INTEGRATED COLLECTIONS DEVELOPMENT

Quantifying value of garden collections for decision making and prioritization

The *Quercus* collection at The Morton Arboretum, an internationally recognized collection accredited by the American Public Gardens Association Plant Collections Network, with hundreds of specimens, requires careful planning for allocation of care and space, and future accessions replacement

What is your garden's mission? How do you know if you are achieving it?

Conserving, curating and showcasing the world's botanic diversity is a monumental challenge. Botanic gardens must make careful curation decisions to have the greatest impact. Fortunately, tools and approaches are available to help with collections decision making!

Plants are essential to achieving a botanic garden's mission, whether the mission is to showcase plant beauty and diversity, conserve species and their genes, adapt landscapes to climate change, provide botanical education, or preserve historical legacies. To identify priorities for plant collections management, botanic gardens can use integrated collections development.

Defining integrated collections development

The process of collecting and evaluating information about a garden's "holdings, as well as the holdings of others, to make complementary and synergistic collection management decisions including acquisitions, propagations, and distributions, in order to maximize diversity within and across species" (Meyer, 2018). The goal is to "facilitate the rational allocation of limited resources [to] achieve the greatest conservation impact." It builds on and applies the concepts of metacollections - the combined holdings of a group of collections - (Griffith et al., 2019) and systematic conservation planning (Margules et al., 2000) to living collections.

Data and tools can help to assess and plan collections. Such evaluation can characterize how different species or accessions fulfill a garden's mission, inform allocating special care to some plants, help with collections management, prepare for rapid decision making when disasters happen, and track collections value over time.

Integrated collections development involves several steps: (1) define values that are important to the institution(s), (2) decide how to translate those values into characteristics or dimensions which can be quantified, (3) gather data about current and potential accessions, (4) formulate calculations or metrics that translate data into values for each accession, (5) use the findings to inform decision making, which may include rank ordering accessions to prioritize accessions for special care, acquisition, deaccessioning, or interpretation opportunities, (6) discuss findings with leadership, supporters, visitors, and other audiences, and (7) repeat steps 3 to 6 periodically to assess changes over time. This process requires participation of a diverse team including scientists, curators and collection managers, and garden leadership.

To summarize, the process is: (1) define your values, (2) decide how to measure values, (3) gather data, (4) calculate a metric for each accession, (5) inform decision making including prioritization, (6) share findings, and (7) repeat over time.

Piloting integrated collections development at The Morton Arboretum

Here, we showcase evaluation of five dimensions of value to the Science and Curation teams and mission of The Morton Arboretum, including how we gathered data, preliminary findings, and lessons learned. We found that performing integrated collections development was useful but challenging. Benefits include better articulating values underlying a mission, and better understanding of how individual specimens and accessions in the collections contribute to the mission.

Four priority genera at The Morton Arboretum

We focused on four priority genera (*Malus*, *Quercus*, *Tilia* and *Ulmus* - crabapple, oak, basswood, and elm), but the approach could be used for single genera, plant families, other categories (e.g., geographic or thematic collections), or the entire list of current and potential future species maintained at a garden. We hope this document can help you if you have any of the following questions!

- How do living collections support my garden's mission?
- Which components of our collections are more important than others and why?
- How do our collections complement other collections for broader scientific or other purposes?
- Can our collections be more complete?
- In what ways are collections vulnerable?


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Examples of the four genera used to test prioritization for integrated collections development in this project:

1. *Malus floribunda*,
2. *Tilia 'Zamoyskiana'*,
3. *Quercus macrocarpa*,
4. *Ulmus americana*

Each have different evolutionary, environmental, genetic diversity, endangerment, and horticultural values.

Environmental Value

Every plant species has a set of environmental conditions in which it can survive and thrive – its environmental niche. Gardens may seek to identify which species' niches (a) align with the environmental conditions of the garden (e.g., climate, soils) and are thus likely to survive, and/or (b) provide an opportunity to showcase interesting plant traits or how a diversity of uncommon or unique environmental characteristics of species contribute to overall biodiversity.

Over decades, people have documented where species have been found growing naturally in the wild (occurrence data). They have also collected systematic observations of environmental conditions such as temperature, precipitation, soil characteristics and more (although the scale and resolution of this data varies across the globe). A combination of occurrence data, climate, soil and other environmental data can be used to define the relative niche of every potential species in a collection. Such analysis can (a) identify good, marginal or poor overlap with a garden's location, and/or (b) identify species which exhibit highly unique environmental characteristics.

Much occurrence and environmental data is freely accessible at regional and global scales. For example, we used occurrence data available through resources such as GBIF (gbif.org), BIEN (https://bien.nceas.ucsb.edu/bien/), IUCN Red List (iucnredlist.org/), and others. For this project we used global-scale, gridded current climate data from TerraClimate (climatologylab.org/terraclimate.html), and soil properties from Harmonized World Soil Database (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/). We then compare the environmental envelopes of each species using a Principal Component Analysis for each genus.

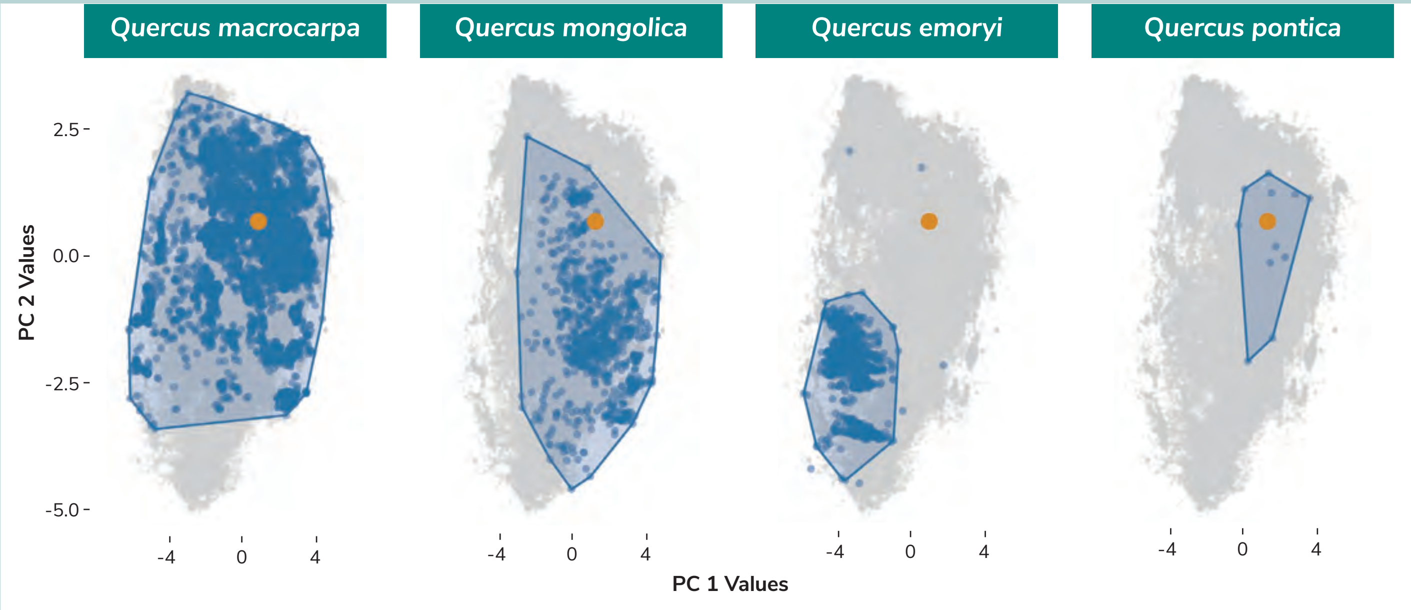
Quercus pontica, an oak species whose environmental niche overlaps with The Morton Arboretum, as shown on the next page

Quercus acerifolia, a species of high conservation concern found on only four mountains in Arkansas. Could this narrow-range endemic survive at our garden?

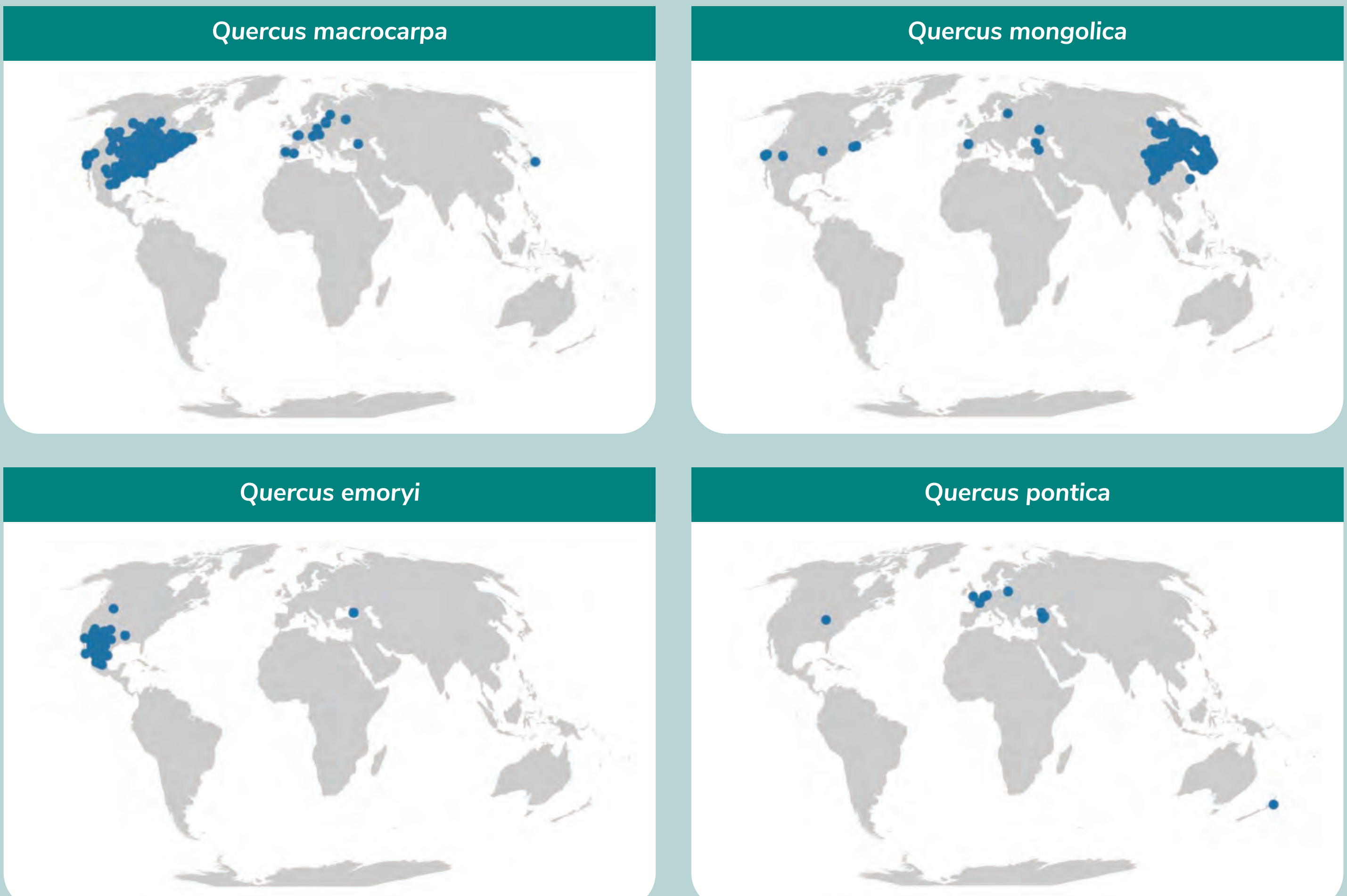
Using this approach, we learned that 53% of *Malus*, 47% of *Quercus*, 63% of *Tilia*, and 41% of *Ulmus* taxa under consideration for cultivation at The Morton Arboretum are likely suitable under current conditions based on the environmental characteristics we evaluated. As shown in the figure on the next page, we were also able to identify species that may represent contrasting or unique environmental space, such as *Quercus emoryi* compared to *Quercus mongolica*.

Lessons, challenges, and future work

- Analyzing species' environmental niches is feasible, but must be done with care. Special caution must be taken with species with poor data (e.g. few data points). Additionally, all metrics produced by our methods are relative to the species included in the analysis.
- Analysis of species' environmental niches is useful and engaging for decision makers. Placing species in environmental space can help determine a species' alignment with a garden's current habitat suitability.
- The resolution and availability of climate and environmental data can vary across the world. Global analyses may need to use coarser spatial or temporal resolution than analyses focused on specific geographic regions. Therefore, the geographic scope of interest will influence what data can be used.



Distribution of four species in environmental space (blue points) as well as the environmental envelope (blue area) and relative position of The Morton Arboretum (orange point). Although environmental niches are defined with many dimensions (e.g., max annual temperature, annual precipitation; soil types), techniques such as PCA can help reduce much of the variation into two dimensions, facilitating visualization. Here we see *Quercus macrocarpa*, *mongolica*, *emoryi*, and *pontica* each of which has a different environmental envelope and different degrees of overlap with The Morton Arboretum.



Known occurrence points of the four species obtained from GBIF.

Evolutionary Value

Gardens seek to conserve and showcase “biodiversity” and “species”. But there is more to diversity than the number of species in a collection. Species are also defined by evolutionary history: they are tips on the Tree of Life four billion years old. Using the Tree of Life, we can quantify how long a species has evolved separately from others. This measure is called *evolutionary distinctiveness*. Evolutionarily distinctive species such as ginkgo, sweetgum, and Wollemi pine often have unique ecological attributes or traits. A garden collection that maximizes *evolutionary distinctiveness* has high evolutionary diversity, which is useful for conservation, interpretation, and scientific study.

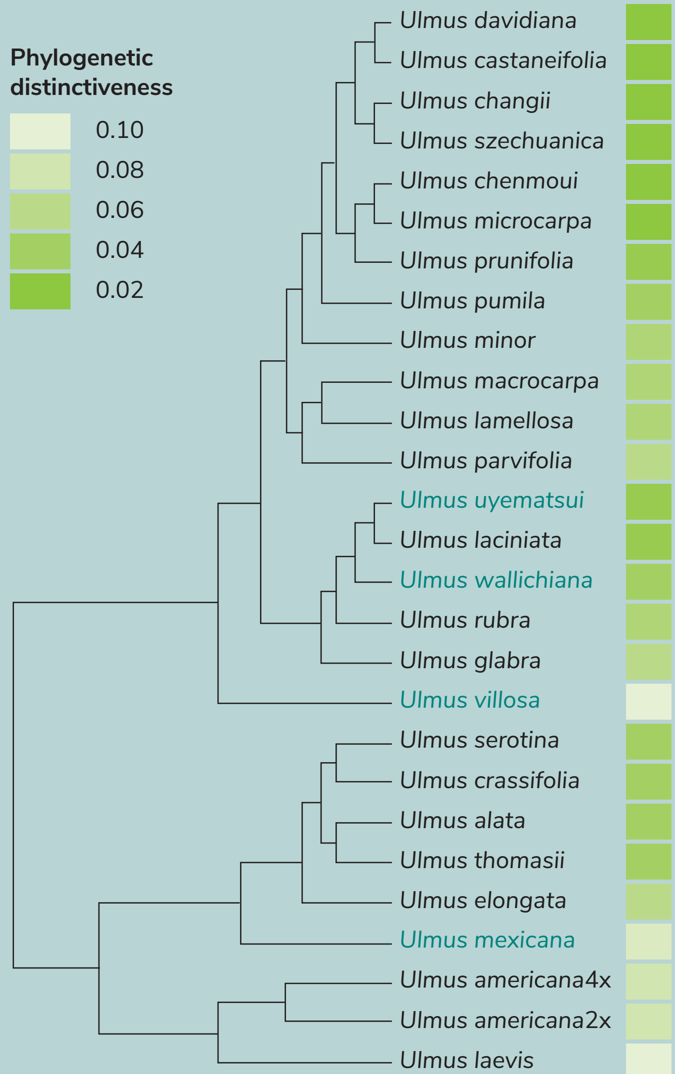
Scientists have a broad understanding of the Tree of Life (see for example Smith & Brown 2018), and very detailed knowledge of some genera. In fact, a rough Tree of Life for nearly all seed plants has been assembled. But there are many gaps in knowledge, and DNA data will often be needed to evaluate each species’ contributions to evolutionary distinctiveness in an ex situ collection.

For our project we used restriction-site associated DNA sequencing, or RAD-seq, that provides snippets of data across the genome. We used these data to estimate evolutionary distance between each available species within each of four target genera (*Malus, Quercus, Tilia, Ulmus*). We are still working through challenges such as hybrids and polyploids (individuals that contain genomes from multiple species). For now, we have gained a very good understanding of *Quercus* and *Ulmus*, and a preliminary understanding for *Tilia* and *Malus*. For example, the figure on the right points to *U. villosa, laevis, mexicana*, and *americana* as particularly high priorities.

If gardens aim to preserve living representatives of the millions of years of history that has shaped biodiversity – the innovations that make each species unique – then evolutionary distinctiveness and diversity are important considerations.

Lessons, challenges, and future work

- Evolutionary distinctiveness is a useful way to identify species that have the most evolutionary distance.
- Estimating a species’ place on the Tree of Life will require teaming up with researchers, and it is not always straightforward to infer or interpret results. How do hybrids contribute to phylogenetic diversity, for example?
- Tools to implement these analyses are somewhat limited. An R package is provided to help with the analyses presented here (https://github.com/andrew-hipp/edivColl), but more user-friendly tools for using the Tree of Life are needed.



Estimate of evolutionary distinctiveness of *Ulmus* species, from RAD-seq. Species names in black are already present in The Morton Arboretum living collections; names in green are candidates for acquisition. The colors in the boxes show evolutionary distinctiveness, where light green is most distinctive, and dark green is least distinctive.

Ulmus americana, growing at The Morton Arboretum, is one of the most evolutionary distinct *Ulmus* species at the Arboretum

Genetic Diversity Value

Genetic diversity is essential for species to survive climate change, new pests and diseases, and other environmental changes. Genetic diversity is the diversity at the DNA level within and among populations of species, which provides variation in traits, survival, and adaptation. This variation may be visible in flowering or bud break time, leaf and flower colors, seed size, or other visible traits, or it may only be visible by examining the DNA of many individuals within a species.

There may be substantial genetic differences within and among populations of species reflecting adaptations or biogeographic history, such as this arid adapted *Quercus havardii* (foreground, note this variety is also known as *Q. havardii* var. *welshii* or *Q. welshii*), and sufficient sampling of individuals and populations are needed to conserve the species' adaptive potential.

Taxa	Recommended number of plants
Hibiscus waimeae var. *waimeae*	58
Magnolia asheii	63
Pseudopheonix sargentii	94
Quercus georgiana	138
Quercus boyntonii	181
Zamia decumbens	205
Quercus havardii	481

Minimum number of individual accessions recommended for several selected taxa analyzed using genetic data; this size should safeguard at least 95% of genetic diversity, under conservative assumptions.

An increasing number of gardens seek to conserve genetic diversity across species' geographic ranges, to safeguard adaptive potential. Genetic diversity in a botanic garden collection can be assessed by comparing DNA of individual plants from wild populations with DNA of plants maintained at the botanic garden. Using this DNA approach, it is possible to directly calculate a percentage of wild genetic diversity conserved ex situ. As yet, only a few dozen studies have measured genetic diversity in botanic garden collections, but this work is increasingly affordable.

It is common, however, that DNA-based analyses are not available, and proxies for genetic diversity can be used to estimate genetic conservation in an ex situ collection. For example, the number of populations sampled from across a species' range is a proxy for conserving genetic diversity among populations. In addition, the number of individuals and maternal lines conserved ex situ is a proxy for conserving genetic diversity and a proxy for long term ex situ population viability (as in zoos, see Wood et al., 2020).

At The Morton Arboretum, we have obtained new DNA data for high priority species, and we have used geographic and demographic proxies for genetic diversity conservation. We quantified variation among species in how much DNA level diversity is currently conserved, from 40% to 95% across 11 taxa (Hoban et al., 2020, Zumwalde et al., 2022), though more examples from species with a variety of characteristics are needed. We also found that geographic area conserved varied from 1% to 100% with an average of 30% across 48 species (a finding which is consistent with Khoury et al., 2020). Also, using simulations we found that a genetically comprehensive collection should be at least several hundred plants, spread across the species' geographic range (Rosenberger et al., 2022).

Lessons, challenges, and future work

- We can ensure that garden collections conserve more of a species' genetic diversity and adaptive potential. An emerging challenge is making sure that enough genetic diversity in collections is carried forward into future generations or when garden materials are used for ecological restoration.
- In addition to considering the number of populations and individuals represented ex situ, increasing the number of maternal lines and collecting over multiple years can provide greater genetic diversity than a single effort.
- Coordination among conservation collections – i.e., meta-collections – is effective and necessary to collectively ensure that gardens together meet genetic diversity goals.

Horticulture Value

Gardens have long been a haven for weird and wonderful varieties developed by, or found in the wild and propagated by, horticulturists. From disease resistance to divergent flower colors, forms, or leaves, horticultural novelties are a priority for many garden collections. And yet, many gardens showcase the same cultivated varieties (cultivars) found at other gardens, and many cultivars are unnoticed or neglected. So, which cultivars should a garden choose?

Cultivar lists are helpful. There are documented checklists (registers) of all known cultivars of certain plants, their origin and history, their identifying characteristics, etc. In some genera, these lists may be hundreds of cultivars long. Dedicated curators and horticulturists periodically update these lists. The BGCI PlantSearch database can also be used to identify how many other gardens are currently holding certain cultivated varieties.

Cultivar checklists can be analyzed by looking for certain characteristics or historical aspects which also allow for interpretation and public engagement opportunities, in addition to preserving the legacy of cultivars and ensuring that unique varieties are not lost through time.

Understanding why a particular cultivar has been named and selected is critical for determining whether to acquire it, or retain it, for a collection. Cultivars selected for interesting habit or foliar morphology need not be directly compared to cultivars with superior regional performance, for example.

For our project we developed a recent *Magnolia* cultivar checklist with approximately 1600 cultivars (Lobdell, 2022), and a *Tilia* checklist with approximately 400 cultivars. The checklists provide information on how each cultivar originated, distinguishing characteristics, and notes about flowering time, size, fragrance, cold hardiness, and color. Curators can consult these checklists to find rare or common varieties, environmental suitability, and color and bloom time variation. The lists can also be useful for verifying whether accessions in a collection are correctly named – a very important task. Other interesting discussions include why and when certain cultivars are higher priority than others. For instance, cultivars developed for pest or disease resistance will be less useful when the pest adapts to overcome the resistance.

Lessons, challenges, and future work

- Variation in horticultural diversity can be documented in narrative form through cultivar checklists, but is challenging to quantify; there is room for research on this, such as by employing textual analysis and machine learning.
- Rarity may or may not contribute to value: some rare cultivars have become rare due to poor performance or having been supplanted by superior varieties.
- Cultivar checklists are a rich source of data for curators, and can help conserve horticultural varieties for future generations.
- A challenge is how to update these lists in a systematic way over time, align them with cultivar registers, and make them accessible and easily searchable to all audiences.

Examples of *Magnolia* cultivars and their descriptions, which can provide information on color, flower structure, flowering time, hardiness, size, and more, which can help collection managers

'Caerhays Belle'

(*M. sargentiana* × *M. sprengeri*). Floriferous selection with large, textured, bright salmon-pink flowers. Broad tepals.

'Jim Wilson'

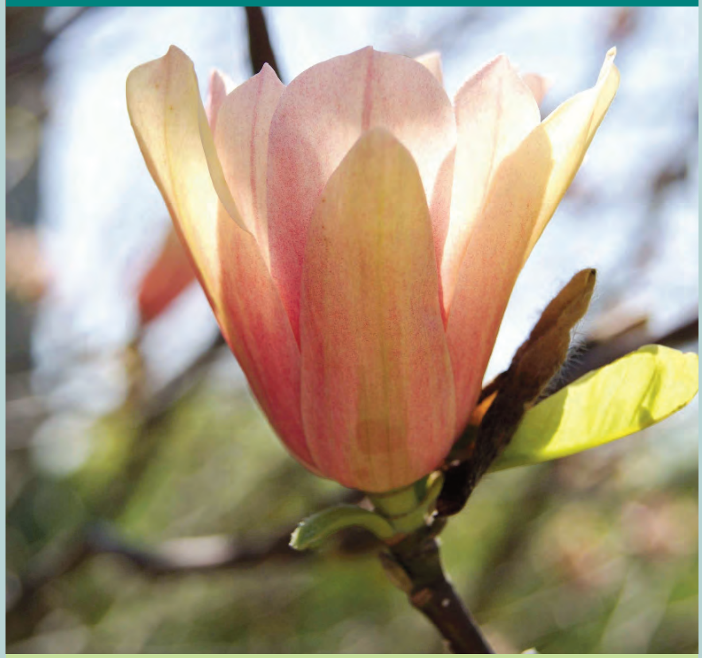
Cold hardy (to ca. -35C with no damage), resistant to wind and ice, vigorous, flowers slightly larger than typical for species, and adaptable to various soil types. Marketed as MOONGLOW, which is often misused as the cultivar epithet.

More examples of *Magnolia* cultivars and their descriptions

'Sunsation'

Upright, narrow habit, to ca. 3 × 2 m. Flowers deep yellow, to 17 cm, appearing late season but before leaf out. Sister seedling to 'Sun Spire', but faster growing.

'Coral Lake'



Semi-fastigiate, to ca. 3-4 m in 10 years. Flowers blended with pink shading and vertical yellow stripes, to ca 18 cm diameter. 11 tepals. Flowering late, but before expansion of leaves.

'Gold Star'

Small to medium-sized upright tree. Leaves bronze red when opening, turning green (paler beneath) as they mature. Flowers creamy yellow, starlike to 10 cm diameter. Fourteen strap-shaped tepals comparable to *M. stellata*.

'Morris Fragrant'

Fragrance fantastic, compare grape juice or grape chewing gum (or potentially *M. salicifolia* 'Grape Expectations'). Propagated and distributed by Pleasant Run Nursery circa 2010. Sometimes referred to as *M. × loebneri*, though flowers consist of 6 wide tepals more akin to *M. kobus*.

Endangerment Value

Approximately one third of all plant species are threatened with extinction, meaning they are likely to completely disappear from the Earth within the lifetimes of ourselves and our children. Plants that are not currently threatened may soon be so, due to increasing introductions of pests and diseases, resource extraction and direct harvest, and the worsening climate crisis. Some species are safeguarded in botanic gardens – in fact, about 100,000 plant species are present in gardens to some degree (Mounce et al., 2017) – but many are not. Those species in gardens also have different levels of protection and genetic diversity due to being in more gardens, or being more thoroughly sampled (e.g., more maternal lines).

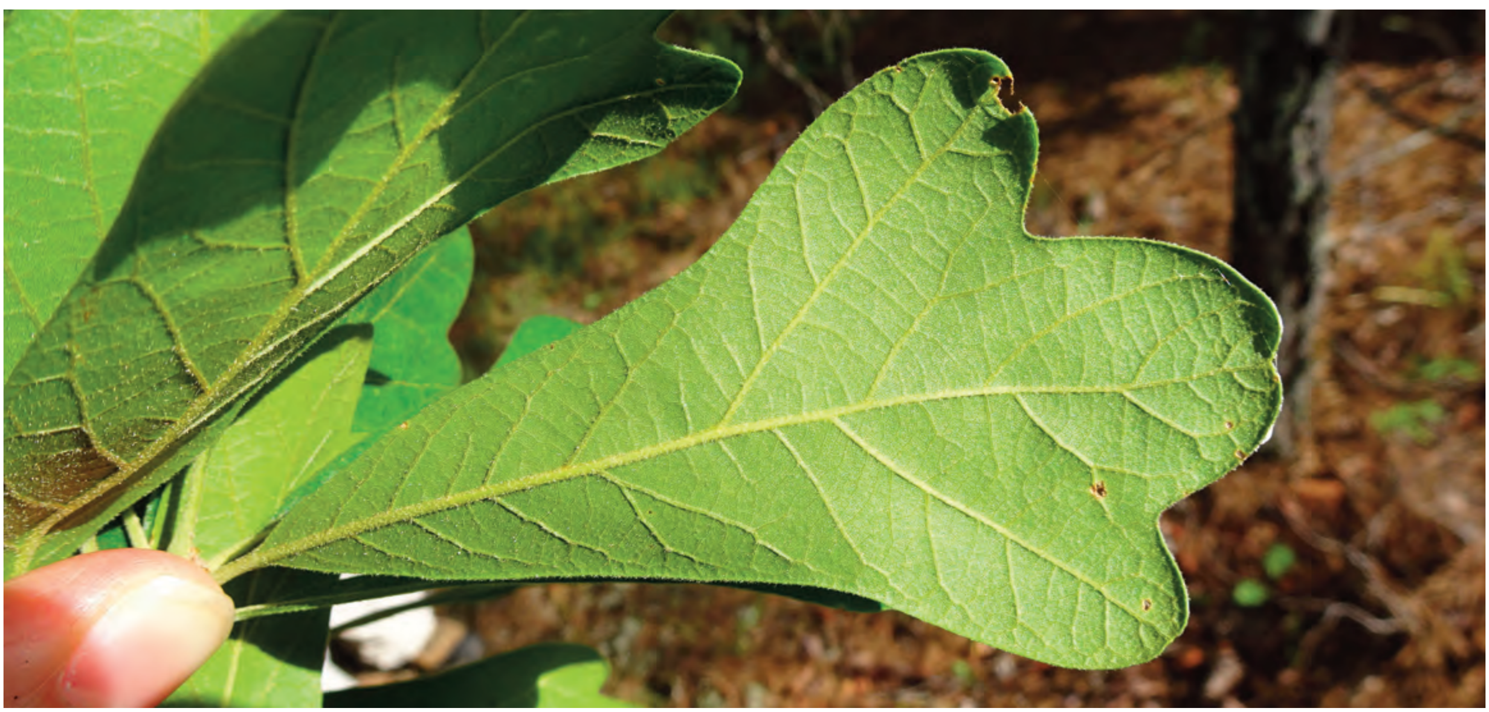
For these reasons, different species have different degrees of endangerment – different likelihoods of becoming extinct. Individual gardens, and increasingly consortia of gardens, seek to save these species from extinction and give them a brighter future. Conserving biodiversity at all levels also helps support stable and sustainable societies.

Prioritizing endangerment across species can focus limited resources on species that need extra care and attention, that could benefit from metacollection management, and that offer important conservation stories for education and outreach products. The IUCN Red List and NatureServe threat assessments are quantitative ways to assess species extinction risk. Records held in the BGCI PlantSearch database and by garden consortia can be analyzed to determine how many gardens hold a species, how many accessions are held, and which accessions are of wild provenance. Other assessments are available for some groups, such as pest and disease vulnerability, or estimations of how much of a species' range will change or disappear under future climate change scenarios (see Table on next page).

We recently created an endangerment value calculation to help organize and synthesize this varied information, combine the different data, and give each species a single endangerment value. As shown in the table below, we sourced data from the IUCN Red List, BGCI, a custom-designed survey of botanic gardens, and scientific literature on threats to trees. We summed quantitative metrics to a single value, and explored the degree to which weighting these values impacted decision-making.

Endangerment Value Lessons

- Using a sensitivity analysis, we found that the species which are prioritized for endangerment value may depend on the type of data considered in the analysis. Therefore, care should be taken in interpreting results.
- We considered adding species' traits to the endangerment value, such as life span or susceptibility to fire, but data were not available for a sufficient percentage of species and the contribution of traits to extinction risk are likely dependent on local context.
- Gardens will need to update their analysis of endangerment value on a regular basis, as new threats to species emerge, as some species may recover in their native habitats, and other changes occur.



Quercus boyntonii consistently ranked as one of the highest priorities when evaluating endangerment value for target species at The Morton Arboretum

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

The types of data and sources used to quantify endangerment values of 182 target species at The Morton Arboretum, and their purpose within the endangerment value. Note that not all species had data available for every metric.

Strategic planning for palm collections at Montgomery Botanical Center, shown here, has long considered qualitative endangerment, horticultural, and conservation values. Applying the more quantitative integrated collections development methodology allows leadership to perceive hidden gaps in the collection, and focus resources on closing those gaps.

Lessons and Future Work

Quantifying the value of accessions was a challenging and lengthy process, but was rewarding and useful. We found that:

- There are data and methods available to help quantify the value of individual accessions and the entire collection for decision making.
- BUT don't trust single methods too strongly – it is important to consider how different sources of data or different decisions about data can influence the value assigned.
- Valuation should always have the human element at the beginning (i.e., matching data to values) and at the end (i.e., interpretation and decision making).
- It was useful and fruitful to collaborate between the science department, garden leadership, and collections departments, and to gain insight and advice from other institutions.

Our work builds on Meyer (2018) and Griffith et al., (2019), and many others, calling for systematic integrated collections development. We hope this inspires other gardens to quantify the value of current and potential future accessions for their collections to help make decisions about collection management. There is much potential work for the future as well:

- There are other dimensions of plant accession value that we did not consider in our work so far – such as historical, educational, plant health, and more. Each garden should consider the values most appropriate to their mission.
- Scientists are able to project how environmental conditions such as climate will change in the future; the environmental analysis we performed could include such projections into the future to highlight how environmental suitability to a given garden, like The Morton Arboretum, is likely to change (see also the BGCI Climate Assessment Tool, https://cat.bgci.org/).
- Quantifying collections value could also create opportunities for helping different audiences engage with the collection, with potential such as conservation advocacy, visitor engagement, or leadership decisions.
- We evaluated aspects of collection value at a single point in time but suggest it should be done periodically to a) evaluate change over time, and b) incorporate changing data (on climate change, taxonomy, and species' threat status, for example).

Five types of value examined at The Morton Arboretum	
Environmental	Both 1) the degree to which a species' environmental niche aligns with the institution, and 2) the uniqueness of the species' niche, compared to the other target species
Evolutionary	Both 1) the evolutionary distinctiveness of a species on the tree of life, and 2) a species' effect on the evolutionary diversity of the *ex situ* collections
Genetic diversity	Proportion of a species' genetic diversity conserved in ex situ collections
Horticulture	Rarity of the cultivar and significance of valuable horticultural traits
Endangerment	Rarity and vulnerability of a species in the wild, and degree to which it is conserved in *ex situ* collections
Examples of other values that gardens might consider	
Historical/ Cultural	Donor value, heritage, type specimen, importance to indigenous peoples, etc.
Educational	Engagement of visitors, specific educational messages important to the garden, etc.
Economic	Ease of propagation, lifespan, health of specimen, cost to obtain again if lost, etc., as well as potential value for agriculture, medicine, or other uses

Summary of collection values considered in our project, and other values that gardens might consider. See also Smith, 2021.

Conclusions

We hope that these valuation approaches can help within and across gardens to better meet our missions. This process can help gardens with decisions about special plant care, maintenance, deaccessioning, and future planning.

We conclude that the value of a garden plant is subjective, but metrics can make it more objective. Measuring the value of accessions in a living plant collection and tracking the overall and specific collection values involves both subjective decisions and quantitative calculations. It is very important to consider which values are most important to the institution or to a cross-institutional effort (e.g., metacollections). It is also important to evaluate how robust the results are, such as by trying different data sources and weighting criteria more or less strongly.

The garden community can use integrated collections development to provide broader coordination, strategic focusing of limited resources, and greater impact to goals such as public education and inspiration, conservation, scientific study, and horticultural advancements.

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Seedlings of butternut (*Juglans cinerea*), growing in a greenhouse. This species has cultural, agronomic, and other values, in addition to the five values examined in our work.

Part of The Morton Arboretum crabapple (*Malus*) collection, showcasing diversity among species and individual trees of form, flowering time, size, color, and geographic origin.

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