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LETTER

Horticultural plant use as a so-far neglected pillar of ex situ conservation

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Abstract
We demonstrate how native and nonnative plant taxa used as ornamentals in private and public urban green spaces can significantly strengthen plant conservation in time of extinctions by expanding the capacity for ex situ living collections and raising awareness among professional and private gardeners and plant collectors. Based on global databases, we document the current representation of threatened plant taxa in horticulture compared to collections in botanical gardens. A substantial number of threatened taxa are already used in gardening, however, there is great unused potential—especially to reach high enough representation of genetic diversity and plant material for reintroduction and restoration programs. Considering urban greening as an integral part of ex situ conservation strategies can provide critically needed additional space and human resources for ex situ collections, while increasing the often low genetic, species and phylogenetic diversity of many newly established plantings that make them vulnerable to climate change and disease risks.

KEYWORDS
BGCI PlantSearch, Botanic Garden, ex situ conservation, horticulture, IUCN Red List, urban green space

1 | INTRODUCTION

With almost 40% of global plant diversity threatened with extinction (Nic Lughadha et al., 2020), the integrity of the biosphere is eroding. Plant species for which in situ conservation (alone) cannot guarantee species survival depend on ex situ conservation (Cochrane et al., 2007); that is, conservation in seed banks or living collections outside of their habitat (Oldfield, 2009). Target 8 of the Global Strategy for Plant Conservation (GSPC) requires that by 2020 at least 75% of threatened plant species are conserved ex situ, with at least 20% available in sufficient numbers for restoration (Convention on Biological Diversity, 2010). These targets have not yet been reached (Mounce et al., 2017), and post-2020 targets have not yet been formulated.

Although seed banks are efficient in terms of space, maintenance costs, and capturing genetic diversity (Li & Pritchard, 2009), they halt reproduction and evolutionary response to a changing environment. Further, a third of all threatened plant species cannot be stored in seed banks due to their recalcitrant (i.e., desiccation sensitive) seed (Wyse et al., 2018). To secure the necessary genetic diversity for successful reintroductions of a species, at least 25–30 individuals from each of several populations across a species' complete range—that is, a total of several hundred individuals—have to be kept in ex situ collections (Hoban & Schlarbaum, 2014). This is difficult to achieve within botanical gardens in particular for tree species due to their sheer sizes (Oldfield, 2009). Although botanical gardens devote currently only 10% of their capacity to threatened species and therefore should have the capacity to meet the 75% target of threatened species in ex situ cultivation (Mounce 2017), the living collections do not include sufficient intraspecific genetic diversity for meeting the 20% target of threatened species available for reintroductions (Sharrock, 2020).

Alongside botanical gardens, ornamental plant use in private gardens and public green spaces (hereafter domestic plant use or domestic gardening) may have the potential to support ex situ conservation of threatened plant species. Gardening has a long tradition of collecting and propagating wild plant species from around the world. Rare and special species are often particularly sought for (van Kleunen et al., 2018). These domestic collections of plant diversity are effectively ex situ collections. However, it is unknown how relevant threatened plant species collections in domestic gardening are and therefore to what extent they could assist plant conservation.

The potential of horticultural propagation for domestic gardening to reduce harvesting pressure on wild populations and as a cost-effective ex situ conservation strategy has been acknowledged (e.g., Raven, 1976), but has also been criticized because it opens opportunities for laundering wild provenances and can increase harvesting from the wild for supplementing breeding stocks (Liu et al., 2019). Although trade and access are internationally regulated for ca. 30,000 plant taxa (CITES, 2019), harvesting from the wild and illegal trade remain major threats (Phelps & Webb, 2015; Sharrock, 2020). As shown for orchids, especially hobbyists are frequently involved in smuggling or laundering of CITES-listed plants of wild origin (Hinsley et al., 2017).

Various urban green spaces, including gardens and parks, harbor threatened native (Planchuelo et al., 2019) as well as threatened nonnative plant species (Ossola et al., 2020). Although domestic gardening is sometimes considered as an ex situ conservation tool, the focus is solely on native species (e.g., Hirst et al., 2019; Sawyer, 2005; topos, 2019), while ex situ conservation and propagation of nonnative species is common practice in botanical gardens (Mounce et al., 2017). With the exception of some species extinct in the wild (EW; Maunder et al., 2000; Maunder, Cowan, et al., 2001), scientific assessments of ex situ cultivation focus only on stocks within botanical gardens (e.g., Kozlowski et al., 2012).

In this study, we assess the current availability of threatened plant species for domestic gardening to evaluate the potential contribution to ex situ conservation, irrespective of their status of being native. Based on global databases, we compare the threatened plant taxa held in botanical gardens to those available in horticultural trade, and we analyze the representation of different growth forms of threatened plant taxa in domestic gardening. We conclude by highlighting opportunities and challenges of ex situ conservation through domestic plant use.

2 | METHODS

2.1 | Data compilation

Using the R package *rredlist* (Chamberlain, 2020), we downloaded from the IUCN Red List API (https://apiv3.iucnredlist.org/, accessed May 4, 2021) the list of threatened plant taxa (species, subspecies, varieties; "vulnerable" [VU], "endangered" [EN], "critically endangered" [CR], and "EW"). These data include the global conservation status and growth form according to the IUCN Red List version 2021-1 (IUCN, 2015). Growth forms were grouped into herbs, shrubs (including cycads), succulents, trees, vines, epiphytes, ferns, hydrophytes, lithophytes, and parasites (with multiple assignments per species possible).

Representation in ex situ collections in botanical gardens was extracted from the PlantSearch database of Botanic Gardens Conservation International (BGCI, http://www.bgci.org/plant_search.php, accessed April 28, 2021). Additionally, we extracted from the PlantSearch database the number of ex situ collection sites worldwide. It has to be noted that not all taxa recorded in the PlantSearch database are also reported to occur in at least one ex situ site (i.e., are certainly growing ex situ).

Taxa used in domestic gardening were extracted from Dave's Garden PlantFiles (DG, http://davesgarden.com/guides/pf/, accessed March 23, 2016) and the Plant Information Online database (PIO, https://plantinfo.umn.edu/, accessed November 22, 2017) for a previous analysis (van Kleunen et al., 2018). Although more species might have been added to those databases in the last couple of years, the numbers are likely neglectable. Furthermore, although both databases claim to be of global scope, it should be noted that DG and PIO have a primary focus on North

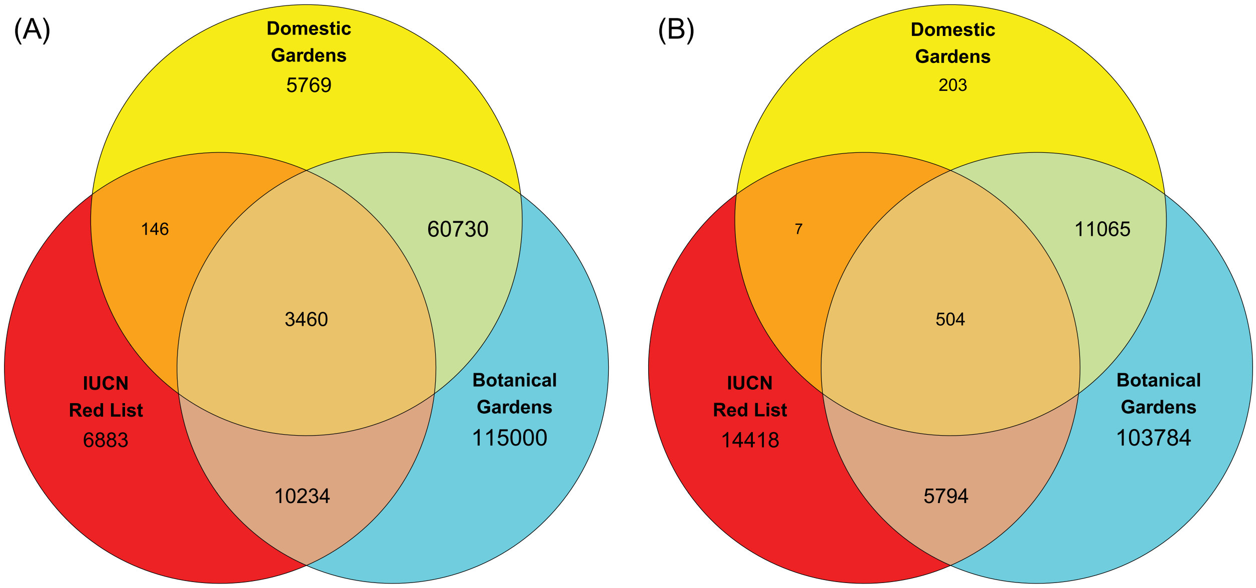

FIGURE 1 Number of threatened plant taxa and their representation in botanical and/or domestic gardens for (A) the "Full" and (B) the "SubSet" dataset. Font size of numbers are proportional to the log-transformed numbers

America, and that there might be a bias against tropical taxa. From these databases, we extracted the number of vendors selling a taxon (from DG), and number of retail and of wholesale nurseries offering a taxon (from PIO). This was used to identify taxa that are recorded in DG and PIO but are not reported to be offered by a vendor or nursery (i.e., are not certainly used in domestic gardening).

Taxonomic names were standardized based on The Plant List (www.theplantlist.org, version 1.1, September 2013) using the R package *Taxonstand* (Cayuela et al., 2019). We excluded all nonvascular plants as well as cultivars.

To account for the possibility that not all taxa recorded in the databases might actually occur in botanical gardens or are available for domestic gardening, we used two datasets for our analyses: the complete dataset ("Full") and a reduced conservative dataset including only taxa certainly growing ex situ in botanical gardens and used in domestic gardening ("SubSet"). The Full dataset included all taxa that are threatened according to the IUCN Red List or occur in the BGCI or DG and PIO datasets. For the SubSet data, the following taxa were excluded from the Full data: all taxa for which the number of ex situ sites in BGCI PlantSearch or the number of retail locations in the combined domestic gardening databases was zero. The full dataset includes 202,222 taxa (20,723 from the IUCN Red List; 189,424 from BGCI PlantSearch; and 70,105 from DG and PIO) and the subset consists of 135,775 taxa (20,723 from the IUCN Red List; 121,146 from BGCI PlantSearch; and 11,779 from DG and PIO).

2.2 | Data analysis

To visualize the overlap of taxa representation in ex situ collections of botanical gardens versus domestic gardening, we plotted Venn diagrams. To investigate whether certain growth forms of threatened taxa were over- or underrepresented in domestic gardens—or alternatively in botanical gardens—we calculated the relative frequency of growth forms among those in domestic gardening (viz. in botanical gardens) compared to all threatened plant taxa and evaluated significance with a resampling test based on 9999 randomizations.

3 | RESULTS

Figure 1 shows the overlap of threatened taxa in botanic gardens (BGCI PlantSearch) and domestic gardening databases. Of all threatened plant taxa ($n = 20{,}723$), 66.1% ($n_{\mathrm{Full}} = 13{,}694$) are recorded in BGCI PlantSearch, that is, are presumably held in ex situ collections of botanical gardens (SubSet: 30.4%, $n_{\mathrm{SubSet}} = 6298$). Of all threatened plant taxa, 17.4% ($n_{\mathrm{Full}} = 3606$) occur in domestic garden collections (either DG or PIO, or both; SubSet: 2.5%, $n_{\mathrm{SubSet}} = 511$). The majority of threatened taxa used in domestic gardening occur also in botanical gardens (Full: 96.0%, $n_{\mathrm{Full}} = 3460$; SubSet: 98.6%, $n_{\mathrm{SubSet}} = 504$), while less than 1% of threatened taxa are exclusively used in domestic gardening but not botanic gardens (Full: 0.7%, $n_{\mathrm{Full}} = 146$; SubSet: 0.03%, $n_{\mathrm{SubSet}} = 7$; species list provided in Table S1). Qualitatively similar results were found when the

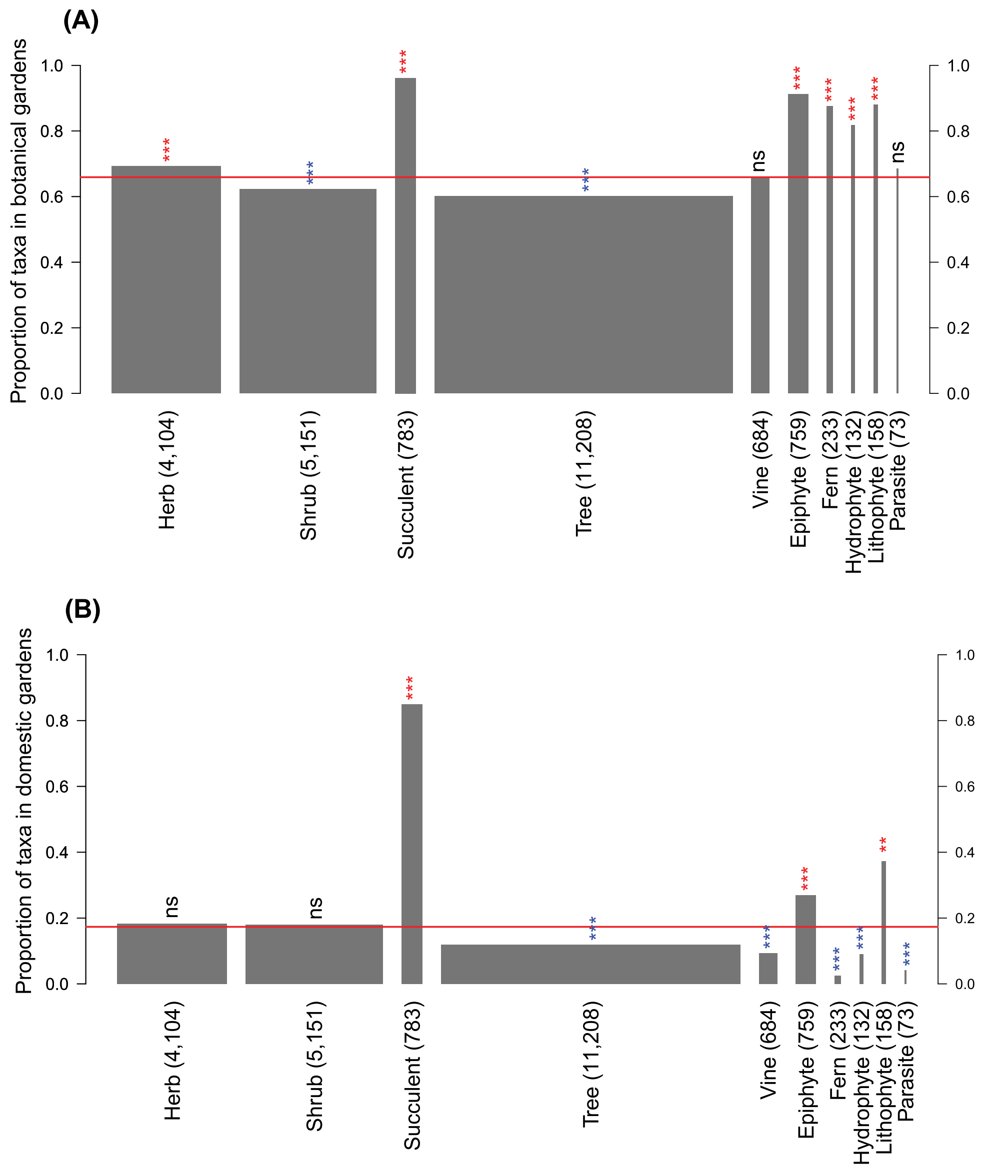

FIGURE 2 Over- and underrepresentation of growth forms of threatened plant taxa in botanical gardens (A) and in domestic use (B) based on the "Full" dataset. The width of the bars is proportional to the number of taxa in each category of growth form, and these numbers are given in brackets. The red horizontal lines indicate the proportion of threatened plants species in botanical and domestic gardens, respectively. Significance levels: $**p < 0.01$, $***p < 0.001$ (red for overrepresentation and blue for underrepresentation)

analyses were done separately for the different threat categories except for the 41 "EW" taxa that were overrepresented in domestic gardening (Full: 70.7%, $n = 29$; SubSet: 22.0%, $n = 9$; Figures S1 and S2). None of the taxa assessed as EW appear exclusively in the domestic gardening databases.

Among threatened plants in botanical gardens, herbs, succulents, epiphytes, ferns, hydrophytes, and lithophytes were significantly overrepresented, and shrubs and trees were underrepresented (Figure 2A). In domestic gardening, succulents, epiphytes, and lithophytes were significantly overrepresented, while trees, vines, ferns, hydrophytes, and parasites were underrepresented (Figure 2B).

4 | DISCUSSION

A substantial number of threatened plant taxa are used in domestic gardening ($n_{\mathrm{Full}} = 3606$, $n_{\mathrm{SubSet}} = 511$), and in particular succulent taxa are overrepresented. Considering that currently only around 13% of all described plant species have been assessed under the IUCN Red List and that the databases on plants used in domestic gardening are not exhaustive, the number of effectively threatened taxa used in domestic gardening is certainly higher. Some plant groups such as cacti, cycads, and conifers have been assessed comprehensively (Goettsch et al., 2015) and are therefore not affected by this potential bias. It is noteworthy that many of the horticulturally used threatened taxa belong to phylogenetic distinct lineages or represent "living fossils" consisting of only one or very few relict species within their genus or family (e.g., *Araucaria*, *Cercidiphyllum*, *Cycas*, *Eucommia*, *Ginkgo*, *Metasequoia*, *Sequoia*, *Sequoiadendron*, *Wollemia*, *Zelkova*)—thus representing particularly high conservation value. The threatened taxa that occur exclusively in domestic gardens but not botanical gardens ($n_{\mathrm{Full}} = 146$; $n_{\mathrm{SubSet}} = 7$; Table S1) represent mostly trees and shrubs ($n_{\mathrm{Full}} = 79$, but for 40 taxa there is no growth form recorded). The often very attractively flowering families Proteaceae and the Malvaceae contain the most threatened taxa recorded exclusively in domestic gardens (Proteaceae: $n_{\mathrm{Full}} = 23$, Malvaceae: $n_{\mathrm{Full}} = 15$). It seems that factors like (phylogenetic) uniqueness and also rarity can contribute to the attractiveness of plants for gardeners. Indeed, rarity has been shown to stimulate demand, willingness to pay, and risk-taking of specialized plant collectors (Courchamp et al., 2006). Such a preference for rare species can be a conservation concern due to illicit harvesting from the wild, for instance, among Cactaceae (Goettsch et al., 2015) and also other taxonomic groups (Courchamp et al., 2006); but, as we demonstrate, can also be an opportunity.

Most threatened taxa used in domestic gardening occur also in botanical gardens, which might partly reflect the important role of botanical gardens in plant explorations and the horticultural supply chain (van Kleunen et al., 2018). Consequently, domestic ex situ conservation has at present its main potential in complementing ex situ conservation efforts of botanical gardens by providing massive additional space and human resources for achieving the number of seed sources or plant individuals needed for reintroduction and restoration programs. In particular, for long-lived and large taxa (such as trees, shrubs and some succulents, vines, and long-lived forbs), space constraints limit the number of individuals that can be kept in botanical gardens. In the United Kingdom alone, members of The Royal Horticultural Society annually plant more than 150,000 trees (RHS, 2021a), underlining the potential of private gardens. In any case, it is advisable that threatened taxa are first included in botanical garden collections and only thereafter also used in domestic gardening in close partnership with plant conservation experts to ensure that effective horticultural protocols are used for successfully growing the different species (Corcoran et al., 2014). Botanical gardens are well-positioned in terms of expertise, facilities, and networks for implementing a successful global plant conservation strategy but need more resources to do so (Westwood et al., 2020). By engaging with hobbyist gardeners and public green-space managers, botanical gardens could extend their efforts in ex situ plant conservation and establish many more viable ex situ populations (compare for cultivars, e.g., RHS, 2021b).

The promotion of native plant species in urban green space is increasingly recognized as a conservation measure for fostering urban plant diversity and associated wild species such as birds and insects (Blackmore, 2019; Bretzel et al., 2016). The potential of domestic plant use for supporting threatened species is, however, rarely considered in scientific literature. One exception is oceanic islands, where most native species have become rare, and thus threatened species are almost inevitably used for landscaping (Webb, 2009). For instance, luxury resorts on the Seychelles maintain restoration areas on their land including threatened species and use their projects for marketing of ecotourism (Kueffer & Kaiser-Bunbury, 2014), while, in New Zealand, city councils promote threatened native plants in diverse urban settings (e.g., parks or along streets) with the involvement of the local botanical garden and citizens (Sawyer, 2005). On continents, we are, for instance, aware of three innovative approaches aimed at harnessing the capacity of gardeners for plant conservation. In Switzerland, volunteers were trained by a specialized conservation organization to grow threatened herbaceous species in their private gardens with the aim to produce seed material for reintroduction programs (topos, 2019), while at the Royal Botanic Gardens Victoria (Australia), genetically diverse planting stocks of threatened native forbs are maintained to supply conservationists, plant collectors but also the general ornamental horticulture market (Hirst et al., 2019). While these two projects focus on ex situ propagation of species within their native range, the International Conifer Conservation Programme (ICCP) has established a network of over 200 "safe sites" mainly in private estates and gardens to safeguard around 14,000 specimens of threatened native as well as nonnative conifers (Gardner et al., 2019).

Examples of cycad cultivation in Mexico (Vovides et al., 2010) and bulb propagation in Turkey (Entwistle et al., 2002) indicate that propagation of threatened plants for the horticultural market can also contribute to the economy of local communities. Indeed, especially in poorer countries it is important to ensure that cultivation is economically more profitable than harvesting from the wild (Williams et al., 2014), which can be supported through cultivation-training programs (Williams et al., 2012). A possible extension of such programs could include a certification scheme for commercial nurseries and hobbyist gardeners, which defines standards for domestic ex situ cultivation of threatened plant taxa. This would ensure good practices for, among others, documentation, propagation techniques, and managing genetic diversity, and it reduces the risks of illegal trade or unsustainable harvesting from the wild. Documentation of such ex situ collections would ideally be coordinated through existing international programs and institutions such as BGCI.

Although ex situ cultivations should preferably be within a taxon's country of origin, most botanical gardens are in temperate regions with a strong overrepresentation of Europe and North America (Mounce et al., 2017). Considering this, many threatened taxa will have to be cultivated outside their native range to meet GSPC Target 8. Because many threatened nonnative plant taxa are already used in domestic gardening, ex situ plant conservation programs involving public and private green-space owners hold great potential for threatened taxa also beyond their historical range. Wider geographic distribution of ex situ collections can also reduce the loss of species due to unexpected events (such as political instability, fires, climate change).

4.1 | Managing genetic diversity in domestic ex situ conservation

An important challenge of ex situ collections is to maintain high genetic diversity and to conserve genetic uniqueness. Even in botanical gardens, loss of genetic diversity in living collections is a challenge (Maunder, Higgens, et al., 2001) due to processes such as genetic drift, inbreeding, adaptation to garden conditions, horticultural selection (Ensslin et al., 2015), hybridization (Maunder et al., 2004), and outbreeding (McKay et al., 2005). Such genetic processes might be aggravated if the origins of individuals are not adequately documented (Maunder, Higgens, et al., 2001), which is particularly relevant for ex situ holdings in public and private green spaces where provenances are normally not considered.

Existing horticultural collections might, however, also have particularly high genetic value. Many long-lived taxa, and especially old trees in urban green areas, might represent source populations and hence genotypes that have gone extinct in the wild and are not represented in botanical gardens. For instance, individuals of *Sophora toromiro* (a tree EW from Easter Island) found in private gardens contribute unique genotypes to the total remaining ex situ population (Maunder et al., 2000). Similarly, *Erica verticillata* was thought to be extinct but was rediscovered in botanical and private garden collections and therefore successfully propagated to establish new ex situ and in situ populations (Hitchcock & Rebelo, 2017). Comparisons of genetic composition between wild and planted trees could provide essential insights into the conservation value of many more individuals of threatened taxa commonly used in parks and gardens (e.g., *Sequoia sempervirens*, *Sequoiadendron giganteum*, *Aesculus hippocastanum*, *Ginkgo biloba*, *Cedrus libani*, *Pinus radiata*). The 19th century was a period of plant exploration when arboreta and public parks attempted to curate collections of special trees from different biogeographic regions (Woudstra, 2003). The remaining living urban trees planted during this period—that were at the time presumably collected in wild places that are meanwhile destroyed—and their early progenies are now often senescent. As a consequence, the window of opportunity to harness the genetic diversity of these oldest city trees is narrowing.

In contrast, the conservation value of recently planted ornamental trees and short-lived taxa is probably often limited because they are often selected, bred, and propagated extensively from few genotypes thereby losing the genotypes of wild origin. Consequently, offspring of such cultivars are not suitable for supporting threatened plant taxa due to potential swamping of the remaining wild genotypes with horticulturally selected genotypes (Ellstrand et al., 1999). Still, cultivars could contribute to conservation of their species: If collections from the wild can effectively be controlled, commercial cultivation has the potential for reducing harvesting pressure on wild populations (Williams et al., 2014). Certainly, it is important to reverse the trend toward low genetic, species and phylogenetic diversity among the most widely used ornamental plants in urban spaces. This is a serious concern because high biological diversity in urban plantings is essential to promote urban biodiversity and resilience to climate change, diseases, and other global changes.

5 | CONCLUSIONS

We should better harness the capacity of domestic gardening for ex situ conservation of threatened plants, and especially so in a time of accelerated species extinctions. Investing in long-term and mutually beneficial partnerships with the horticultural and landscaping industry, plant collectors and private gardeners will be essential to achieve Target 8 of the GSPC. Such partnerships are also a unique opportunity to raise awareness for plant conservation. The example of ex situ plant conservation through horticulture demonstrates how urban areas can inspire new conservation approaches for the Anthropocene. By acknowledging the value of nontraditional conservation actors—such as horticulturalists and private gardeners—and of cultivated threatened species—whether native or nonnative—it might indeed be possible to reach the ex situ conservation targets of the GSPC. Certainly, the already existing horticultural plantings of threatened taxa, whether in the native or nonnative range, should be considered as valuable ex situ collections that often require better recognition and protection.

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AUTHOR CONTRIBUTIONS

Christoph Kueffer and Sascha A. Ismail conceived the study. Robin Pouteau, Mark van Kleunen, and Noëlie Maurel conducted the analysis with inputs from Sascha A. Ismail. Sascha A. Ismail wrote the manuscript with the assistance of Christoph Kueffer and contributions from all co-authors. Christoph Kueffer led the study.

ETHICS STATEMENT

The manuscript complies with ethical scientific standards.

DATA ACCESSIBILITY STATEMENT

All databases used in this study are openly available from the IUCN Red List API at https://apiv3.iucnredlist.org/, from the PlantSearch database of Botanic Gardens Conservation International at http://www.bgci.org/plant_search.php, from Dave's Garden PlantFiles at http://davesgarden.com/guides/pf/, and from the Plant Information Online database at https://plantinfo.umn.edu/.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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