Received: 24 January 2020 | Revised: 10 June 2020 | Accepted: 23 June 2020
DOI: 10.1002/ppp3.10134

Plants People Planet PPP Open Access

OPINION

Botanic garden solutions to the plant extinction crisis

Murphy Westwood[1,2] | Nicole Cavender[1] | Abby Meyer[3] | Paul Smith[2]

[1]Science & Conservation, The Morton Arboretum, Lisle, IL, USA
[2]Botanic Gardens Conservation International, Surrey, UK
[3]Botanic Gardens Conservation International-US, San Marino, CA, USA

Correspondence
Murphy Westwood, Global Tree Conservation, The Morton Arboretum & Botanic Gardens Conservation International. 4100 IL Route 53, Lisle, IL 60532, USA.
Email: mwestwood@mortonarb.org

Social Impact Statement
Botanic gardens and arboreta have evolved significantly from their origins as oases reserved for the elite, to the conservation powerhouses they are today, visited by over half a billion people annually. Now, with their sophisticated facilities and botanical expertise, gardens are uniquely positioned to address many of the challenges associated with preserving plant diversity for the benefit of people and the planet. Globally, however, resources for and awareness of these efforts are limited. Funders, governments, corporations, and global citizens need to greatly increase their support of gardens, recognizing the critical role they play in a scientifically informed, coordinated, global effort to save plants from extinction – because all life depends on plants.

Summary
Over centuries, botanic gardens and arboreta have evolved considerably in purpose and audience, from a historic focus on teaching and reference collections to championing plant conservation today; gardens fill a major global conservation need at the intersection of horticulture, living collections, plant science, and public education. With a sixth global mass extinction event underway, we are losing plant species before they can even be described, and over 20% of plant species are threatened with extinction. In response to this crisis, gardens are increasingly placing the conservation of plant diversity at the center of their missions, programming, and collections. However, there are significant challenges to preserving the world's vast plant diversity, and plant conservation efforts remain chronically underfunded. We envision a future where gardens have the resources, coordination, and capacity needed to reverse the plant extinction crisis. With sufficient resources, the garden community could: (a) operate an active network of globally coordinated gardens with capacity to carry out integrated plant conservation focused in biodiverse regions; (b) complete threat assessments for all plant species, to inform and prioritize conservation efforts; (c) conserve all "exceptional species" in genetically diverse living collections; and (d) ensure more informed, resilient, and productive landscape restoration efforts are successfully sequestering carbon and supporting biodiversity globally. The garden community is poised to lead these global efforts to preserve and protect plant diversity. Gardens have the expertise, tools, facilities, and networks in place to be the strongest force for plant conservation – they just need the resources to match the global need.

KEYWORDS
arboretum, biodiversity hotspot, capacity building, ex situ conservation, exceptional species, in situ conservation, integrated plant conservation, landscape restoration

1 | INTRODUCTION

The environmental movement today is focused on several major themes including climate change, deforestation, and biodiversity loss, but the specific loss of plant diversity is often overlooked, despite the fact that an estimated 80,000 (>20%) plant species are threatened with extinction (Brummitt et al., 2015). To put this in context, there are likely more threatened plant species than all described birds, mammals, reptiles, amphibians, and fishes combined (IUCN, 2020). It is well known that plant conservation receives a disproportionately small amount of funding relative to animal conservation (Havens, Kramer, & Guerrant Jr., 2014; Negrón-Ortiz, 2014; Roberson et al., 2020). Yet, plants are the framework that terrestrial ecosystems are built upon, providing critical habitat, food, and ecosystem services (Brummitt et al., 2015). The pressing environmental crises of climate change and biodiversity loss can be addressed with plant-based solutions. Conserving plant diversity ensures that we have more potential solutions in our toolkit to address future global challenges. Botanic gardens and arboreta (hereafter referred to as gardens) sit at the nexus of an unparalleled set of skills, facilities, and expertise that make them uniquely placed to save plant diversity and prevent extinctions (Cannon & Kua, 2017; Chen & Sun, 2018; Krishnan & Novy, 2016; Mounce, Smith, & Brockington, 2017; O'Donnell & Sharrock, 2017; Smith, 2018; Volis, 2017). With added capacity and funding, the garden community is poised and ready to expand its role in leading a global force to ensure plant diversity is secure and thriving in healthy ecosystems for the benefit of humans and nature.

In this article, we summarize how the role of botanic gardens in society has evolved over millennia from pleasure gardens of the elite, to reference collections for intellectuals, to plant conservation champions in the 21st Century. We then present four challenges to conserving plant diversity that gardens today are particularly well positioned to overcome, and we postulate what the future could be if gardens were sufficiently funded to tackle these challenges and reverse the plant extinction crisis we face today.

2 | THE EVOLUTION OF GARDENS: FROM REFERENCE COLLECTIONS TO CONSERVATION CHAMPIONS

Botanic garden concepts have existed since ancient civilizations in Egypt, Rome, Mesopotamia, India, China, and Mexico (to name a few) began cultivating medicinal plants, exotic fruit trees, and spices in royal palaces, religious sites, and private estates of the wealthy (Spencer & Cross, 2017). The early modern "physic gardens" of the 1500s in Europe, such as the walled botanic garden at the University of Padua, focused on plants with medicinal properties that were used for teaching purposes in university medical schools or monasteries. The 1500–1800s was an era of extensive botanical exploration and expansion, with new botanic gardens being established all over the world, largely as a result of European colonialism. During this period, botanic gardens were critical to the advent of the scientific fields of botany, plant taxonomy and systematics (the naming and categorization of species). While contributing greatly to the world's collective botanical knowledge, these early modern gardens, with their strong focus on economic botany, drove the global distribution of valuable plant-based commodities such as rubber, tea, coffee, cinchona, and opium, resulting in large-scale land use change (Krishnan & Novy, 2016; Spencer & Cross, 2017). Given their historical role in driving broad land use change and the commoditization of plants, it is apt that modern gardens should have a role in securing plant diversity for future human innovation, adaptation, and resilience (Smith, 2018).

According to the Botanic Gardens Conservation International (BGCI) *Manual on Planning, Developing and Managing Botanic Gardens*, a botanic garden today can be defined as "an institution holding documented collections of living plants for the purposes of scientific research, conservation, display and education" (Gratzfeld, 2016, p. vii; originally from Peter Wyse Jackson). Gardens today include over 3,000 institutions worldwide, employing over 60,000 botanical experts such as plant scientists, educators, and specialist horticulturists. Gardens house world-class facilities including seed banks, herbaria, greenhouses, nurseries, and research laboratories. Living plant collections still form the core of a garden and are crucial resources for taxonomy, systematics, and teaching, but today, these collections serve many additional scientific and conservation purposes. Plant collections support ex situ conservation of threatened species, provide a source of material for restoration of threatened species and degraded habitats in the wild, and are the subject of research studies investigating population genetics, climate change responses, pest and disease susceptibility, and plant adaptive capacity (Chen & Sun, 2018; Dosmann & Groover, 2012; Griffith et al., 2019). Gardens today hold at least one third of all known plant species in their collections, including over 40% of threatened species, as well as dozens of species that are extinct in the wild (Mounce et al., 2017).

Modern gardens are also a key link between people and plants. In increasingly urbanized societies, gardens provide urban green space that may be the only access many people have to plants and nature. This exposure to nature can provide many physical, mental, and social benefits to the people of these cities (Turner-Skoff & Cavender, 2019). In addition, gardens now provide extensive education programs for everyone from preschoolers to PhD students and beyond. Public engagement is a cornerstone of garden missions;

no longer are gardens restricted in access to an elite few. Today the world's ~3,000 gardens welcome over half a billion visitors a year (based on our unpublished analysis of BGCI's GardenSearch database; https://www.bgci.org/resources/bgci-databases/gardensearch/), with a growing focus on expanding access, diversity, and inclusion for garden audiences, and preserving and celebrating local and indigenous plant knowledge and biocultural heritage (Gratzfeld, 2016). Gardens also interface with community groups, NGOs, industry, corporations, government agencies, universities, and other sectors to conduct research, advance conservation efforts, and build awareness for the importance of plant diversity. Despite the long and evolving history of gardens, and the fact that the thousands of gardens currently in existence are all unique, gardens today collectively fulfill an inimitable conservation role, positioned at the intersection of plant science, living collections, horticulture, in situ conservation, and public outreach and education (Figure 1).

3 | CHALLENGES TO SAVING PLANT DIVERSITY: WHERE CAN GARDENS HAVE THE BIGGEST IMPACT?

Gardens are uniquely placed to address several challenges to conserving the world's plant diversity, if sufficient resources are allocated. Gardens are already rising to meet these challenges in innovative ways, and there are great opportunities to increase the garden community's collective plant conservation impact. In the following sections, we outline four specific challenges to conserving plant diversity, highlighting what gardens are already doing to address these challenges, and we describe what could be achieved in the future if gardens were sufficiently resourced to overcome each challenge.

FIGURE 1 Gardens fulfill a unique conservation role, positioned at the intersection of plant science, living collections, horticultural expertise, in situ conservation, and public outreach and education

3.1 | Mobilizing and coordinating plant conservation and capacity building, especially in biodiverse regions

Currently, gardens tend to engage in plant conservation projects that are locally focused, often funded for the short term through "soft money" (e.g., restricted grants), and relatively small in scale, such as conducting habitat restoration on site or nearby the garden itself (Hardwick et al., 2011; A. Meyer, unpublished data from GardenSearch and the North American Plant Conservation and Biodiversity Benchmarking tool, American Public Gardens Association, https://www.publicgardens.org/communicating-climate-conservation). Some gardens with higher capacity (particularly in high-income economy countries) have large conservation departments and are able to deploy their tools and expertise further afield and even internationally, but that is not currently the norm in all countries. There is a great imbalance in garden conservation capacity in different regions of the world. For example, according to BGCI's GardenSearch database, two thirds of the 551 gardens that report having a plant conservation program are from high-income economy countries as defined by the World Bank (GardenSearch, 2020). Indeed, a fundamental challenge that must be overcome is that the majority of the world's botanic gardens are concentrated outside of the most biodiverse regions. A spatial analysis of BGCI's GardenSearch database of over 3,000 known gardens reveals that only about one third are located in one of the 36 defined global biodiversity hotspots (Figure 2; GardenSearch, 2019; https://www.cepf.net/our-work/biodiversity-hotspots/hotspots-defined). Unfortunately, it is these regions holding the majority of the world's plant diversity (including the most undescribed species) that have low capacity for conservation and need the most support (Heywood, 2017; Joppa, Roberts, Myers, & Pimm, 2011).

In order to address a challenge at the scale of the global plant extinction crisis, garden-led conservation efforts must be massively scaled up and coordinated across institutions, sectors (government agencies, universities, NGOs, etc.), geographies, and political boundaries. Furthermore, botanical capacity must be channeled to support existing gardens and create new gardens in biodiversity hotspots

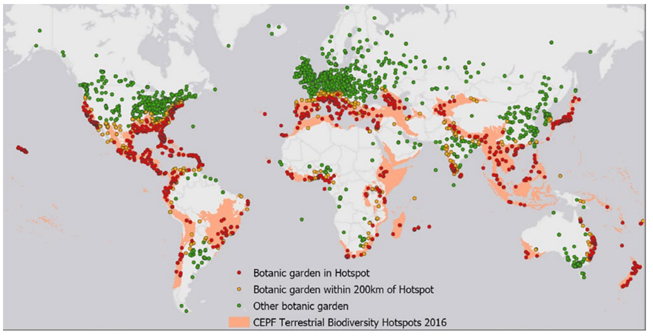

FIGURE 2 Two thirds of the world's 3,000+ gardens are located outside the world's 36 defined biodiversity hotspots. Map credit: Julie Ho, The Huntington Library, Art Collection, and Botanical Gardens, and BGCI-US (2019)

and low-income economy countries of greatest conservation priority. Successful mobilization and coordination of plant conservation efforts requires robust, active networks led by trusted, inclusive organizations, to share best practices and meet standards, aggregate information to inform and prioritize action, and scale up initiatives and mobilize expertise when and where it is needed most. Successful models for this within the garden community already exist and with greater financial support significant conservation outcomes can be achieved, especially in the most biodiverse regions.

As an example, BGCI (bgci.org), the world's largest plant conservation network, promotes a rational, cost-effective 'Global System' for the conservation of all threatened plant diversity (Smith, 2016). This models the United Nations Food and Agriculture Organization (FAO) *"global system for the conservation and utilization of plant genetic resources for food and agriculture"* (FAO, 2011). Under BGCI's Global System, the *Global Strategy for Plant Conservation*, a program of the (Sharrock, 2012), provides the policy and monitoring framework that guides global efforts. BGCI's unique databases of threatened plant species (ThreatSearch), country-level tree checklists (GlobalTreeSearch), ex situ plant collections (PlantSearch), and botanic gardens and infrastructures (GardenSearch) enable data sharing and provide the means to prioritize and coordinate conservation actions (examples of garden-led or garden-focused databases that aggregate, standardize, and disseminate data in support of global plant biodiversity and conservation can be seen in Table 1). BGCI also establishes and coordinates regional garden networks in priority plant diversity areas including Southeast Asia, Africa, and South America. Action is further supported through BGCI's directories of expertise, extensive plant conservation training programs, and targeted financial support (e.g., the Global Botanic Garden Fund), which all prioritize conservation capacity building for gardens in biodiversity hotspots.

ArbNet (arbnet.org), the interactive network of arboreta, is another support structure for tree-focused gardens around the world. ArbNet works to catalyze the establishment of new arboreta, sets standards and best practices among the global arboretum community, offers funding and international arboretum partnership opportunities, provides professional training, and offers an arboretum accreditation program (Westwood, 2015). ArbNet's global database of over 2,000 tree-focused gardens (the Morton Register of Arboreta) and online resource library complement BGCI's databases, fostering collaboration and growth among the global arboretum community (Table 1). In addition to these global networks dedicated to supporting gardens, there are also many regional or national garden networks which could deliver greatly increased plant conservation outcomes with additional funding. Australia, China, France, Indonesia, Japan, Mexico, South Africa, and the U.S. are some of the countries with robust national garden networks that support and coordinate plant conservation efforts among their members.

There are also many conservation-focused collaborative initiatives led by gardens which involve mobilizing expertise, focusing efforts, and/or providing funding for specific plant conservation activities. For example, the Center for Plant Conservation's National Collection of Endangered Plants preserves more than 1,600 of the

TABLE 1 Examples of garden-led or garden-focused databases that aggregate, standardize, and disseminate data in support of global plant biodiversity and conservation. Each supports one or more of the targets of the Global Strategy for Plant Conservation (GSPC)

Database	Records	Description	Supports GSPC Target(s)
CPC Rare Plant Academy https://academy.saveplants.org/	100's of videos, guidelines, protocols, photos, and forum topics	Learning and resource hub for sharing best practices for plant conservation	Targets 3, 7, 8, 15
GardenSearch https://www.bgci.org/resources/bgci-databases/gardensearch/	>3,600 institutions	Listing of the world's botanical institutions with information on collections, facilities, conservation, and research programs	Targets 15, 16
GlobalTreeSearch https://www.bgci.org/resources/bgci-databases/globaltreesearch/	>60,000 species	Only global listing of tree species and their country-level distributions	Target 1
Morton Register of Arboreta http://www.arbnet.org/about-register	>2,000 tree-focused institutions, including >400 accredited arboreta from >30 countries	Listing of the world's arboreta and public gardens that have a substantial focus on woody plants	Targets 15, 16
PlantSearch https://www.bgci.org/resources/bgci-databases/plantsearch/	>1,400,000 records from >1,100 institutions	Plants in cultivation in the world's gardens, seed orchards, and seed banks. Includes living plants, seeds, and tissue cultures.	Targets 8, 9, 10
Seed Information Database https://data.kew.org/sid/	>100,000 records	Seed biological trait data for determining seed conservation methodology	Targets 8, 9
ThreatSearch https://www.bgci.org/resources/bgci-databases/threatsearch/	>300,000 assessments for >180,000 taxa	Most comprehensive compilation of threat assessments for plant species published on any platform at any geographic scale	Target 2
World Flora Online http://www.worldfloraonline.org/	1,324,210 plant names; 350,633 accepted species; 55,272 images; 129,400 descriptions; 31,676 distributions; 1,153,711 references	Open-access, online flora of all known plants	Target 1

most imperiled native plants in the U.S. and supports on-the-ground conservation work by its 60+ member institutions (saveplants.org). The Millennium Seed Bank Partnership, coordinated by the Royal Botanic Gardens, Kew (U.K.), works in partnership with local gardens and seed banks in more than 95 countries and has banked the largest and most diverse seed collection of wild plant species in the world (kew.org/wakehurst/whats-at-wakehurst/millennium-seed-bank). The Global Trees Campaign, led by BGCI and Fauna & Flora International, is an excellent model of garden-led in situ conservation that deploys botanical expertise and builds capacity in priority plant biodiversity regions, in partnership with local communities and stakeholders, to ensure threatened trees are conserved and sustainably managed in their native habitats (globaltrees.org). The Mulanje Cedar Project is one success story of the Global Trees Campaign which has resulted in restoring the once extirpated national tree of Malawi, *Widdringtonia whytei*, producing over half a million seedlings established in locally owned nurseries and community lands, and providing employment for over 150 community members (Smith, 2015).

These garden-led initiatives are all aimed at identifying and filling gaps in conservation activities, capacities, expertise, and plant collections. With sufficient funding to fully develop and grow the networks and initiatives described above, the global garden community would have the ability to coordinate, prioritize, and collaboratively implement urgently needed plant conservation efforts worldwide. Great benefit would come from a vibrant, globally coordinated garden network with the capacity to channel funding from governments, foundations, corporations, and other sectors to support and scale up garden-based plant conservation activities, deploying expertise and resources to fill critical gaps, like supporting the establishment of gardens and conservation projects in biodiversity hotspots where conservation capacity is most urgently needed. By working with these garden networks and garden-led conservation initiatives, funders would ensure their support is used in a coordinated and strategic manner that addresses the highest priority plant conservation projects globally. Individual gardens would tap into the support of their national and global networks, receiving much needed funding, drawing on available guidance, standards, and training, and leveraging their membership in the broader networks to increase funding and raise their profile locally and regionally with governments, funders, and the public.

3.2 | Quantifying the scope of the plant extinction crisis

The world is entering a sixth mass extinction, which is driven by human activity. We are losing plant species before they have even been described, and much faster than the average background rate of extinction over the past several million years (IPBES, 2019). It is gardens that are at the forefront of cataloging and quantifying global threats to plants. The Global Tree Assessment (GTA; https://globaltreeassessment.org/) is an ambitious, garden-led initiative to determine the extinction risk of all of the world's 60,000+ tree species by the end of 2020. Since 2015, the GTA effort has compiled, updated, or completed threat assessments for over half of the world's trees, and revealed that at least 20% of tree species are threatened with extinction (Figure 3). Other significant efforts to evaluate extinction risk for plants include the IUCN Species Survival Commission (SSC) Specialist Groups for cycads (the world's most threatened plant group; Brummitt et al., 2015), cacti & succulents, conifers, Hawaiian endemics, and Madagascar endemics – all of which are led by gardens.

While these efforts have resulted in exponential growth in the number of plants assessed for extinction risk in the past decade (IUCN, 2020), the botanical community will not meet its goal of evaluating all plants by the end of 2020, as proposed by the *Global Strategy for Plant Conservation* (Sharrock, 2012). This shortfall is not due to a lack of skills or commitment, but a lack of funding. Many of the rarest plants, especially those in the least developed countries and biodiversity hotspots, will either be not evaluated or deemed "Data Deficient" because of a lack of information on species distributions, population decline rates, and threats. Yet, these are the species that will most likely be on the verge of extinction (Joppa et al., 2011; Pimm & Joppa, 2015). In some cases, the data are in fact available, but there are simply not enough people working on the global threat assessment effort to evaluate every plant species. Another reason these efforts are likely to fall short of their goal is the sheer scale of the task: there are around 380,000 validly named plant species on Earth, with an estimated 70,000 more yet to be formally described

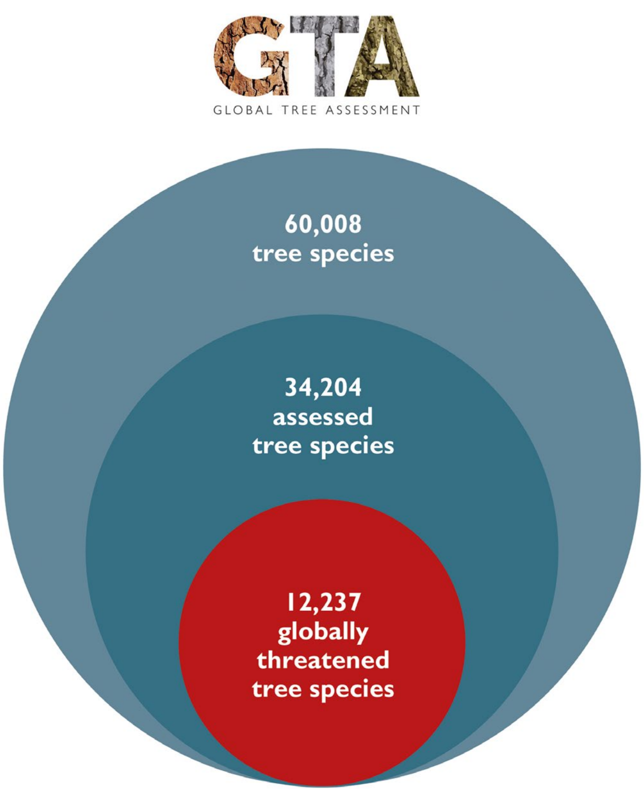

FIGURE 3 Progress (as of March, 2020) on the Global Tree Assessment, an ambitious, garden-led initiative to evaluate by 2020 all ~60,000 of the world's tree species for their risk of extinction

(Pimm & Joppa, 2015; Raven, 2020). To put this in context, there are more tree species alone (~60,000) than there are mammals, birds, reptiles, and amphibians combined (~36,000). Unsurprisingly, only 10% of described plant species have been assessed for the IUCN Red List of Threatened Species, while the assessment rate for the “charismatic” vertebrates is around 72% (IUCN, 2020).

The United Nations reports that the next decade is a critical time to act to avert a climate crisis, and that the impacts of climate change are already being felt around the world and are occurring faster than expected (United Nations, 2019). The botanical expertise of the garden community is needed now, more than ever, to track and monitor the responses of plant communities in myriad ecosystems to our rapidly changing world. More support to build capacity for initiatives like the GTA and others that quantify the scope of the plant extinction crisis are urgently needed so that conservation practitioners, land managers, and policymakers have objective threat assessment data available to make informed decisions to better protect threatened plants and habitats. With additional support for garden-led plant threat assessment efforts, we could achieve a full and clear picture of the extinction risk of all plant species – as has happened for the charismatic animal groups, such as birds – to support scientifically informed and strategically prioritized conservation efforts to prevent the extinction of plant species.

3.3 | Conserving “exceptional species” to preserve genetic diversity

To conserve plant diversity and prevent species extinctions, it is widely accepted that an integrated approach that leverages in situ and ex situ conservation approaches is the best strategy (Oldfield and Newton, 2012; Heywood, 2017; Volis, 2017). However, a recent analysis of the PlantSearch database revealed that only 41% of the world's known threatened plant species are conserved in ex situ collections (Mounce et al., 2017). The most efficient and effective way to capture a high proportion of genetic diversity in an ex situ conservation collection is through seed banking using conventional freezer conditions recommended by the FAO (FAO, 2014; Guerrant, Havens, & Maunder, 2004; O'Donnell & Sharrock, 2017; Walters & Pence, 2020). This approach has some limitations though, and is not applicable to all plant species. “Exceptional species” produce seeds that cannot be seed banked through conventional methods of low humidity and freezer storage (Pence, 2013). As such, exceptional plant species require alternative ex situ storage platforms or conservation measures, such as cryopreservation (see Walters & Pence, 2020, for a synthesis of cryopreservation) or living collections, to preserve genetic diversity (Fant et al., 2016; Griffiths et al., 2019; Hoban et al., 2020). Many iconic plant groups are exceptional, including all magnolias, oaks, and cycads, as well as an estimated 40% of tropical tree species (Tweddle, Dickie, Baskin, & Baskin, 2003). These represent taxonomic and regional priorities for conservation efforts.

Living collections are critically important tools in the integrated plant conservation toolkit for exceptional species, but their conservation value is highly dependent on the level of genetic diversity captured. To be effective, these collections must include dozens, if not hundreds, of individuals of known wild origin, collected from multiple mother plants across the geographic and ecological range of the species (Cavender et al., 2015; Fant et al., 2016; Griffith et al., 2019; Guerrant et al., 2004). Furthermore, these collections must be replicated across institutions as a back-up measure in case of loss due to attrition, institutional closure, pests and disease outbreaks, natural disasters, or theft (Hoban, 2019). Additional considerations for living conservation collections include climate resiliency and ensuring a healthy age demographic within a collection. For conserving exceptional plant species, gardens are the institutions that have the botanical expertise and specialist horticulture facilities required to meet these requirements.

One new initiative that exemplifies the efforts of the garden community to preserve exceptional plant species isthe Global Conse rvation Consortium for Oak (GCCO) led by The Morton Arboretum in partnership with BGCI. The GCCO was designed to address the challenges of conserving oaks in living collections of high conservation quality. In order to sufficiently capture representative genetic diversity, the GCCO relies on its network of coordinated living plant collections at multiple sites – a metacollection – to conserve genetic diversity of priority threatened oak species, much like the model that zoos use to manage captive populations of rare animals (Fant et al., 2016; Griffith et al., 2019; Hoban et al., 2020). The GCCO and its community of local partners also work to ensure threatened oaks are conserved in situ. A cornerstone of the GCCO is to build capacity to empower and mobilize in-country partners in the two global biodiversity centers for the oak group: Mexico and Southeast Asia (Figure 4). This model is especially relevant because it integrates solutions to all of the major challenges highlighted so far in this article. The consortium: (a) involves the coordination of efforts around the world through a transparent governance system, and emphasizes

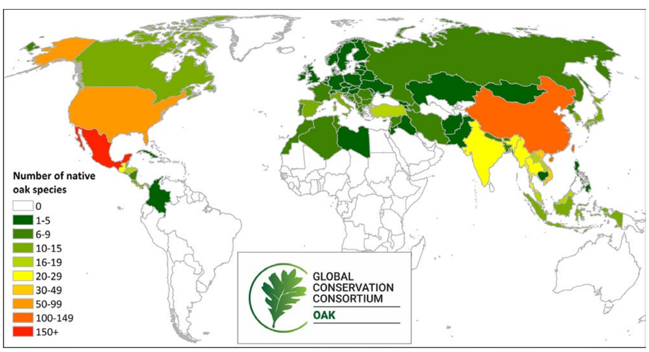

FIGURE 4 Global diversity centers of the world's ca. 450 oak species, representing the regional priorities for the Global Conservation Consortium for Oak (GCCO). Mexico, China, the U.S., and Southeast Asia harbor the highest number of native oak species, and are priority regions for the GCCO's in situ conservation, capacity building, and ex situ collections efforts. Map credit: Emily Beckman, 2019

TABLE 2 Four key challenges to conserving plant diversity that botanic gardens and arboreta are uniquely positioned to address, what is being done currently, and what could be done in the future with more funding.

Key challenge gardens are uniquely positioned to address	What gardens are currently doing	What gardens *could* achieve with more funding
International coordination of efforts and capacity building in biodiversity hotspots	• Advising and establishing new gardens and garden networks, especially in under-resourced, biodiverse regions • Providing training, funding, expertise • Increasing participation in sharing data and plant material • Developing conservation priorities and tracking progress towards goals • Supporting and coordinating collaborative conservation efforts Successful models/programs • Networks: BGCI, ArbNet • Conservation programs: Center for Plant Conservation, Millennium Seed Bank Partnership, Global Trees Campaign, International Conifer Conservation Programme • Various databases and online tools (see Table 1)	• Active global network of coordinated gardens and conservation programs, working efficiently and effectively towards ambitious, strategic, shared goals • Capacity to carry out integrated plant conservation, focused in the most biodiverse regions, engaging local communities and supporting livelihoods • More gardens and regional networks in biodiversity hotspots of urgent need • Robust data sharing platforms for rapid, comprehensive gap analysis and prioritization • Greater collaboration across borders and sectors
Quantifying the scope of the plant extinction crisis	• Leading taxonomically or geographically focused efforts • Some plant groups completely assessed (e.g., conifers, cycads, oaks, magnolias, cacti) Successful models/programs • Global Tree Assessment • ThreatSearch database • Garden-led, plant-focused IUCN species specialist groups	• Gardens actively contributing relevant data on threats, conservation actions, collections, and expertise. • Completed and up-to-date threat assessments for all plant species, to inform and prioritize conservation efforts • Capacity to rapidly mobilize efforts to reassess plant groups and regions in response to a rapidly changing climate and newly evolving threats
Conserving exceptional species	• Working to identify which species are exceptional • Developing new tools and alternatives to conventional seed banking (e.g., cryobiotechnologies) • Increasing focus on genetically diverse and representative living collections of exceptional species • 40% of threatened plant species held in ex situ collections Successful models/programs • Global Conservation Consortium for Oak • Other consortia in development for cycads, dipterocarps, magnolias, maples, rhododendrons, etc. • Exceptional Plant Conservation Network	• Research and protocols in place to identify and conserve all exceptional species • All exceptional species conserved in genetically diverse living collections, supporting integrated conservation in the wild • Data and technology available to manage strategic breeding programs between institutions holding genetically valuable germplasm • Living collections are complemented by cryopreserved material
Using plant-based solutions effectively to combat climate change while also preserving plant biodiversity	• Growing >16,000 tree species in garden collections • Establishing best practices and guidance for collecting, propagating, and planting trees • Conducting and publishing cutting-edge applied tree science • Engaging in local and regional landscape restoration and reforestation initiatives Successful models/programs • Ecological Restoration Alliance of Botanic Gardens • Plant Conservation Alliance National Seed Strategy (U.S.)	• More informed, resilient, and productive landscape restoration efforts across the globe, successfully sequestering carbon and supporting biodiversity • Initiatives reach critical regions and ecosystems in need of restoration/reforestation through expanded and strengthened networks and initiatives • Gardens are engaged and a trusted voice in planning large-scale restoration and reforestation initiatives • Large-scale tree planting efforts are scientifically informed and used appropriately, effectively, and strategically to achieve climate mitigation and biodiversity objectives

capacity building in biodiverse regions; (b) relies on updated threat assessments and accurate biodiversity data to inform conservation priorities, and promotes data sharing and documentation of collections; and (c) is founded on conserving exceptional plant species.

Gardens around the world are poised to replicate the GCCO model, and additional global conservation consortia are being established to focus on other priority exceptional plant groups, including cycads, magnolias, maples, and rhododendrons. But with likely tens of thousands of species falling into some level of exceptionality (i.e., unable to be conventionally seed banked), there is a great opportunity to deploy this strategy more widely, especially for tropical trees. With increased support to individual gardens and garden networks leading these types of initiatives, the global garden community could operate a robust network of taxonomically focused conservation consortia, integrating ex situ and in situ efforts, engaging local communities, and ensuring that no threatened exceptional plant species go extinct.

3.4 | Using plant-based solutions effectively to combat biodiversity loss and climate change

Governments, corporations, and civil society are now well aware of the intertwined challenges of climate change and biodiversity loss, and the need to address these challenges. The recent Intergovernmental Panel on Climate Change (IPCC) report makes it clear that land use change is required in order to mitigate climate change and reduce global CO_2 emissions (IPCC, 2018). This will mean halting deforestation, reducing meat consumption, and planting more trees. Indeed restoration and reforestation initiatives at many scales are already underway, such as the Bonn Challenge (https://www.bonnchallenge.org/) to restore 350 Mha of degraded land by 2030.

As well as a climate crisis, we have a biodiversity crisis – over a million species of plants and animals face extinction due to the activities of humans (Díaz et al., 2019; IPBES, 2019). So, what will global-scale reforestation mean for biodiversity? More forests do not necessarily mean more biodiversity. In fact, the effect can be the opposite, as already seen in many tree plantations in both tropical and temperate regions (Chen et al., 2019; Zhai, Xu, Dai, Cannon, & Grumbine, 2013). To avoid even greater pressure on native ecosystems around the world, governments, corporations, and tree-planting organizations need to factor in biodiversity and ecosystem services other than carbon sequestration, such as erosion control, soil health, water provision and resilience to pests, diseases, and fire. Furthermore, it has been shown that forests with high biodiversity have higher productivity (Liang et al., 2016; Osuri et al., 2020). Unfortunately, there is increasing evidence that humanity's response to the call to plant more trees is to plant as many trees as possible on any available sites, without due consideration to the long-term benefits and costs (Bond, Stevens, Midgley, & Lehman, 2019; Lewis, Wheeler, Mitchard, & Koch, 2019). The reasons for this are largely to do with the lack of regionally appropriate and diverse planting material, information, knowledge, and availability of land. As a wide range of sectors and stakeholders start to embark on large-scale tree-planting and restoration initiatives that, collectively, will cover hundreds of millions of hectares, it is essential that they have access to the best science and practical advice, as well as suitable native plant material.

The world's botanic gardens and arboreta grow at least one third of all known plant species, including >16,000 tree species (Mounce et al., 2017; PlantSearch, 2019). This professional community of >60,000 scientists and horticulturists specializes in both fundamental research and applied practice, and can offer data, skills, and advice to address this challenge. Gardens are of course specialists in growing diverse species assemblages in transformed landscapes (garden collections), but not generally at a large scale. Over the past decade or so gardens have increasingly become involved in the science and practice of ecological restoration (Chen, Cannon, & Hu, 2009; Hardwick et al., 2011). For example, there are now over 40 garden members of the Ecological Restoration Alliance of Botanic Gardens (erabg.org), which aims to build capacity for restoration, including by setting up 100 demonstration sites across a range of ecosystems that restore degraded areas, provide training, and communicate the value of adopting a science-based approach to ecological restoration.

We urgently need to scale up these efforts and engage with broader society on what are now shared goals to protect and restore biodiversity and mitigate climate change. Now it is imperative that gardens provide data, advice, and skills to a much wider range of stakeholders, including governments, corporations, and civil society. In a future with increased funding and support, garden experts including forest ecologists, horticulturists, tree breeders, and climate scientists should be directly involved in large-scale reforestation and habitat restoration initiatives, and should have a seat at the table with relevant decision-makers. Gardens will be able to provide: advice on which native species to plant where; training and protocols for plant collection, germination, and propagation techniques; guidance on the establishment of infrastructure such as seed banks and nurseries; support to local nurseries and tree-planting initiatives to ensure more locally sourced native plant material is in production; guidance on after care and management of newly planted trees; expertise on habitat management and restoration methodologies, and species recovery monitoring and evaluation.

4 | CONCLUSIONS

The concept of a botanic garden has been around for millennia, but the garden's role in society has changed over time, from a pleasure garden for the elite in ancient times, to establishing the disciplines of botany and systematics, to today being a driving force for plant conservation. Today, gardens are uniquely placed to save plants from extinction, and are the key actors to address some of the greatest challenges facing plant diversity, including: (a) mobilizing and coordinating plant conservation efforts, especially in biodiversity hotspots,

(b) quantifying the scope of the plant extinction crisis, (c) conserving exceptional plant species, and (d) using plant-based solutions effectively to combat biodiversity loss and climate change (Table 2). The garden community already has innovative, proven models of initiatives and programs that overcome these obstacles. What is lacking is the support and capacity to scale these efforts up to amplify impact and deliver cost-effective results for biodiversity conservation.

The support that the garden community needs could take many forms. First and foremost, financial support is needed, including donations, grants, operating support, tax credits, and fees for services. But other types of non-monetary resources and support are valuable, including equipment, infrastructure, land, political influence, public recognition of gardens' roles in plant conservation, and ensuring garden experts have a seat at the table during discussions relating to the environment, restoration, tree planting efforts, protected areas, public works projects, or any other decision-making process that impacts plant diversity. The garden community is working towards being able to quantify just how much funding will be needed to achieve major global conservation targets (e.g., for achieving the GSPC), but a clear picture of the financial landscape for garden-led plant conservation at the global scale does not currently exist. What we do know is that the global garden community needs more support to scale up conservation efforts, and that funding and resources are needed at both the level of the individual garden and for broader networks and conservation initiatives, like the ones highlighted in this article.

So *how* can gardens secure additional funding and support? Gardens can start by being stronger advocates for their own unique conservation roles and credentials by building awareness among key stakeholder groups, including government agencies at all levels, corporations, funders, foundations, and the public. Social media campaigns, popular science articles, letters to the editors of local media outlets, public outreach events, engaging in local politics (if allowable), garden interpretation, and providing education programs are some ways to build that awareness. Gardens can also participate in and promote the networks and successful initiatives outlined in this article, which provide proof-of-concept for the impact that gardens can and do have on plant conservation outcomes. Gardens can also work to identify alternative sources of income than the traditional mechanisms of endowments, donations, memberships, earned revenue, and support from a governing body or institution. For example, developing partnerships with corporations to help them achieve sustainability goals, providing consultancy services, leveraging large garden consortia and networks to collectively apply for high volume grants (>US$1M), or tapping into the recent global influx of funding for and interest in tree planting initiatives and landscape restoration at a large scale.

Engaging and inspiring the public about the value of plant diversity is a key step to mobilizing resources and addressing the plant extinction crisis. Gardens have a growing public audience of over half a billion visitors each year globally. This unparalleled access to such a large section of society means gardens have a powerful voice for changing environmental perceptions and attitudes (Williams, Jones, Gibbons, & Clubbe, 2015). Gardens provide an impactful conduit for presenting consistent messages and fact-based information on important or controversial topics such as climate change, evolution, biotechnology, food security, and the fundamental importance of plant biodiversity. Now, more than ever, there is an urgent need for trusted institutions providing science-based services and information that help to ensure successful conservation outcomes. Gardens can and should send a strong conservation message to their millions of visitors, as a shift in public opinion towards valuing plant diversity will also drive resources and funding to plant conservation.

Botanic gardens and arboreta are hubs of botanical expertise, they are the critical link between people and plants, and they are the world's greatest force for plant conservation. But, gardens will not be able to achieve the results needed to avert the plant extinction crisis without a revolution in the way resources, funding, and public attention are focused. This includes not only the need for more funding overall for garden-led plant conservation initiatives but also more reliable, long-term, steady funding sources that reflect the time scales necessary to secure threatened plant species, especially long-lived species like trees. We call on funders, governments, corporations, and global citizens to recognize and support gardens as a critical part of the solution to tackling the world's most pressing environmental crises, including the loss of plant diversity.

ACKNOWLEDGMENTS

The authors thank Jessica B. Turner-Skoff and two anonymous reviewers for providing insightful comments on the manuscript. We also thank Peter Raven and the symposium organizers for the invitation to present this article at the National Geographic Symposium, *A World of Plants*, which led to valuable discussions on this topic.

AUTHORS' CONTRIBUTIONS

All four authors collaboratively conceived of the ideas presented in this opinion piece. M. Westwood presented the article at the "A World of Plants" symposium at the National Geographic Society in October, 2019, and was the editor of the manuscript.

ORCID

Murphy Westwood https://orcid.org/0000-0002-4828-954X
Nicole Cavender https://orcid.org/0000-0001-5804-061X

REFERENCES

Bond, W. J., Stevens, N., Midgley, G. F., & Lehman, C. E. R. (2019). The trouble with trees: Afforestation plans for Africa. *Trends in Ecology & Evolution*, *34*, 963–965.

Brummitt, N. A., Bachman, S. P., Griffiths-Lee, J., Lutz, M., Moat, J. F., Farjon, A., … Nic Lughadha, E. M. (2015). Green plants in the red: A baseline global assessment for the IUCN sampled red list index for plants. *PLoS One*, *10*(8), e0135152. https://doi.org/10.1371/journal.pone.0135152

Cannon, C. H., & Kua, C.-S. (2017). Botanic gardens should lead the way to create a 'Garden Earth' in the Anthropocene. *Plant Diversity*, *39*, 331–337. https://doi.org/10.1016/j.pld.2017.11.003

Cavender, N., Westwood, M., Bechtoldt, C., Donnelly, G., Oldfield, S., Gardner, M., … McNamara, W. (2015). Strengthening the conservation value of ex situ tree collections. *Oryx*, *49*(3), 416–424. https://doi.org/10.1017/S0030605314000866

Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R. K., … Myneni, R. B. (2019). China and India lead in greening of the world through land-use management. *Nature Sustainability*, *2*, 122–129. https://doi.org/10.1038/s41893-019-0220-7

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

Chen, J., Cannon, C. H., & Hu, H. B. (2009). Tropical botanical gardens: At the in situ ecosystem management frontier. *Trends in Plant Science*, *14*, 584–589.

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., … Zayas, C. N. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science*, *366*(6471), eaax3100. https://doi.org/10.1126/science.aax3100

Dosmann, M., & Groover, A. (2012). The importance of living botanical collections for plant biology and the “next generation” of evo-devo research. *Frontiers in Plant Science*, *3*, 137. https://doi.org/10.3389/fpls.2012.00137

Fant, J. B., Havens, K., Kramer, A. T., Walsh, S. K., Callicrate, T., Lacy, R. C., … Smith, P. P. (2016). What to do when we can't bank on seeds: What botanic gardens can learn from the zoo community about conserving plants in living collections. *American Journal of Botany*, *103*(9), 1541–1543. https://doi.org/10.3732/ajb.1600247

FAO. (2011). *The second global plan of action for plant genetic resources for food and agriculture*. Commission for Genetic Resources for Food and Agriculture, FAO. Retrieved from www.fao.org/agriculture/crops/thematic-sitemap/theme/seeds-pgr/gpa/en/

FAO. (2014). *Genebank standards for plant genetic resources for food and agriculture* (Rev ed.). Rome: FAO. http://www.fao.org/3/a-i3704e.pdf.

GardenSearch. (2019). Retrieved from https://www.bgci.org/resources/bgci-databases/gardensearch/

GardenSearch. (2020). Retrieved from https://www.bgci.org/resources/bgci-databases/gardensearch/

Global Tree Assessment. (2019). Retrieved from https://globaltreeassessment.org

Gratzfeld, J. (Ed.). (2016). *From idea to realisation – BGCI's manual on planning, developing and managing botanic gardens*. Richmond, UK: Botanic Gardens Conservation International.

Griffiths, M. P., Beckman, E., Callicrate, T., Clark, J., Clase, T., Deans, S., … Wood, J. (2019). *Toward the metacollection: Safeguarding plant diversity and coordinating conservation collections*. San Marino, CA: Botanic Gardens Conservation International-US.

Guerrant, E. O., Havens, K., & Maunder M. (Eds.). (2004). *Ex situ plant conservation: Supporting species survival in the wild*, Washington, DC: . Island Press.

Hardwick, K. A., Fiedler, P., Lee, L. C., Pavlik, B., Hobbs, R. J., Aronson, J., … Hopper, S. D. (2011). The role of botanic gardens in the science and practice of ecological restoration. *Conservation Biology*, *25*(2), 265–275. https://doi.org/10.1111/j.1523-1739.2010.01632.x

Havens, K., Kramer, A. T., & Guerrant, E. O. Jr (2014). Getting plant conservation right (or not): The case of the United States. *International Journal of Plant Sciences*, *175*(1), 3–10. https://doi.org/10.1086/674103

Heywood, V. H. (2017). Plant conservation in the Anthropocene – Challenges and future prospects. *Plant Diversity*, *39*, 314–330. https://doi.org/10.1016/j.pld.2017.10.004

Hoban, S. (2019). New guidance for ex situ gene conservation: Sampling realistic population systems and accounting for collection attrition. *Biological Conservation*, *235*, 199–208. https://doi.org/10.1016/j.biocon.2019.04.013

Hoban, S., Callicrate, T., Clark, J., Deans, S., Dosmann, M., Fant, J., … Griffith, M. P. (2020). Taxonomic similarity does not predict necessary sample size for *ex situ* conservation: A comparison among five genera. *Proceedings of the Royal Society B.*, *287*, 20200102. https://doi.org/10.1098/rspb.2020.0102

IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, & C. N. Zayas (Eds.). Bonn, Germany: IPBES Secretariat.

IPCC. (2018). *Summary for Policymakers*. V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty(p. 32). Geneva, Switzerland: World Meteorological Organization

IUCN. (2020). IUCN Red List version 2020–1: Table 1a. Last updated: 19 March 2020.

Joppa, L. N., Roberts, D. L., Myers, N., & Pimm, S. L. (2011). Biodiversity hotspots house most undiscovered plant species. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(32), 13171–13176. https://doi.org/10.1073/pnas.1109389108

Krishnan, S., & Novy, A. (2016). The role of botanic gardens in the twenty-first century. *CAB Reviews*, *11*(23), 1–10. https://doi.org/10.1079/PAVSNNR201611023

Lewis, S. L., Wheeler, C. E., Mitchard, E. T. A., & Koch, A. (2019). Restoring natural forests is the best way to remove atmospheric carbon. *Nature*, *568*, 25–28. https://doi.org/10.1038/d41586-019-01026-8

Liang, J., Crowther, T. W., Picard, N., Wiser, S., Zhou, M., Alberti, G., … Reich, P. B. (2016). Positive biodiversity-productivity relationship predominant in global forests. *Science*, *354*(6309), aaf8957. https://doi.org/10.1126/science.aaf8957

Mounce, R., Smith, P., & Brockington, S. (2017). Ex situ conservation of plant diversity in the world's botanic gardens. *Nature Plants*, *3*, 795–802. https://doi.org/10.1038/s41477-017-0019-3

Negrón-Ortiz, V. (2014). Pattern of expenditures for plant conservation under the Endangered Species Act. *Biological Conservation*, *171*, 36–43. https://doi.org/10.1016/j.biocon.2014.01.018

O'Donnell, K., & Sharrock, S. (2017). The contribution of botanic gardens to ex situ conservation through seed banking. *Plant Diversity*, *39*(6), 373–378. https://doi.org/10.1016/j.pld.2017.11.005

Oldfield, S., & Newton, A. (2012). *Integrated conservation of tree species by botanic gardens: A reference manual*. Richmond, UK: Botanic Gardens Conservation International.

Osuri, A. M., Gopal, A., Raman, T. R. S., DeFries, R. S., Cook-Patton, S. C., & Naeem, S. (2020). Greater stability of carbon capture in species-rich natural forests compared to species-poor plantations. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ab5f75

Pence, V. C. (2013). In vitro methods and the challenge of exceptional species for target 8 of the global strategy for plant conservation. *Annals of the Missouri Botanical Garden*, *99*(2), 214–220. https://doi.org/10.3417/2011112

Pimm, S. L., & Joppa, L. N. (2015). How many plant species are there, where are they, and at what rate are they going extinct? *Annals of the Missouri Botanical Garden*, *100*(3), 170–176. https://doi.org/10.3417/2012018

PlantSearch. (2019). Retrieved from https://www.bgci.org/resources/bgci-databases/plantsearch/
Raven, P. (2020). Plants make our existence possible. *Plants, People, Planet*. in press.
Roberson, E. R., Frances, A., Havens, K., Maschinski, J., Meyer, A., & Ott, L. (2020). Fund plant conservation to solve biodiversity crisis. *Science*, *367*(6475), 258.
Sharrock, S. (2012). *Global strategy for plant conservation: A guide to the GSPC, all the targets, objectives and facts*. Richmond, UK: Botanic Gardens Conservation International.
Smith, P. (2015). Saving Malawai's national tree. *BGJournal*, *12*(2), 34–36.
Smith, P. (2016). Building a global system for the conservation of all plant diversity: A vision for botanic gardens and for botanic gardens conservation international. *Sibbaldia*, *14*, 5–13.
Smith, P. (2018). The challenge for botanic garden science. *Plants, People, Planet*, *1*(1), 38–43. https://doi.org/10.1002/ppp3.10
Spencer, R., & Cross, R. (2017). The origins of botanic gardens and their relation to plant science, with special reference to horticultural botany and cultivated plant taxonomy. *Muelleria*, *35*, 43–93.
Turner-Skoff, J. B., & Cavender, N. (2019). The benefits of trees for livable and sustainable communities. *Plants, People, Planet*, *1*(4), 323–335. https://doi.org/10.1002/ppp3.39
Tweddle, J. C., Dickie, J. B., Baskin, C. C., & Baskin, J. M. (2003). Ecological aspects of seed desiccation sensitivity. *Journal of Ecology*, *91*(2), 294–304. https://doi.org/10.1046/j.1365-2745.2003.00760.x
United Nations. (2019). *Report of the secretary-general on the 2019 Climate Action Summit and the way forward in 2020*. Retrieved from https://www.un.org/en/climatechange/assets/pdf/cas_report_11_dec.pdf.
Volis, S. (2017). Conservation utility of botanic garden living collections: Setting a strategy and appropriate methodology. *Plant Diversity*, *39*(6), 365–372. https://doi.org/10.1016/j.pld.2017.11.006
Walters, C., & Pence, V. C. (2020). The unique role of seed banking and cryobiotechnologies in plant conservation. *Plants, People, Planet*. https://doi.org/10.1002/ppp3.10121
Westwood, M. (2015). The Global Trees Campaign and ArbNet- Working together to advance professionalism and tree conservation in arboreta. *Bgjournal*, *12*(2), 30–33. Retrieved from https://www.bgci.org/wp/wp-content/uploads/2019/04/BGjournal%2012_2.pdf
Williams, S., Jones, J., Gibbons, J., & Clubbe, C. (2015). Botanic gardens can positively influence visitors' environmental attitudes. *Biodiversity and Conservation*, *24*(7), 1609–1620. https://doi.org/10.1007/s10531-015-0879-7
Zhai, D.-L., Xu, J.-C., Dai, Z.-C., Cannon, C. H., & Grumbine, R. E. (2013). Increasing tree cover while losing diverse natural forests in tropical Hainan, China. *Regional Environmental Change*, *14*, 611–621. https://doi.org/10.1007/s10113-013-0512-9

How to cite this article: Westwood M, Cavender N, Meyer A, Smith P. Botanic garden solutions to the plant extinction crisis. *Plants, People, Planet*. 2020;00:1–11. https://doi.org/10.1002/ppp3.10134