Quantifying Endangerment Value: a Promising Tool to Support Curation Decisions

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Abstract

Botanic garden collections are increasingly seeking to quantify and improve the value of their collections for science, horticulture, conservation and other uses. Quantifying the value of a collection depends on the mission of the institution. Many botanic gardens are prioritising the conservation of rare and threatened species towards preventing plant extinctions. In doing so, botanic gardens must make decisions about which plants should remain, be replaced or be added to their collections, and how to allocate staff and resources to care for individual plants, while considering funding and space limits. So, how can curators make the biggest impact towards conserving plant species? We present a promising method to quantitatively assess which plant species might be higher or lower conservation priority to an *ex situ* collection, using what we term 'endangerment value' – the value of collections for preventing plant extinction. We apply this method to four genera of high importance at The Morton Arboretum and showcase advantages of this approach as well as pitfalls. We found this method useful for priority setting, but note that the inclusion and exclusion of different data and how they are weighted impacts the ranking of priority species – an important lesson for any prioritisation method. We hope this method will inspire and help other botanic gardens to evaluate their current and future endangerment value and set priorities for maintaining and growing *ex situ* collections globally.

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Introduction

Botanic gardens are in part defined by the particular landscape and climate they occupy, but they are also defined by their curatorial decisions, and the values underlying those decisions. For centuries, botanic gardens existed with a primary purpose to study and house useful medicinal or agricultural plants, and have long been important to the study of botany and plant taxonomy (O'Donnell & Sharrock, 2018). In recent decades, many botanic gardens have been increasingly leveraging their collections to achieve high conservation impact and to provide education, advocacy and historical context to these collections in addition to collaboratively curating metacollections that are distributed across institutions (Cavender *et al*., 2015; Westwood *et al*., 2021).

Botanic gardens are also interested in measuring progress towards these goals via metrics on 'collection value' or 'conservation value', which track the diversity, representativeness and distinction of plants in a collection (Redford *et al*., 2011; Cibrian-Jaramillo, 2013). While most botanic garden managers know the number of taxa and accessions in their collections, these numbers do not necessarily represent how effectively the collection is achieving its goals, as each accession might not have the same value for the institution. Good metrics facilitate sound management choices, efficient use of resources, and increased access and understanding by users, and can help collections reach their full potential. Recent evaluations (Godefroid *et al*., 2011; Guerrant *et al*., 2014; Cavender *et al*., 2015; Larkin *et al*., 2016) concur that botanic gardens need to more effectively catalogue, represent and conserve botanical diversity, to benefit research and public education.

Quantifying collections with respect to their goals can help managers prioritise resources and decide on the most effective next steps (Cavender *et al*., 2015). For instance, if a collection aims to represent a breadth of taxonomic diversity, one might identify gaps in the phylogeny, as has been performed with The Millennium Seed Bank Partnership for legumes (Griffiths *et al*., 2015). A detailed examination of a botanic garden's conservation value can also identify plants that might be deaccessioned to make room for cultivars, taxa or populations that are more central to the collection's goals (Maunder *et al*., 2001; Stephens, 2011; Griffith *et al*., 2017). Finally, in-depth analysis can help identify accessions of special value that warrant extra attention or investment. Because resources – space, labour, finances – are always constrained, decisions about which plants to maintain and what actions to take eventually become decisions about what not to do. Lastly, quantifying and showcasing value can provide communication opportunities to leadership, funders, staff and visitors about the importance of a collection.

Many botanic gardens are working to prevent extinctions – the disappearance of a species from the planet. With approximately 40 per cent of all plants threatened with extinction in the wild, strategic conservation effort is vital (Antonelli *et al*., 2020). Protecting species in their natural habitats is essential for ecosystem services (Cavender-Bares *et al*., 2022), and seed can economically safeguard species and their genetic diversity in the event of wild population loss. Meanwhile, botanic gardens complement these efforts by providing 'safe sites' for species that cannot be stored long term in conventional seed banks (Cavender *et al*., 2015; Westwood *et al*., 2021). These species are known as 'exceptional species': they produce little or no

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viable seed, cannot be dried sufficiently for conventional storage, only maintain viability for a short period of time in storage, and/or have deep dormancy (Pence *et al*., 2022). Botanic gardens provide an *ex situ* repository of germplasm that can receive greater protection from threats in the wild such as conversion of habitat, and may also be used to produce propagules that can be used for restoration, both of which can reduce the risk of extinction.

To support botanic gardens in their efforts to safeguard species and prevent extinctions, data-driven metrics are needed to inform collections management decisions such as which species or individuals in a collection should receive additional attention and care, which should be lower priority or deaccessioned, and which should be targeted for adding to the collection. In this article, we examine this aspect of a collection's conservation value: how species within the collection and new target species contribute to the value of a collection in regard to preventing species extinctions, or what we term the 'endangerment value' of the collection. We use four of The Morton Arboretum's flagship genus-level collections as a case study to explore the possible application of these quantitative metrics for endangerment value.

Curation to advance conservation goals at The Morton Arboretum

Over its 100-year history, The Morton Arboretum (TMA; Lisle, IL, USA) has established various geographic and taxonomic collections for different purposes. The Arboretum's previous Strategic Plan (2016–2020) highlighted as a key aim to 'strengthen the conservation value of *ex situ* tree collections' via 'a thorough review of collections holdings, gap analyses, and audits that will direct priorities for collections' (Table 1). With 16,087 inventoried plants representing 3,622 taxa (20 October 2022) across more than 1,700 acres (688 ha), the Arboretum faces resource constraints. Systematic assessment and planning are necessary to ensure that limited resources are used efficiently to advance collection value.

The Morton Arboretum has traditionally recognised different collection values,

Table 1 Definition of terms used to describe plants in a botanic garden.

accession *(noun)*	An accession is a documented plant or group of plants that has come from the same source at the same time and is now growing at a botanic garden. The term is not used consistently among botanic gardens. One accession may represent a single plant in a collection, several plants derived from material (seeds, scions, grafts, cuttings and so on) from a nursery, several plants that came from the same mother tree, or several plants grown from material combined from multiple mother trees in a single population.
collection *(noun)*	This word has multiple meanings in the botanic garden domain. Here, we use it to refer either to an entire garden's holdings of living plant material, such as an '*ex situ* collection', or to a specific group of plants at one or more gardens, such as the '*Quercus* collection' at The Morton Arboretum.
plant *(noun)*	An individual. A single plant may fully or partially represent one accession.

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including horticultural variation and biodiversity conservation. For the first 50 years after its founding in 1922, the Arboretum obtained plants primarily from nurseries or other arboreta, seeking to represent high numbers of species, though some material of documented wild origin was acquired. Starting in the 1980s, the Arboretum initiated efforts to safeguard wild genetic and ecological diversity by acquiring specimens directly from wild populations. The North American China Plant Exploration Consortium (NACPEC), for example, has conducted 14 China expeditions since 1993. Since 2012, more than 1,000 new accessions of documented wild origin from both the US and abroad have been added to the Arboretum's collections. In the last five years, the Arboretum has also started examining how its collections compare to and complement other existing collections globally for target genera or species, and ultimately how they contribute to safeguarding against species extinction. This has included pioneering a conservation gap analysis methodology to identify target species' native populations that are not yet represented in *ex situ* collections (Beckman *et al.*, 2019). Now, the Arboretum recognises the need for further evaluation of our collections' conservation value by applying systematic metrics for prioritising species and individuals based on factors related to their extinction risk.

Accuracy and completeness are important goals of any collections programme (Hohn, 2022). Efforts to achieve the former can be accomplished through an active Collections Management Policy. At TMA, Lists of Desiderata identify taxa targeted for acquisition and inclusion within an identified collection. Per the Arboretum's Collections Management Policy, species may be acquired given a reasonable expectation that they can survive cultivation in outdoor conditions present on site. Therefore, the Arboretum's Lists of Desiderata generally include species native to temperate North America and Eurasia. But many species from more moderate climates are able to survive harsher conditions in botanic gardens due to the ability of garden staff to strategically position plants in microclimates within a landscape, treat pests and diseases, and provide horticultural care. Species from climates with less severe conditions may therefore be suitable for the Arboretum, though subtropical or tropical taxa generally are not.

To support curation focused on preventing species extinctions, we compiled and analysed data on value for multiple endangerment criteria for four of TMA's flagship tree collections (Table 2). These data will be used to inform and improve collection guidance and management as they can be used to create a rank order list of target taxa that are priorities for adding to the collection or for providing extra care for those which are already in the collection. In this analysis, we focus on *ex situ* conservation at the species level. In the following sections we will:

1. explain how we developed a method for quantifying the endangerment value of a living collection and share findings for four of the flagship genus-level tree collections at TMA: *Malus*, *Quercus*, *Tilia* and *Ulmus*
2. showcase steps and data needed so other botanic gardens can follow our method and evaluate its fit to their needs and collection values
3. share lessons learned and other considerations when applying this method.

Table 2 Genus-level flagship tree collections at TMA. These were selected as pilot collections for creating a metric to quantify the endangerment value of botanic garden living collections.

Genus	Current collection size (20 October 2022) at TMA	Number of Desiderata species currently in TMA's collection	Collection's special focus at TMA
Malus (crab apples)	152 taxa 501 individuals	14 of 30 species (47%)	This collection originally served to showcase ornamental crab apple cultivars, but it has expanded to focus on both native species and species that represent diverse habitats worldwide.
Quercus (oaks)	94 taxa 1,048 individuals	45 of 100 species (45%)	One of the most significant collections of oaks globally according to Botanic Gardens Conservation International, this collection has an increasing focus on threatened North American species with a goal of conserving genetic diversity and assisting reintroductions (for example *Quercus boyntonii* and *Q. havardii*).
Tilia (lindens)	45 taxa 193 individuals	15 of 18 species (83%)	Diverse and attractive, this collection has been prioritised for expansion and, due to space limits, is being relocated to a new site via select propagation of existing specimens and new targeted collections in the wild.
Ulmus (elms)	72 taxa 320 individuals	28 of 34 species (82%)	Particularly rich in taxa native to eastern Asia and other taxa resistant to Dutch elm disease, this collection was used by TMA staff to breed hardy, disease-resistant selections in the 1980s and 1990s (Miller & Ware, 1999).

Developing a method for quantifying endangerment value

Selecting target species

Lists of Desiderata for four of TMA's flagship tree collections – *Malus*, *Quercus*, *Tilia* and *Ulmus* – were combined for this project into one taxon list. Botanical nomenclature and taxon concepts were reconciled across publications by synonymising them to the IUCN Red List of Threatened Species™ (iucnredlist.org, version 2022-1; hereafter referred to as the IUCN Red List), with a few exceptions for priority taxa for the Arboretum that have some taxonomic uncertainty.

For this study, we excluded taxa below the species level, such as subspecies or varieties, as well as hybrids and cultivars, though these may be of conservation significance in some regions and genera. Infraspecific taxa could be included at the level of species if a garden wishes; however, most hybrids and cultivars would be hard to fit into the framework we propose, which focuses on species that have wild populations.

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The final species-level list used for analyses (hereafter referred to as 'target species') included 182 species (Supplementary Material A).[11] We then gathered synonyms for these species. For each target species, we assembled a list of synonyms in March 2021, from Tropicos (2021), Integrated Taxonomic Information System (ITIS, 2021) and Plants of the World Online (POWO, 2021); using the *taxize* package in R (Chamberlain & Szocs, 2013); and from the World Checklist of Vascular Plants v.2.0 (WCVP, 2020), World Flora Online v.2019.05 (WFO, 2019) and IUCN Red List assessment synonyms by manual name-matching. All synonyms were then reviewed manually to remove uncommon and/or historical synonyms (mostly homonyms) and those that represented a different taxonomic concept.

Gathering endangerment data

To quantify the endangerment value of each target species, we compiled data for four metrics relating to the risk of extinction:

1. the likelihood of extinction in the wild
2. the presence of the *ex situ* collection within a country of the species' native distribution (yes/no)
3. the extent of representation of the species in *ex situ* collections globally
4. the vulnerability of the species to additional predicted threats in the wild (Table 3).

These data were gathered for each of the 182 target species for TMA's *Malus*, *Quercus*, *Tilia* and *Ulmus* collections. Most data are easily accessible online and do not require extensive time to compile. The next four sections detail the purpose, sources and processing needed for each metric.

[11] Supplementary Material A can be downloaded from the same location as this article.

Likelihood of extinction in the wild

Extinction risk, sometimes referred to as threat status, provides a metric to describe the likelihood of a species becoming completely extinct in the wild – meaning no populations remain within its natural distribution. Due to its comprehensiveness and recognition as an important tool globally, we chose extinction risk categories from the IUCN Red List as a central component for quantifying endangerment value (Rodrigues *et al*., 2006). Under the IUCN Red List, species are assessed and assigned to an extinction risk category using criteria such as range size, population demographics and trends, habitat, uses, threats and conservation actions. Extinction risk categories include Extinct, Extinct in the Wild, Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern and Data Deficient. Species not yet assessed on the IUCN Red List are considered Not Evaluated. Assessments are compiled and reviewed by a global network of scientists, conservationists and additional experts. The IUCN Red List only allows assessments for species and infraspecies (for example varieties and subspecies). It does not permit assessments of hybrids, cultivars or taxa with unresolved taxonomic standing. We obtained the global IUCN Red List category (https://www.iucnredlist.org, version 2022-1) for each of our target species. For species that had not yet been evaluated for the IUCN Red List, or had out-of-date (>10 years old) assessments, we attempted to update or complete new assessments. See Supplementary Material A for details.

Presence of the *ex situ* collection within a country of the species' natural distribution

Restoration activities are often easier within the country where a species naturally occurs. Plant material held in a botanic garden in

Table 3 Types of data and sources used to quantify the endangerment value of 182 target species at TMA, and their purpose within the endangerment value.

<table>
<tr><th colspan="2">Metric</th><th>Data source</th><th>Purpose within endangerment value</th></tr>
<tr><td colspan="2">Likelihood of extinction in the wild (categories)</td><td>IUCN Red List</td><td>Quantify the risk of extinction in the wild</td></tr>
<tr><td colspan="2">Presence of the ex situ collection within a country of the species' native distribution (yes/no)</td><td>IUCN Red List</td><td>Proxy for logistic ease of local reintroduction, as well as communication to the public</td></tr>
<tr><td rowspan="3">Extent of representation in ex situ collections globally</td><td>Number of ex situ collections growing the species</td><td>BGCI's PlantSearch database</td><td>Relative security or redundancy of ex situ material (more sites = higher security)</td></tr>
<tr><td>Number of ex situ collections with wild or cultivated-from-wild germplasm</td><td rowspan="2">Accessions-level ex situ collections survey performed for this study</td><td>Relative safety of wild-origin ex situ material (more sites = higher security)</td></tr>
<tr><td>Number of wild or cultivated-from-wild accessions in ex situ collections</td><td>Proxy for genetic diversity captured in ex situ living collections</td></tr>
<tr><td rowspan="2">Vulnerability to additional predicted threats in the wild</td><td>Climate change vulnerability (categories)</td><td>Potter et al. (2017)</td><td rowspan="2">Additional measures of potential extinction risk sometimes not captured in the IUCN Red List category</td></tr>
<tr><td>Pest/disease vulnerability (categories)</td><td>Potter et al. (2019)</td></tr>
</table>

Note that not all species had data available for every metric.

a country where the species is native does not have to be transported internationally and thus avoids permitting, shipping and quarantine logistics and costs. Further, it is often logistically easier for staff to visit, monitor and work in regions within their own country. Native plants may also inspire public visitors about local and national conservation issues. This does not, however, discount the value of keeping non-native species in botanic garden collections or the value of garden staff supporting international conservation work. To identify our target species as native or non-native to the country where our botanic garden exists (the US), we consulted country-level distribution data from the IUCN Red List. For TMA, if natural populations of a target species are found in the US, there may be a higher likelihood of conservation implementation using seed from the Arboretum's collections for restoration of that species.

Another, finer-scale metric could be added based on the botanic garden's distance from the nearest wild population, whether the species is found in the same ecoregion as the garden, or another regional measure such as hardiness zone. This metric may reflect easier use and access for restoration or reintroduction purposes, benefits for education and avoidance of adaptation via artificial selection to non-native environmental conditions. Development of such a fine-scale metric of 'native' or 'nearness' is recommended for a future version of the endangerment matrix, depending on data available for target species and the botanic garden's own goals. For TMA, the country-level measure was sufficient for this initial study, since easier logistics and lower costs associated with a collection being made within the US were the main values we sought to capture, rather than material's physical or ecological nearness to our site.

Extent of representation in *ex situ* collections globally

Ex situ collections are also often called 'safe sites' for rare or threatened species. Germplasm located outside an area threatened by location-specific impacts such as land use change or sea level rise can be considered 'safe' if removed from threats, or it can be provided with additional protective resources such as disease treatments. For this endangerment value metric, we assume that the more *ex situ* collections holding a target species and the more individuals growing in *ex situ* collections, the less likely the species is to face global extinction. Presence in more botanic gardens can also potentially contribute to greater public awareness of the species' rarity and, if interpretation is provided to the public, could motivate action and advocacy. There can also be a positive relationship between the number of *ex situ* sites or individuals and the genetic diversity captured in those collections, and thus increased potential future resilience and adaptation of the species. Three measures make up our metric quantifying the extent of a target species' representation in *ex situ* collections:

1. the number of *ex situ* collections growing the species
2. the number of *ex situ* collections with wild or cultivated-from-wild accessions
3. the number of wild or cultivated-from-wild accessions in *ex situ* collections

We included both the number of accessions that are of wild origin and the number of *ex situ* collections growing wild-origin material because plants from some species are grown in large numbers at only one or a few botanic gardens, while others are grown in few numbers at many gardens. Both scenarios contribute to safeguarding a species against extinction, but in different ways and to differing extents.

To assess the number of *ex situ* collections growing each target species, we downloaded publicly available data from Botanic Gardens Conservation International's (BGCI) PlantSearch database (BGCI PlantSearch, 2021), which includes seed banks and living collections. The BGCI PlantSearch data represent a minimum estimate of the number of *ex situ* institutions growing a species, since the database relies on the voluntary reporting of current, accurate *ex situ* collections data by collection-holding institutions. BGCI PlantSearch is the most up-to-date, already compiled estimate of how many institutions hold living material of target species. Currently, BGCI PlantSearch only tracks species-level collections data, although work is underway to include accessions-level and individual-level provenance data in the future.

To assess the number of *ex situ* collections growing wild or cultivated-from-wild material and the number of accessions that are wild or cultivated-from-wild, direct email requests for accessions-level data were sent to curators and plant records officers at botanic gardens who reported target species to BGCI PlantSearch (as of July 2019), totalling 558 botanic gardens in 67 countries. The data request was also shared through the International Oak Society, ArbNet, the Plant Conservation Alliance and the American Public Gardens Association discussion forums, newsletters and mailing lists. Data from the survey were compiled in R (R Core Team, 2022). Synonyms compiled at the start of the project were used to match additional records.

Vulnerability to additional predicted threats in the wild

Some known threat or vulnerability information is not easily incorporated into an IUCN Red List assessment but still informs the endangerment of the species. For example, a species' vulnerability to climate change can be incorporated into an IUCN Red List assessment if the information is expressed as the percentage of the population size or range/habitat projected to be lost due to climate change within a certain timeframe. This can be difficult to predict with confidence. Yet various scientific studies have quantified species' vulnerability and provide important information that can be used to prioritise species for conservation. We obtained data from two recent analyses of US tree species' vulnerability to climate change (Potter *et al*., 2017) and to pests and diseases (Potter *et al*., 2019). These analyses assessed 300+ native US tree species using a unique combination of (1) thorough literature review; (2) consultation with dozens of experts to identify species-specific traits that may affect climate change and pest/disease vulnerability; and (3) spatial modelling of predicted outcomes due to exposure to the threat. Using these inputs, the method quantifies each species' sensitivity to the threat (climate change or pest/disease pressure), its ability to adapt to the change and the severity of the threat, resulting in a 'vulnerability class' for each species. From these works we obtained this quantitative ranking of selected US species to the threats of climate change and pest and disease. Large-scale analyses such as these, which cover many species and incorporate species' life history traits and expert input with modelling, were only available for native US species. For target species outside the US, we used the mean of all species that did have data, therefore these species are assumed to have an 'average' level of threat from these factors, an admittedly strong assumption.

Quantifying endangerment value

To calculate an endangerment value score for each target species, we designed an endangerment value matrix based on the metrics described above (Supplementary Material A). This matrix supports data-driven curation focused on preventing species extinctions by highlighting species with higher endangerment value based on the factors included. In the matrix, species are listed in the first column, with one row for each target species. Subsequent columns hold the endangerment-related data we gathered – we call these 'metrics'. The furthest-right column calculates a total score for each species. The following sections outline how each metric is scored and weighted, how the total score is calculated and how the robustness of the final matrix was assessed.

Calculations

Data for each metric were added to the endangerment value matrix and used to calculate the relative value and the priority for each target species (Fig. 1). The metrics were scored in the matrix using values between zero and one. Most data in the matrix were categorical, so numeric values were assigned to each category for scoring. *Ex situ* analyses were the exception, and scores were given in these columns through a log-transform of the raw

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Metrics considered in the endangerment value matrix								
Metrics →	Extinction risk (IUCN Red List categories)	Presence of the *ex situ* collection within a country of the species' native distribution	Number of *ex situ* collections growing the species	Number of *ex situ* collections with wild or cultivated-from-wild germplasm	Number of wild or cultivated-from-wild accessions in *ex situ* collections	Climate change vulnerability (Potter *et al.*, 2017 categories)	Pest/disease vulnerability (Potter *et al.*, 2019 categories)	Total score
Scoring method →	EW = 1 CR = 0.8 EN = 0.6 VU = 0.4 NT = 0.2 LC = 0 DD = 0.4 NE = 0.2	Yes = 1 No = 0	Log-transformed then scaled in reverse from 1 (min of all species) to 0 (max of all species) `= 1-((ln(x+1)-min)/(max-min))`			A = 1 B/C/D = 0.5 E1/E2/E3 = 0.1 E4 = 0 Not assessed = mean of all species with scores	A1 = 1 A2/A3/B = 0.5 A4/C/D = 0.1 E = 0 Not assessed = mean of all species with scores	`= 100 * sum (each metric * weight)` Scaled from 0 (lowest priority) to 100 (highest priority)
Relative weighting →	30%	5%	10%	5%	25%	12.5%	12.5%	Weights add up to 100%
Species-specific examples								
Quercus boyntonii	CR = 0.8	Yes = 1	17 = 0.624	9 = 0.376	28 = 0.503	B = 0.5	B = 0.5	62.19
Malus rockii	LC = 0	No = 0	30 = 0.510	2 = 0.702	2 = 0.838	No data = 0.352	No data = 0.274	37.38

Fig. 1 Scoring method for each metric considered in the endangerment value matrix and two species-specific examples of filling in the matrix and calculating a final score.

value, then scaling in reverse from one to zero; low representation in collections therefore gives a high score and high representation gives a low score (following Larkin *et al.*, 2016).

Testing for redundancy among factors

Next we examined the extent to which the metrics were correlated, and thus contain duplicative information content. If different metrics are highly correlated, one or more metrics (columns) may need to be removed from the matrix or may need to be weighted lower. To examine correlation, we calculated all pairwise correlations for the metrics in the endangerment matrix, for all species as well as each genus separately (Supplementary Material B).[12]

For TMA's 182 target species, only one pair of metrics had a high correlation ($|r| > 0.9$): the number of *ex situ* collections with wild or cultivated-from-wild germplasm, and the number of wild or cultivated-from-wild accessions in *ex situ* collections. There was a moderately strong correlation ($|r| > 0.7$) between both of these factors and the number of *ex situ* collections growing the species. This means that the number of *ex situ* collections (from BGCI PlantSearch) alone captures much of the information contained in the accession-level data from the more intensive *ex situ* survey. All other correlations were quite low ($|r| < 0.5$), which suggests that each source contains important, unique information for our target species. To address the redundancy (strong correlation) among the factors that quantify the extent of species' representation in *ex situ* collections, we weighted one factor highly (number of wild or cultivated-from-wild accessions in *ex situ* collections) with the other two receiving a lower weight; see the next section for further

[12] Supplementary Material B can be downloaded from the same location as this article.

justification. We acknowledge there is a level of redundancy in keeping both metrics; another approach would be to entirely remove the two highly correlated metrics instead of downweighting them.

Weighting

The endangerment matrix calculates a value for each metric, for each species. Summing the score for all metrics results in a single value for each species, but doing so implies that each metric provides equally important information to quantifying endangerment. Based on institution-specific priorities or mission, some metrics or factors may be more or less important to calculating endangerment value. Adding weights allows each institution to adjust the overall endangerment value. To determine appropriate metric weights for our goals at TMA, we surveyed the project team (10 persons) to assess whether each metric is very important, important, moderately important, not very important, or not important to our mission. This resulted in adding a relative weighting to each metric, which ranged from 0.05 to 0.30. All weights add up to one, so when each metric is multiplied by its weight and the resulting values are summed, each species receives a final score of between 0 and 100.

For TMA's 182 target species, the highest total endangerment score was 65.8 and the lowest score was 9.8 when using our chosen relative weighting scheme within the endangerment matrix. The top four highest-scoring species were *Malus komarovii*, *Ulmus elongata*, *U. gaussenii* and *Quercus boyntonii* (Fig. 2). The top *Tilia* species – *Tilia concinna* – was ranked ninth.

Matrix analysis and synthesis

To highlight species with scores of higher certainty and identify which factors in the matrix are the most important, we looked at how our results change under various scenarios such as removing metrics or altering the metric weights. For example, how do species' scores change if the IUCN Red List category is excluded? This type of analysis is known as a sensitivity analysis. We iteratively recalculated the total endangerment score for each species with one metric excluded, using two different weighting schemes: the weighting our team chose for TMA ('relative' weighting) and a 'simple sum' weighting where all metrics received the same weight. We also tested using the mean of all species with data versus using zero for species without climate change and/or pest and disease vulnerability data. In total, the sensitivity analysis resulted in 18 different possible scores for each species (Fig. 3). These results showed some disagreement in how species were ranked depending on weighting and which factors were included. For example, we can see that a number of species change ranks between different scenarios, some of them quite substantially (Fig. 4).

We then summarised the results of the sensitivity analysis to determine if some target species were consistently ranked highly within all scenarios, and therefore were consistently of high priority. This required first quantifying the number of species moving up or down in rank by more than X per cent; we tried 5 per cent, 10 per cent, 15 per cent and 20 per cent (Supplementary Material C).[13] Finally, we created a high-level summary of 'consistency' by counting how often each species ranked within the top tenth, top fourth and top third of all target species.

For TMA's 182 target species, this summary of the sensitivity analysis resulted

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[13] Supplementary Material C can be downloaded from the same location as this article.

Fig. 2 The highest-ranking target oak species at The Morton Arboretum: *Quercus boyntonii*. This small- to medium-sized tree is endemic to Alabama, and numerous collecting trips have secured wild-origin plants in at least nine botanic gardens globally, including the Arboretum. Photos: Sean Hoban.

Scenario within the sensitivity analysis	Metric's relative weight	Number of species moving >X spots up/down in rank	
		5% (>18 spots)	15% (>36 spots)
All metrics, relative weighting	N/A	'base' scenario (all others tested against)	
All metrics, simple sum weighting	N/A	139	74
No 'extinction risk' metric	30%	116	57
Zero instead of the mean when no data for climate change or pest/disease	25%	124	26
No 'number of wild accessions in *ex situ* collections' metric	25%	92	27
No 'within country of natural distribution' metric	5%	110	0
No 'number of *ex situ* collections growing the species' metric	10%	47	0
No 'climate change vulnerability' metric	12.5%	36	5
No 'pest/disease vulnerability' metric	12.5%	40	0
No 'number of *ex situ* collections with wild germplasm' metric	5%	6	0

Fig. 3 Number of target species moving up or down in rank based on thresholds at 5 per cent and 15 per cent. Eight additional scenarios (not pictured) were performed where the simple sum weighting was used instead of the value-driven weighting for each of the scenarios. The total number of target species is 182. Cell colours highlight the degree of rank-switching; darker orange signifies more species have changed rank between the 'base' scenario and the test scenario, while lighter yellow signifies fewer species have switched ranks.

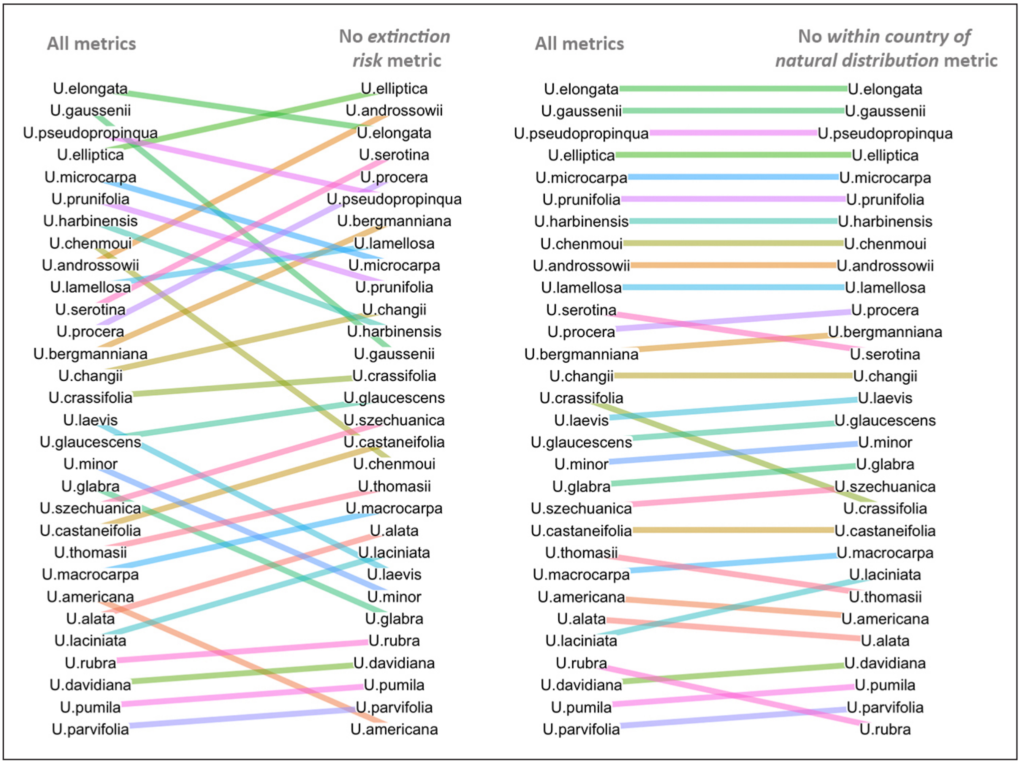

Fig. 4 A visualisation of rank changes for The Morton Arboretum's 30 target *Ulmus* species, resulting from two different scenarios in the sensitivity analysis. The left side of each panel shows the species' rank when the total score is calculated using all metrics and our relative weighting scheme (that is, the base scenario). The right side of each panel shows the new rank order of species when scores are calculated without one metric. Left scenario: removing the extinction risk (IUCN Red List category) metric; right scenario: removing the metric that scores whether or not the species has natural distribution in the country where the *ex situ* collection is located (US for The Morton Arboretum). Line colours help with visualising rank-switching and do not themselves have meaning.

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in one species that ranked in the top tenth through all scenarios, twelve species in the top fourth through all scenarios and fifteen species in the top third through all scenarios. But we also found that these top-priority species had good overlap with the top species in the 'base' scenario (using all metrics and the relative weighting we chose): 11 of the 15 species (73 per cent) are in common between the species that fall in the top third in all scenarios in the sensitivity analysis and those that are in the top 15 in the 'base' scenario. This means the endangerment matrix is a helpful tool for the Arboretum, because most priority species do not significantly change in their relative value. Other botanic gardens using the matrix should quantify correlation among metrics and complete a sensitivity analysis for their set of target species and metrics, to determine robustness of the results. The R script used to calculate correlations and perform the sensitivity analysis of the matrix is available at https://github.com/MortonArb-CollectionsValue/EndangermentValue/blob/main/endangerment_value_scoring.R

Comparison to other work

Our work builds on other recent efforts to quantify value and/or assist with data-informed decision making in *ex situ* collections. Smith (2021) presents a typology of cultural heritage values that a botanic garden (or any collection) may apply to the plants or objects in the collection, including 'heirloom', 'memorial' and 'relict', and a list of value considerations within heritage, such as historical, aesthetic, communal and evidential value. Symes & Hart (2021) describe important considerations of climate change in collections and summarise a '20-year strategy … to respond to climate change risks by guiding the transition of Royal Botanic Gardens Victoria, in Melbourne from existing plantings to a landscape collection better suited to the projected climate and environmental conditions of 2090'. Meanwhile, the phylogenetic diversity value of the legume collection of the Millennium Seed Bank was evaluated by Griffiths *et al.* (2015), who point out that there are tradeoffs between an optimal phylogenetic representation and conserving economically important, endangered and range-restricted species. Liu *et al.* (2018) examined another aspect of value in a collection, usefulness to humans, by enumerating which taxa have agricultural, medicinal or other known uses. They also identify which taxa have been used, such as by distributing seed samples for scientific research or education. Lastly, they evaluate data quality for each specimen (for example data on source habitat, taxonomy and so on) and condition of each specimen (for example seed quality and viability). Such considerations of heritage value, phylogenetic distinctiveness, climate suitability, usefulness and condition or quality are complementary to endangerment value (see more below).

Other organisations are also working on collection value metrics, such as Botanical Software (Ostgaard *et al*., 2021, 2022). They have presented a similar approach to summing multiple metrics to obtain a collection value linked to a botanic garden's mission statement and collections policy. They provide examples (The Dawes Arboretum and Cambridge University Botanic Garden) of quantifying a collection's value and tracking changes over time, using metrics such as the health of each plant, and the provenance, threat status, age and uniqueness of accessions. The importance of data quality is also highlighted, specifically that changing data quality over time can impact scoring metrics and that threat assessments become outdated and may not be updated frequently enough. Lastly, they show how analyses can be used by multiple audiences beyond curators: horticulturists, donors, board members and botanic garden visitors.

To test applicability of the endangerment matrix to other *ex situ* collections, a preliminary assay of selected palm and cycad taxa was performed at Montgomery Botanical Center (Coral Gables, FL, USA) using the same methodology. Nineteen species were examined within the genus *Sabal*. *Sabal miamiensis* received the highest rank for further collections development and *S. mauritiiformis* had the lowest rank (Fig. 5; Supplementary Material A). Interestingly, these conclusions from the endangerment matrix parallel prioritisations found in a more qualitative method (Griffith *et al.*, 2021), which considered only breadth of presence in collections and imperilment, each a major factor in the current method. An advantage of our method is an emphasis on quantifying such factors, making priority more deliberative and easier to compare among species.

Quantifying endangerment value in your botanic garden

In the previous sections, we described in detail the methodology we developed for quantifying endangerment value, which used four priority genus-level tree collections at TMA as a case study. We collected quantitative data on each of the elements we considered important to endangerment value and used the data to rank species by overall endangerment. This resulted in prioritisation of species for either further collecting or extra care in the collections; in the future we will work to integrate our findings into decision making in the garden.

Here, we highlight considerations for how this method can be applied to other institutions and collections. The endangerment matrix framework should be adjusted based on the institution's focus and goals for a collection and availability of data for the target group of taxa. Matrix adjustments could include changing the relative weights of metrics or by adding additional metrics to the endangerment matrix. Different botanic gardens and focal taxonomic groups may have different relevant data available, such as knowledge of inbreeding or fitness in wild populations, or information on biogeographic history and genetic lineages. Future tests with different data will continue to inform the methodology's most effective uses and extent of flexibility. An interactive version of the endangerment value matrix can be downloaded for trialling and adapting, such as removing species to see how priorities are affected, modifying the weighting scheme, starting with a fresh set of species, or adding and removing the metrics considered (Supplementary Material A).

Underlying data

Carefully choosing the set of target species to assess using the endangerment matrix is an important step since it can greatly affect results. Depending on an institution's own reasons for assessing endangerment value, different taxonomic guidelines could be followed (for example including infraspecific taxa and/or hybrids). Decisions about whether to include taxonomically uncertain species may be of special interest, because such species are often found in very few botanic gardens and can therefore score highly in the endangerment matrix. Staff may also wish to calculate the endangerment matrix across species from many genera up

Fig. 5 *Sabal miamiensis*. Above: this plant (MBC #87187) was rescued from the path of development in 1987, shortly after the species was described. Development has now fully extirpated this species from its native habitat. Below: four-year-old seedlings propagated from MBC #87187 for restoration efforts. Photos: M. Patrick Griffith.

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to the entire garden collection, or within each genus separately.

Although the IUCN Red List was useful for quantifying extinction risk in the endangerment matrix for TMA, another framework may be useful depending on which platform has assessments completed for target species and the scope of a botanic garden's mission (for example focus on globally threatened versus regionally threatened taxa). NatureServe Conservation Status Ranks are available for native US and Canadian taxa at both global and state or provincial levels. BGCI's ThreatSearch database (www.bgci.org/threat_search.php) can also be used to find a wide range of threat assessments across the world and is therefore a great place to start. If extinction risk is an important factor in your specific collection's mission and relevant threat assessments have not been completed for target species, assessing target species for extinction risk may be an important step before utilising the endangerment matrix.

Most of the data we used for the endangerment matrix are publicly available and relatively easy to access and download for any set of target species. The main exception is data supporting the metrics quantifying the extent of representation of wild or cultivated-from-wild material in *ex situ* collections, including the number of accessions and number of *ex situ* collections. We gathered these data from an accession-level *ex situ* survey conducted by TMA in partnership with BGCI. Planning and enacting our *ex situ* survey, and data management took multiple months and required knowledge of standard plant collections data fields and expertise in a data processing tool such as R. The endangerment matrix does not, however, rely on having data for every metric nor on using the same set of criteria we do; therefore if it is not feasible to gather accession-level data, then taxon-level data (number of *ex situ* collections holding the species) can be used as the sole data point for current *ex situ* representation in collections. Additionally, BGCI is currently working to add a 'Pedigree' module to BGCI PlantSearch, which may be able to provide accession-level data without the need to conduct an *ex situ* survey. Our approach could also be further developed, used and shared by a centralised organisation such as BGCI. A centralised database and online tool for calculating endangerment value would reduce redundant effort by many botanic gardens individually requesting and processing similar data.

Additional data sources or metrics for the endangerment matrix can also be considered. For example, the Potter *et al*. (2017, 2019) assessments of climate change and pest/disease vulnerability were available for native US tree species in our target genera. Other plant groups may have similar analyses of the predicted impact of threats. We also considered using additional species trait data to directly inform endangerment value. Certain traits may give some species a propensity towards extinction. For instance, lower seed dispersal distance may make species unable to disperse to a new suitable habitat in the face of climate change, while long generation times may make species unable to reproduce fast enough. After considering various sources of species trait data (Schneider *et al*., 2019; Smith & Willoughby, 2021), we decided TRY: Plant Trait Database (Kattge *et al*., 2020) was most likely to have the type of data we were seeking. We downloaded data in fields potentially related to endangerment value for target species, including lifespan; tolerance to frost, shade, drought and fire; dispersal syndrome;

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and growth rate. We found trait data for only 30–50 per cent of our target taxa as well as issues with inconsistent measurement units. Additionally, we realised that most of these traits could not consistently be scored as 'good' or 'bad' within the endangerment value metric – for example, a species' tolerance to fire would have a context-dependent relationship with endangerment. Future work could further explore the application of additional species-specific trait data to endangerment value. Other considerations for adding metrics to the endangerment value matrix could include, for example, the extent of the species' range covered by protected areas, whether the species is exceptional or the type of exceptionality (Pence *et al*., 2022), or, if looking at crop wild relatives, the extent of use by humans.

Weighting scheme and selecting appropriate metrics

The weights placed on different metrics included in the endangerment value matrix have a substantial impact on final species ranks, and therefore require careful consideration. The use of factor weighting in the matrix allows each botanic garden to customise its endangerment scoring approach to reflect the institution's values and goals (though changing metrics and weights would prevent comparison of value among gardens). For example, a botanic garden with a focus on restoration would prioritise native species, while a garden with more emphasis on contributing to genetic diversity may place a higher weight on the number of wild accessions in *ex situ* collections. Metrics can also be removed entirely when they do not align with the institution's goals. After carefully considering the weighting of metrics and whether any metrics should be excluded, remaining uncertainty can be addressed by basing decision making on blocks of species, for example prioritising the top quarter. This places less emphasis on the precise score, a consideration which may be helpful to other botanic gardens too.

Endangerment value interacts with several other axes of biodiversity

We note that there are other aspects of species or collection value that are not actually part of endangerment value but could complement it. Table 4 summarises the metrics used at TMA, and lists some others that may be relevant to botanic garden collections. Some of these assume an underlying goal of conserving biodiversity while others reflect other goals of a collection. Phylogenetic or evolutionary distinctiveness, for example, has been proposed as a conservation criterion (Winter *et al*., 2013; Forest *et al*., 2018; see also Cavender *et al*. (2015) for this and other axes of diversity to consider in *ex situ* collections). Large phylogenies are available that include all seed plants (Zanne *et al*., 2014; Smith & Brown, 2018) and could be used for assessing phylogenetic value. Prioritising phylogenetic distinctiveness may result in different outcomes of rankings than endangerment value. Depending on how threat status and rarity are distributed across the phylogeny, it is not always the case that IUCN Red List status correlates with phylogenetic distinctiveness (Jerome *et al*., 2017). Ecological distinctiveness of species and their suitability for the climate of a botanic garden are two other potential metrics that may or may not correlate with endangerment. Ecological distinctiveness can be quantified using publicly available data on climate and soils to compare the overlap in observed growing conditions with other

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species as well as current or future botanic garden conditions. Genetic diversity value, in terms of the amount of genetic diversity likely already conserved in collections, can also be calculated, with high priority given to the species that have low amounts of their genetic diversity currently conserved in *ex situ* collections. As genetic data can be expensive to generate for every target species, models can leverage proxies of genetic diversity such as geographic range size and abundance (Hoban *et al*., 2018; Hoban, 2019). Lastly, we suggest that horticultural value, in terms of rarity, distinctiveness of certain cultivars for public and horticultural interest, trait variation and aesthetics, may also be important considerations in collection value assessments for certain botanic gardens. Well-curated lists of cultivars and their traits and history may be useful for quantifying horticultural value (Lobdell, 2021). Multiple dimensions of diversity and value interact with each other, and could be assessed on their own or in combination, depending on the botanic garden's goals and priorities. Multiple value dimensions provide the opportunity for a variety of stakeholders and experts within botanic gardens (for example curators, scientists, conservationists, restoration ecologists, educators, interpretation specialists and so on) to come together to discuss priorities, needs and values of the collections. Of course, this may be challenging in practice for many gardens, with regard to both gathering the necessary data and interpreting multidimensional data.

Table 4 Metrics or dimensions for evaluating collections, including five being quantified at TMA, and other values that could be considered.

Dimension	Definition
Five dimensions being examined at TMA	
Endangerment	Rarity and vulnerability of the species in the wild and degree to which it is conserved in *ex situ* collections
Environmental	Both the degree to which a species' environmental niche aligns with the institution and the uniqueness of the species' niche, compared to the other target species
Genetic	Proportion of the species' genetic diversity conserved in *ex situ* collections
Horticultural	Rarity of the cultivar and significance of valuable horticultural traits
Phylogenetic	Both the evolutionary distinctiveness of a species on the global tree of life and a species' effect on the evolutionary diversity of the collection being studied
Examples of other values to consider	
Economic	For example: ease of propagation; lifespan; health of specimen; cost to obtain again if lost
Educational	For example: engagement of visitors; specific educational messages important to the botanic garden
Historic or cultural	For example: donor value; heritage; type specimen; importance to native peoples

Conclusion

Measures of endangerment value may need to adapt in the coming decades. Specifically, climate change will increasingly impact the suitability of species for particular gardens, which is especially challenging for long-lived species. Botanic gardens must make decisions about how far outside their current climate species and genotypes should be sourced, and at what pace plants should be removed and replaced. Pests and disease will also change in the coming decades as new insects and pathogens are introduced, spread or become problematic. Botanic gardens may need to adapt the endangerment value metrics, and consider the current health or condition of specimens.

Endangerment is a subjective but important dimension of collection value that integrates biological attributes of species, conservation work to date and institutional values, which can be calculated with a quantitative metric. Along with other kinds of valuation – phylogenetic, ecological, genetic, horticultural – endangerment can be assessed, quantified and weighted to reflect institutional values. A matrix such as that presented here should be adapted deliberately and strategically to address institutional needs, particularly with respect to data quality, sources, and inclusion and exclusion of data fields in the matrix. One important benefit of utilising endangerment in collections planning and evaluation may be the process that surrounds it: explicitly articulating institutional values, working together as scientists, educators and curators and trying to quantify priorities to help guide collections development and *ex situ* conservation. We see the use of endangerment in collections planning and management as an integrated and iterative process which should occur periodically over time, reflecting changes in the institution and in data quality, and responding nimbly to a rapidly changing climate. That process of collections assessment and evaluation, the group interpretation of the resulting rankings and decisions about how to implement changes can be of great benefit to an institution, as we have learned at TMA. Overall, the process of assessing endangerment value can assist botanic gardens in determining short- and long-term collections priorities and, through time, help an institution improve its collections and meet its mission. As the botanic garden community scales up *ex situ* conservation efforts to address global environmental crises like climate change and biodiversity loss, we hope this valuation methodology can be used across institutions to collectively achieve greater conservation impact.

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Leśnego Banku Genów Kostrzyca; Arboretum Mustila; Arboretum du Passadou; Arboretum des Pouyouleix; Arboretum Wespelaar; Arboretum Zampach; Arizona-Sonora Desert Museum; The Arnold Arboretum of Harvard University; Atlanta Botanical Garden; Auckland Botanic Gardens; Bamboo Brook Outdoor Education Center; Bangladesh Agricultural University Botanic Garden; Bartlett Tree Research Laboratories Arboretum; Batumi Botanical Garden; Bedgebury National Pinetum & Forest; Beijing Forestry University Botanic Garden; Bergius Botanic Garden; Blue Mountains Botanic Garden, Mount Tomah; Borde Hill Garden; Botanic Garden Government College University, Lahore; The Botanic Garden of Smith College; Botanical Garden of Moscow Palace of Pioneers; Botanical Garden of the University of Bern; Botanischer Garten der Universität Zurich; Boyce Thompson Arboretum; Brookgreen Gardens; Brooklyn Botanic Garden; Caerhays National Collection of Magnolias; Cambridge University Botanic Garden; Central Siberian Botanical Garden, Russian Academy of Sciences; Cephalonia Botanica; Chelsea Physic Garden; Chicago Botanic Garden; Connecticut College Arboretum; Cornell Botanic Gardens; The Dawes Arboretum; Delft University of Technology Botanic Garden; Denver Botanic Gardens; Denver Zoological Gardens; Desert Botanical Garden; Donald E. Davis Arboretum of Auburn University; Ed Shinn; The Eden Project; Estancia San Miguel; Evergreen Burial Park and Arboretum; Exbury Gardens; Fairchild Tropical Botanic Garden; Ferme d'Azy at Chassepierre, Belgium; Finnish Museum of Natural History; Florida field genebank, Jeannine Cavender-Bares; FossilPlants; Frances Parker Private Collections; The Frelinghuysen Arboretum; Gabis Arboretum at Purdue Northwest; Ganna Walska Lotusland; Gardens of the Big Bend: Magnolia Garden; Giardino Botanico 'Nuova Gussonea' Monte Etna; Gothenburg Botanical Garden; Green Bay Botanical Garden; Green Spring Gardens; Greenwood Cemetery; Grigadale Arboretum; Harmas de Fabre; Helsinki University Botanic Garden; Hergest Croft Gardens; The Holden Arboretum; Hortus Botanicus Amsterdam; Hoyt Arboretum; Huntington Botanical Gardens; Institute of the Far Eastern Branch Botanical Garden, Russian Academy of Science; Iturraran; Jardín Botánico 'Carlos Thays'; Jardín Botánico Francisco Javier Clavijero; Jardin Botanique Alpin de la Jaÿsinia; Jardin Botanique Exotique 'Val Rahmeh'; Jardin Botanique de Montréal; Jardin Botanique de Paris; Jardin du Mesnil; Le Jardin Le Vasterival; JC Raulston Arboretum; Jerusalem Botanical Gardens; Key West Tropical Forest & Botanical Garden; Landis Arboretum; Les chênes plantés à l'Arboretum de La Bergerette; Lincoln Park Zoo; The Linnaean Gardens of Uppsala; Madison Park, Chicago; Magnolian Grove Arboretum; Mallet Court Nursery; Marie Selby Botanical Gardens; Masaryk University Faculty of Medicine Medicinal Herbs Centre; Memorial University of Newfoundland Botanical Garden; Mission Street Parks Conservancy; Missouri Botanical Garden; Montgomery Botanical Center; The Morris Arboretum; The Morton Arboretum; Mount Auburn Cemetery; Mount Lofty Botanic Garden; Mt Cuba Center; Nanjing Botanical Garden; Naples Botanical Garden; National Tropical Botanical Garden; The New York Botanical Garden; Nicholas Reis; Norfolk Botanical Garden; Orto Botanico dell'Università degli studi di Siena; The Polly Hill Arboretum; Puebla University Botanic Garden; Pukekura Park; Quarryhill Botanical Garden; Quercus Collection of Terry Hanlon; Rancho Santa Ana Botanic Garden; Red Butte Garden and Arboretum; Riverwoods Arboretum; Rogów Arboretum of Warsaw University of Life Sciences; Royal Botanic Garden Edinburgh; Royal Botanic Gardens Sydney; Royal Botanic Gardens Victoria, Melbourne Gardens; Royal Botanical Gardens Ontario; Royal Tasmanian Botanical Gardens; San Diego Botanic Garden; San Francisco Botanical Garden; San Luis Obispo Botanical Garden; Sarah P. Duke Gardens; Scott Arboretum of Swarthmore College; The Sir Harold Hillier Gardens; Sister Mary Grace Burns Arboretum; Smithsonian Gardens; Les Souffrettes; St Andrews Botanic Garden; Starhill Forest Arboretum; The State Botanical Garden of Georgia; State Botanical Garden of Kentucky; Stephen's Lake Park Arboretum; Tallinn Botanic Garden; Tasmanian Arboretum Inc.; Trompenburg Gardens & Arboretum; Tyler Arboretum; UC Davis Arboretum and Public Garden; United States National Arboretum; University of Bergen Botanical Garden; University of British Columbia Botanical Garden; University of California Botanical Garden at Berkeley; University of Exeter Grounds; University of Oslo Botanical Garden; University of Turku Botanic Garden; University of Washington Botanic Gardens; VanDusen Botanical Garden; Von Gimborn Arboretum; The Westonbirt National Arboretum; Willowwood Arboretum; Windsor Great Park; W.J. Beal Botanical Garden; The Yorkshire Arboretum.

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