lack of uptake to date undoubtedly reflects an absence of agreed standards and a requirement for capacity building to assist botanic gardens with risk assessments. Collaboration between the Global Invasive Species Programme (http://www.gisp.org/), an organization with a history of producing invasive species management guidelines, and BGCI could prove beneficial in the development of standard protocols and joint training materials targeting risk assessment approaches for botanic garden living collections.

Weed risk assessment is particularly effective for species with a previous invasion history elsewhere in the world [24–26], but the number of species in living collections suggests that botanic gardens host potentially invasive species with no such history. Information sharing through organizations such as BGCI regarding invasive behaviour of species in botanic gardens (e.g. aggressive vegetative spread, copious seed production and seedling recruitment, observations of seed dispersal over long distances etc.) would prove invaluable to identifying potential threats. Botanic gardens are already being encouraged to use their living collections as sentinel plants to provide advance warning of native pests and pathogens capable of feeding on species from other parts of the world [31]. Similar information sharing on invasive plants would significantly improve risk assessments and inform listing in the Index Seminum to ensure invasive species are not shared among botanic gardens. Although some botanic gardens have opted out of the Index Seminum (e.g. Chicago Botanic Garden), it still represents a major global network of seed exchange among botanic gardens. The consequences of these different actions in terms of foresight can be estimated from past examples where prior knowledge might have prevented introductions of problematic species elsewhere, or at least forewarned of the risk (Box 1). Several species were recorded as escaping from at least one tropical botanic garden (e.g. *Psidium cattleianum*, *Lantana camara* and *Hiptage benghalensis*) as much as a century before they were introduced to other botanic gardens. Information sharing today could certainly avoid making the same errors as in the past.

Conclusions

Botanic gardens are important cultural, aesthetic and scientific resources that need to be sustainably managed to ensure their benefits are maximized without a cost to the environment. The risks posed by invasive species in living collections should not be underestimated, but a balanced approach is required that ensures the few problem species are dealt with effectively and with stakeholder support. An assessment of the invasion risk posed by species in living collections will provide benefits not only to botanic gardens, but also to the horticulture industry and wider conservation organizations, as information on problem species is shared broadly. As a result, resources to combat plant invasions can be targeted at prevention rather than at more costly strategies, such as containment or eradication. Guidelines and protocols now exist that should facilitate appropriate risk management of living collections and what is required is a concerted push to achieve these goals. By showing such leadership, botanic gardens can yield greater influence on the horticulture industry to adopt similar best practices. As a result, botanic gardens can have a key role in the management of invasive plants worldwide and further consolidate their position as leading players in global plant conservation.

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