Conservation Gap Analysis of Native U.S. Hickories

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Carya aquatica (Michx. f.) Nutt. (Water hickory)
Carya cordiformis (Wangenh.) K. Koch (Bitternut hickory)
Carya floridana Sarg. (Scrub hickory)
Carya glabra (Mill.) Sweet (Pignut hickory)
Carya illinoinensis (Wangenh.) K. Koch (Pecan))
Carya laciniosa (Michx. f.) G. Don (Shellbark hickory)
Carya myristiciformis (Michx. f.) Nutt. (Nutmeg hickory)
Carya ovata (Mill.) K. Koch (Shagbark hickory)
Carya pallida (Ashe) Engl. & Graebn. (Sand hickory)
Carya texana Buckley (Black hickory)
Carya tomentosa (Lam.) Nutt. (Mockernut hickory)

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INTRODUCTION

Trees are facing increasing threats globally, including habitat loss, natural systems modification, land use change, climate change, and pests and diseases. With more than 800 native tree species in the continental United States and more than 60,000 tree species globally, prioritizing species and conservation activities is vital for effectively utilizing limited resources. To facilitate this conservation planning, we developed a gap analysis methodology that examines both the accomplishments and most urgent needs for *in situ* (on-site) and *ex situ* (off-site) conservation of priority, at-risk tree groups in the U.S. This methodology was first implemented in our flagship report, *Conservation Gap Analysis of Native U.S. Oaks* (Beckman et al., 2019).

This report is one of seven that present the results of a second phase of gap analyses, which focuses on native U.S. trees within a group of priority genera that were selected due to particular economic importance, potential challenges with conventional *ex situ* conservation, and/or threats from emerging pests and diseases: *Carya, Fagus, Gymnocladus, Juglans, Pinus, Taxus,* and selected Lauraceae (*Lindera, Persea, Sassafras*). In each report, we provide a summary of ecology, distribution, and threats, and present results based on new data from a global survey of *ex situ* collections and a conservation action questionnaire that was distributed in 2019 to a wide range of conservation practitioners in the U.S. and botanical gardens globally. The aim of this report is to help prioritize conservation actions and coordinate activities between stakeholders to efficiently and effectively conserve these keystone trees in the U.S.

ECOLOGY & DISTRIBUTION

There are between ten and 20 species of hickory (*Carya*) native to the United States. Here we follow the treatment in *Flora of North America* (1997), which includes 11 species of *Carya*. All are nut producing trees, which provide shelter and high-quality food to wildlife, though their native habitats differ significantly. Most species are relatively slow growing and do not produce nuts for ten to 40 years. The cultivated pecan, *C. illinoinensis*, is one of the most important nut producing trees native to North America. *Carya* species are also an excellent source of wood for tool handles, due to their high strength and shock resistance, and some species are grown for timber (Flora of North America, 1997). The distributions of different species often overlap, and hybridization is common, though generally only among species with the same level of ploidy. Five native U.S. *Carya* species are tetraploid (*C. floridana, C. glabra, C. pallida, C. texana*, and *C. tomentosa*) and the remaining six are diploid. The tetraploid species accumulate rare-earth elements and also seem to be more adapted to dry sites (Grauke, 2017). In addition to using hickories as an important food source, native American peoples harvested various parts of the trees for tools, clothing, and medicine (Grauke, 2020). All native U.S. hickories are currently assessed as Least Concern on the IUCN Red List of Threatened Species (IUCN, 2020). Native U.S. hickories are distributed across the eastern half of the country, from Texas to Minnesota and Florida to Maine (Figure 1).

Carya aquatica (Susan McDougall)

Carya aquatica (Water hickory) is a large, deciduous shade tree, reaching up to 46 meters. It is distributed across the southeastern U.S., from Texas to Florida along the southern border, then north to Oklahoma, Missouri, Illinois, Kentucky, and Virginia. *Carya aquatica* is found in bayous, river floodplains, bluffs, and seasonally-flooded bottomlands, and can grow well in wet soils, but prefers well-drained moist soils near waterways. It is considered an important plant for cleansing water runoff during flooding. *Carya aquatica* hybridizes with *C. illinoinensis* to form *C.* ×*lecontei* Little, and also reportedly hybridizes with the tetraploid *C. texana* to form *C.* ×*ludoviciana* (Ashe) Little (Flora of North America, 1997; N.C. Cooperative Extension, 2020).

Carya cordiformis (Bitternut hickory) is one of the most widely distributed hickories in North America, native to most of the eastern half of the United States, and reaching north just into Ontario and Quebec. It is a large tree, up to 52 meters tall, preferring open areas in river floodplains, well-drained hillsides, and limestone glades. They are particular in their need for sun but generalists regarding soil type. *Carya cordiformis* is easily distinguished from other native trees by its long, scaly, yellow buds. Carya cordiformis hybridizes with *C. illinoinensis* (*C. ×brownii* Sargent), *C. ovata* (*C. ×laneyi* Sargent), and *C. laciniosa*, and also reportedly with the tetraploid *C. glabra* to form *C. ×demareei* Palmer (Flora of North America, 1997; N.C. Cooperative Extension, 2020).

Carya cordiformis (Ed Hedborn, The Morton Arboretum)

Carya floridana (Scrub hickory) has the most restricted range of any native U.S. hickory and is endemic to central Florida. Though it has a small distribution compared to other native U.S. hickories, it is the most abundant hardwood within sections of its range, including the southern Lake Wales Ridge. *Carya floridana* is one of the smaller hickories, reaching up to 25 meters, and can be found in sand pine woods, sand pine-oak scrub, sand ridge scrub, hardwood hammocks, scrub oak-wiregrass ridges, and scrub barrens. It often aggressively invades open xeric woodlands, but nutrient availability and water limit seedling survival. *Carya floridana* frequently hybridizes with *C. glabra* in areas where their ranges overlap (Coastal Plain Plants, 2020; Flora of North America, 1997).

Carya floridana (Susan McDougall)

Carya glabra (Pignut hickory) is a medium to large deciduous tree (up to 30 meters), with a broad distribution across the eastern half of the United States and parts of Canada. It doesn't reach quite as far west or north as *C. cordiformis*, but is distributed further south along the gulf coast and into Florida. The northern range of *C. glabra* is sometimes described as *C. glabra* var. *odorata* or the distinct species *C. ovalis*. *Carya glabr*a can be found in bayou edges, deep flood plains, well-drained sandy soils, rolling hills and slopes, dry rocky soils, or thin soils on the edge of granite outcrops. It prefers sun or part-sun and well-drained soils, but is adaptable to sandy or clay loams, and is drought tolerant once established, due to its deep taproot. *Carya glabra* is also a highly polymorphic species, with tight bark and large pear-shaped fruit common among trees along the Gulf Coast (known as *C. glabra* var. *megacarpa*, *C. leiodermis*, or *C. magnifloridana*), while exfoliating bark and small, ellipsoid fruits are more common further north in the species range (also called *C. ovalis*). *Carya glabra* hybridizes with *C. floridana, C. pallida*, and *C. texana*, and it is reported to hybridize with the diploid *C. cordiformis* to form *C. ×demareei* Palmer (Flora of North America, 1997; N.C. Cooperative Extension, 2020).

Carya glabra (William (Ned) Friedman)

Carya illinoinensis (Pecan) is perhaps the most well known native U.S. hickory, due to its cultivation for pecan nuts, and it is also the largest of the U.S. hickories. Extensive cultivation and naturalization for hundreds of years make determining the species' native range difficult, but its general distribution is in the south-central United States, from Texas to Iowa and Indiana to Louisiana, with some populations in northeastern Mexico and a disjunct population in Alabama. *Carya illinoinensis* is found in well-drained soils along stream banks and river floodplains. The pecan hybridizes with *C. aquatica* (*C.* ×*lecontei* Little), *C. cordiformis* (*C.* ×*brownii* Sargent), *C. laciniosa* (*C.* ×*nussbaumeri* Sargent), and *C. ovata*, and reportedly with the tetraploid *C. tomentosa* (*C.* ×*schneckii* Sargent). Pecan is the state tree of Texas, and has a variety of cultivars developed for their nut-producing traits (Flora of North America, 1997; N.C. Cooperative Extension, 2020).

Carya illinoinensis (Ed Hedborn, The Morton Arboretum)

Carya laciniosa (Shellbark hickory) is a medium to large deciduous tree reaching up to 41 meters. It has a wide distribution in the central and eastern United States, but does not extend as far northwest, northeast, or southeast as the other widespread *Carya* species in North America; it is not found in Minnesota, Wisconsin, Louisiana, South Carolina, Florida, or east of New York. It is most abundant in Ohio and the upper Mississippi River valleys; the southernmost population of *Carya laciniosa* is an outlier located in Hardin County, Texas. *Carya laciniosa* prefers rich bottomlands, along creeks, and open cedar glades, and can tolerate temporary flooding in the springtime. The nuts are sweet and support a variety of wildlife species. *Carya laciniosa* is known to hybridize with *C. illinoinensis* (*C.* ×*nussbaumeri* Sargent) and *C. ovata* (*C.* ×*dunbarii* Sargent), and possibly *C. cordiformis* (Flora of North America, 1997; N.C. Cooperative Extension, 2020).

Carya laciniosa (Deb Brown, The Morton Arboretum)

Carya myristiciformis (Nutmeg hickory) has a patchy distribution from the mountainous regions of northeast Mexico to the coastal plain of North Carolina. In the U.S., it is only native to Texas, Oklahoma, Arkansas, Louisiana, Mississippi, Alabama, South Carolina, and North Carolina. It is likely the rarest species in the genus native to the U.S., since *C. floridana* is more abundant within its more narrow distribution. *Carya myristiciformis* is a drought tolerant tree reaching up to 35 meters tall, and requires sunny sites. It can be found in river bottomlands, edges of streams, bluffs, and hillsides, and is often located on calcareous prairie soils and marl ridges (Flora of North America, 1997; N.C. Cooperative Extension, 2020).

Carya myristiciformis (Joshua Poland, Arkansas Tech University)

Carya ovata (Shagbark hickory) is a large deciduous tree (up to 46 meters tall) with a broad distribution across the central and eastern United States, reaching up slightly into Canada. It is largely constrained in the east and south by the southeastern plains and in the west by the central great plains, and has some disjunct populations in Mexico. The southern distribution of *C. ovata* is sometimes distinguished as a separate species, *C. carolinae-septentrionalis*. *Carya ovata* can adapt to both sandy and clay loams, but prefers fertile, deep, soil that is well-drained. It grows in both full sun and part shade and is drought tolerant once established. The nuts of *C. ovata* are a valuable source of food for wildlife and sold commercially for human consumption, though it may take up to 40 years for the trees to produce nuts. *Carya ovata* often lives 200-300 years, and hybridizes with *C. cordiformis* (*C. ×laneyi* Sargent), *C. laciniosa* (*C. ×dunbarii* Sargent), and *C. illinoinensis* (Flora of North America, 1997; N.C. Cooperative Extension, 2020).


Carya ovata (Deb Brown, The Morton Arboretum)

Carya pallida (Sand hickory) is native to the southeastern United States, and can be found from Mississippi to Kentucky and Virginia to Georgia, including the Florida panhandle and possible disjunct populations in southern Indiana and Delaware. It is one of the slightly smaller North American hickories, reaching 29 meters in height. *Carya pallida* prefers well-drained sandy or rocky soils on bluffs, ridges, rolling hills, and dry woods. In the northwest edge of its range in Illinois and Missouri *C. pallida* is thought to intergrade with *C. texana*, and it is known to hybridize with *C. glabra* (Flora of North America, 1997).


Carya pallida (Karan A. Rawlins, University of Georgia) 5436001

Carya texana (Black hickory) is a large tree, up to 41 meters tall, which has a somewhat-restricted distribution in the south-central United States, mostly west of the Mississippi River. Its distribution reaches from central Texas through Louisiana, north through Arkansas and Missouri to southern Illinois, and west to central Oklahoma. *Carya texana* is found in well-drained sandy soils on rolling hills and rocky hillsides, and occasionally on low flat lands and marl soils. It hybridizes with *C. glabra* and *C. tomentosa* (*C. ×collina* Laughlin), and seems to also hybridize with the diploid *C. aquatica* (*C. ×ludoviciana* (Ashe) Little) and *C. pallida* in eastern Missouri and southern Illinois (Flora of North America, 1997).


Carya texana (Image Archive of Central Texas Plants)

Carya tomentosa (Mockernut hickory), formerly known as *C. alba*, is a large deciduous tree reaching 36 meters in height. It has a broad distribution in the eastern and central regions of the United States, with a similar distribution to *C. glabra*, but does not reach as far north and extends slightly further west. *Carya tomentosa* is adapted to both sandy and clay loam soils, though good drainage is required. It prefers full sun, and is drought tolerant once established. Rolling hills and rocky hillsides are the species' preference, but it is found occasionally on limestone outcrops. *Carya tomentosa* hybridizes with *C. texana* (*C.* ×*collina* Laughlin) and is reported to hybridize with the diploid *C. illinoinensis* to form *C.* ×*schneckii* Sargent (Flora of North America, 1997; N.C. Cooperative Extension, 2020).


Carya tomentosa (Susan McDougall)

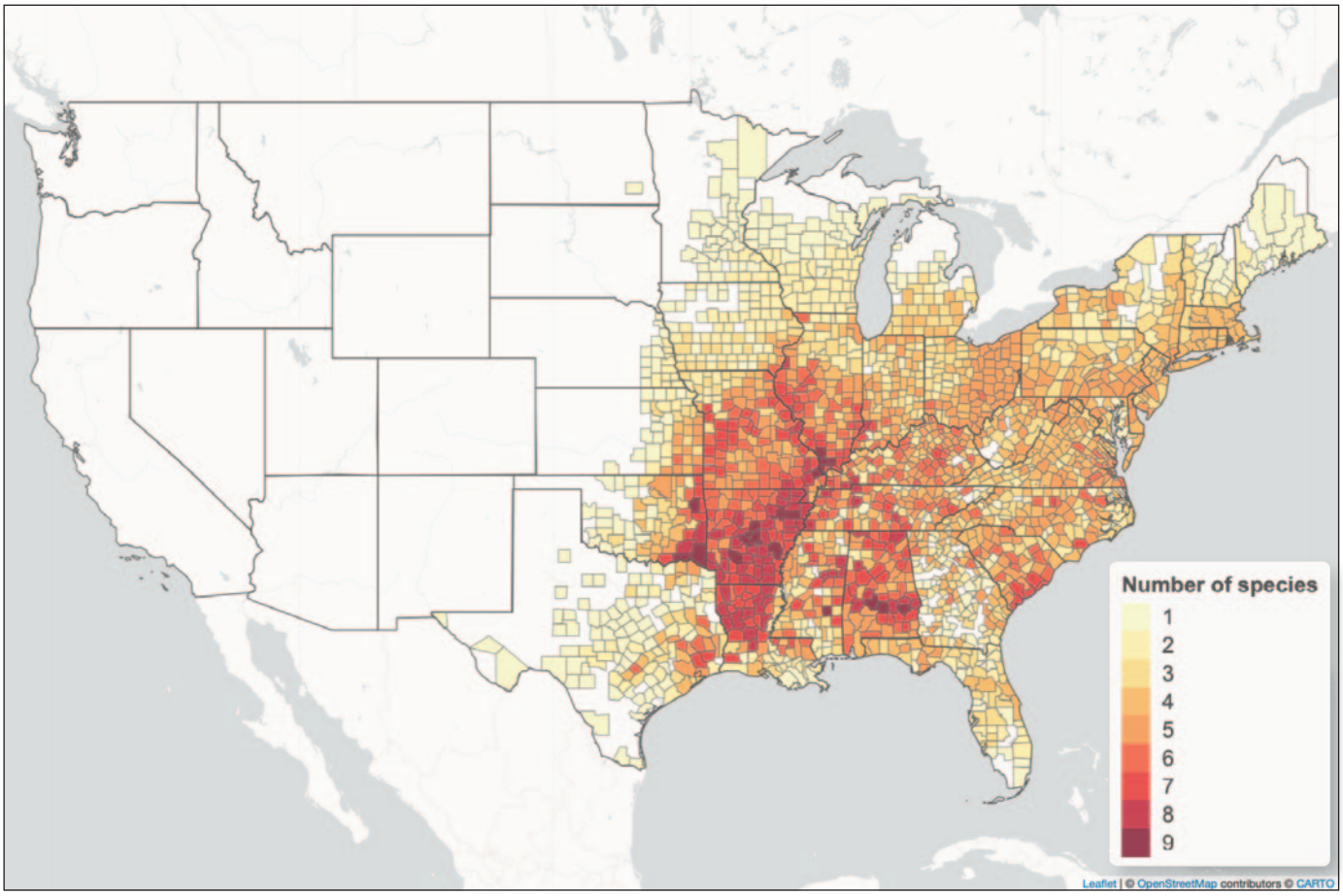


Figure 1. Species richness of native U.S. *Carya* species by U.S. county, including *C. aquatica, C. cordiformis, C. floridana, C. glabra, C. illinoinensis, C. laciniosa, C. myristiciformis, C. ovata, C. pallida, C. texana,* and *C. tomentosa.* County level distribution data from USDA PLANTS and Biota of North America Program (BONAP) have been combined to estimate species presence (Kartesz, 2018; USDA NRCS, 2018).

PESTS & DISEASES

Native U.S. *Carya* species face a variety of pests and diseases, though all are minor. Sometimes, generally for less than 1% of mature trees, these agents are combined with other stressors and lead to mortality. Results from the USDA Forest Service study *Important Insect and Disease Threats to United States Tree Species and Geographic Patterns of Their Potential Impacts* (Potter et al., 2019a) are provided in Table 1, to give an overview of the major pests and diseases affecting native U.S. *Carya* species. That study performed a thorough literature review, including more than 200 sources, and consulted dozens of expert entomologists and pathologists to identify up to five of the most serious insect, disease, and parasitic plant threats facing each of 419 native U.S. tree species; priority was given to pests and diseases causing mortality of mature trees, rather than agents primarily affecting reproductive structures or seedlings. A second USDA Forest Service study, *Prioritizing the conservation needs of United States tree species: Evaluating vulnerability to forest insect and disease threats* (Potter et al., 2019b), combined results from Potter et al. (2019a) with species trait and vulnerability data to further categorize overall pest and disease vulnerability of the 419 target native U.S. tree species. Results from this study are provided in Table 2.

Table 1. The most serious insect, disease, and parasitic plant agents affecting native U.S. *Carya* species, from the results of Potter et al. (2019a), which analyzed 419 native U.S. tree species. Numbers represent the severity of the agent's impact on the host species. Table adapted, with permission, from Potter et al. (2019a).

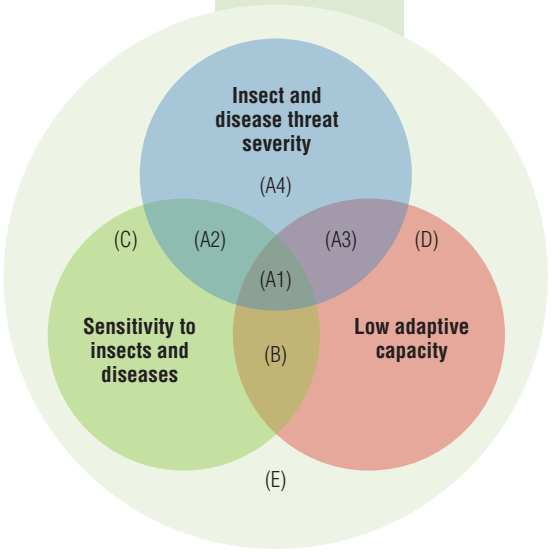
Host species	Insect, Disease, or Parasitic Plant Agent									
	Armillaria root disease (*Armillaria* spp.)	Bacterial leaf scorch (*Xylella fastidiosa*)	Butt rot (*Hericium erinaceus*)	Crown gall (*Agrobacterium tumefaciens*)	Hickory bark beetle (*Scolytus quadrispinosus*)	Hickory borer (*Goes pulcher*)	Hickory spiral borer (*Agrilus arcuatus torquatus*)	Nectria canker (*Nectria ditissima*)	Pecan carpenterworm (*Cossula magnifica*)	Spiculosa canker (*Phellinus spiculosus*)
Carya aquatica			1			1				
Carya cordiformis					1	1		1		1
Carya floridana							1			
Carya glabra					1			1		1
Carya illinoinensis		1		1	1	1				1
Carya laciniosa					1	1				
Carya myristiciformis					1					
Carya ovata	1			1	1					1
Carya pallida										
Carya texana										
Carya tomentosa					1	1	1		1	1

Severity of agent's impact

10 = near complete mortality of all mature host trees (>95%)
8 = significant mortality of mature host trees (25% to 95%)
5 = moderate mortality of mature host trees (10% to 25%)
3 = moderate mortality in association with other threats, such as drought stress (1% to 10%)
1 = minor mortality, generally to host trees that are already stressed (<1%)

Table 2. Pest and disease vulnerability of native U.S. *Carya* species, from the results of a USDA Forest Service study that analyzed 419 native U.S. tree species. Species are ordered by overall rank, from most vulnerable to least vulnerable. Figure is adapted, with permission, from Potter et al. (2019b).

Species	Vulnerability Class	Overall Rank (of 419)
Carya myristiciformis	B	27
Carya floridana	C	52
Carya carolinae-septentrionalis (southern range of *C. ovata*)	C	112
Carya pallida	B	144
Carya laciniosa	B	167
Carya aquatica	B	191
Carya illinoinensis	B	216
Carya ovalis (northern range of *C. glabra*)	C	233
Carya texana	E	310
Carya cordiformis	D	314
Carya ovata	D	337
Carya alba (now *C. tomentosa*)	D	360
Carya glabra	E	376



Vulnerability Classes

A) High current severity
   1) High vulnerability
   2) Potential adaptation
   3) Potential persistence
   4) Potential persistence and adaptation

B) Potential high vulnerability to future threats

C) Potential high sensitivity to future threats

D) Potential low adaptation to future threats

E) Low current and potential vulnerability


Carya aquatica (John Bradford)


Carya illinoinensis (Ed Hedborn, The Morton Arboretum)

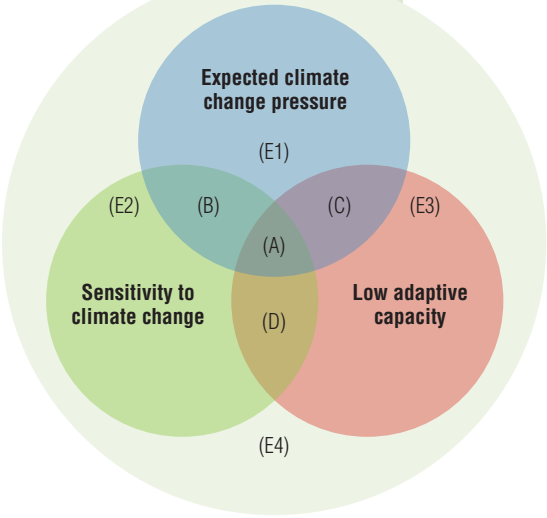
CLIMATE CHANGE VULNERABILITY

Native U.S. *Carya* species face varying impacts from climate change, though most are predicted to have high vulnerability but potential persistence. Using a similar methodology to Potter et al. (2019b), which focuses on species-specific traits in addition to vulnerability data, Potter et al. (2017) analyzed species vulnerability to climate change in the study, *A United States national prioritization framework for tree species vulnerability to climate change*. A selection of 339 native U.S. tree species were assessed through comprehensive literature review, in addition to input from 25 USDA Forest Service resource managers and scientists from across the country and varying departments within the agency. Results from that study are provided in Table 3.

Carya ovata (Susan McDougall)

Table 3. Climate change vulnerability of native U.S. *Carya* species, from the results of a USDA Forest Service study that analyzed 339 native U.S. tree species. *Carya floridana* was not included in the study. Species are ordered by overall rank, from most vulnerable to least vulnerable. Figure is adapted, with permission, from Potter et al. (2017).

Species	Vulnerability Class	Overall Rank (of 339)
Carya myristiciformis	A	43
Carya laciniosa	C	45
Carya pallida	C	50
Carya illinoinensis	C	73
Carya aquatica	C	125
Carya cordiformis	C	164
Carya texana	C	173
Carya ovata	C	205
Carya glabra	E4	219
Carya alba (now *C. tomentosa*)	E4	247



Vulnerability Classes

A) High vulnerability, little adaptation or persistence potential

B) High vulnerability, potential adaptation

C) High vulnerability, potential persistence

D) Potential high future vulnerability

E) Low current vulnerability

EX SITU SURVEY RESULTS

Carya species are considered exceptional, meaning their seeds cannot be stored long-term in conventional seed bank conditions of low temperature and moisture. Their seeds are short-lived in seed banks, losing viability within one to two years, and can last for three to five years at room temperature and high humidity (Bonner, 2008; Burns & Honkala, 1990). Therefore, other methods of long-term *ex situ* preservation are necessary for conserving genetic diversity, including living collections and new seed storage technologies such as cryopreservation (Walters & Pence, 2020).

In 2018, we conducted a global accessions-level *ex situ* survey of priority native U.S. tree species within nine target genera: *Carya, Fagus, Gymnocladus, Juglans, Lindera, Persea, Pinus, Sassafras*, and *Taxus*. The request for data was emailed directly to target *ex situ* collections, including arboreta, botanical gardens, private collections, and USDA Forest Service seed orchards. We started with institutions that had reported collections of these genera to BGCI's PlantSearch database, and whose contact information was available in BGCI's GardenSearch database. The data request was also distributed via newsletters and social media through ArbNet, the American Public Gardens Association, Botanic Gardens Conservation International, the Center for Plant Conservation, the Plant Conservation Alliance, The Morton Arboretum, and the USDA Forest Service. A total of 143 collections from 25 countries provided accessions data for our target genera, including 100 collections from 21 countries reporting native U.S. *Carya* species (Figure 2). See Appendix A for a list of participating institutions. When providing *ex situ* collections data, institutions were asked to include the number of individuals in each accession. When such data were unavailable, we assumed the accession consisted of one individual; therefore our results represent a conservative estimate. Also, because *Carya* species can last for short periods of time in seed banks, it is possible that the *ex situ* survey results presented here include some seed-banked individuals in addition to individuals in living collections.

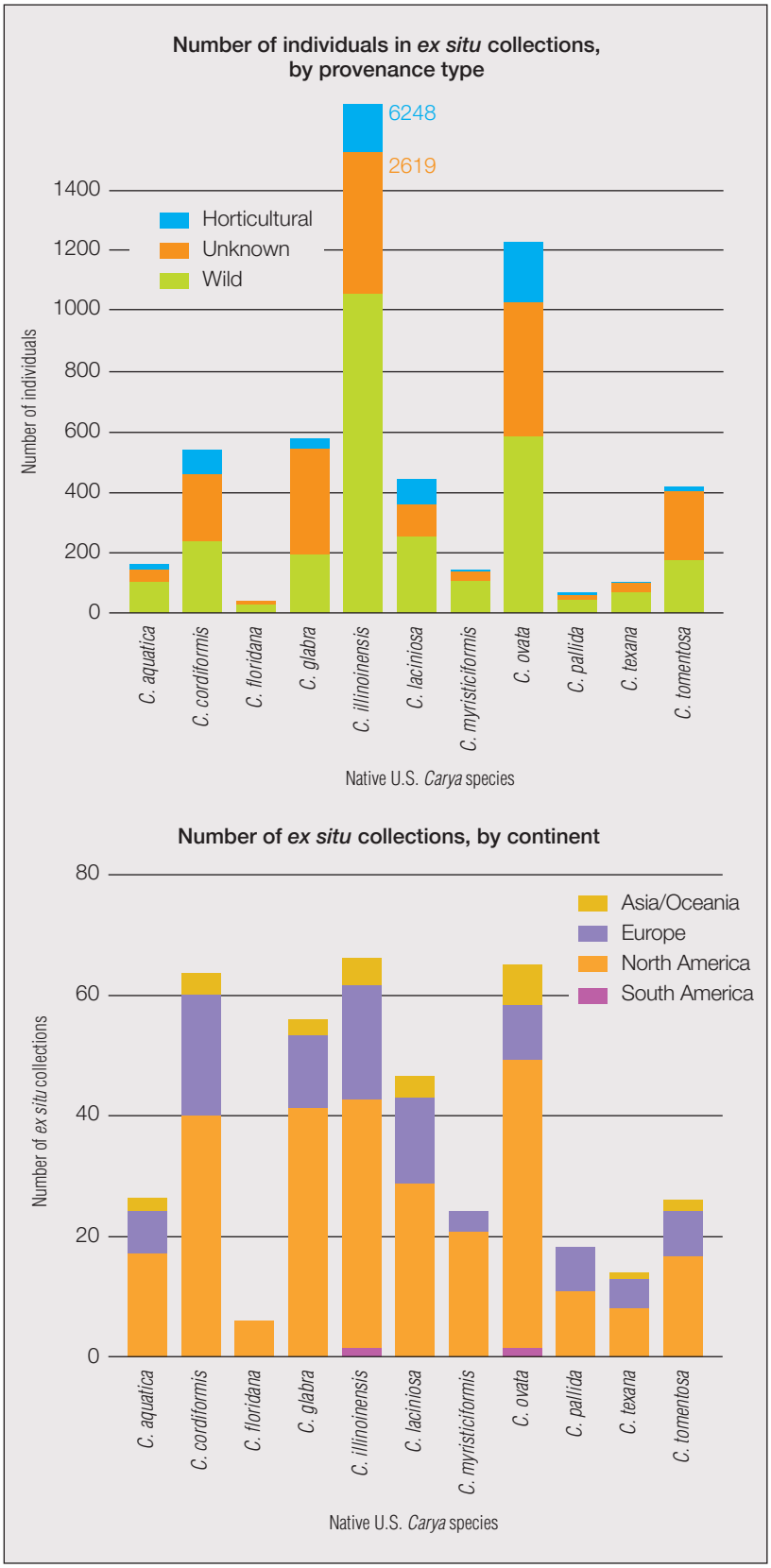


Figure 2. Results from a 2018 global accessions-level *ex situ* survey for native U.S. *Carya* species. Colored numbers above a bar indicate the value exceeds the limits of the chart.

SPATIAL ANALYSIS OF *EX SITU* COLLECTIONS

Ex situ collections conserve the most genetic diversity when they represent a large percent of the target species' geographic and ecological range. Therefore, identifying under-represented populations and ecoregions is vital to improving the conservation value of *ex situ* collections. To prioritize regions and species for future *ex situ* collecting, we mapped and analyzed the estimated native distribution of each target species versus the wild provenance localities of germplasm in *ex situ* collections. Based on threat rankings, including IUCN Red List Category and NatureServe Global Status, climate change vulnerability, impact from pests and diseases, and representation in *ex situ* collections, two priority native U.S. *Carya* species were identified as targets for these further spatial analyses: *C. floridana* and *C. myristiciformis*.

We used two proxies for estimating *ex situ* genetic diversity representation: geographic and ecological coverage. These proxies are based on the assumption that sampling across a species' full native distribution and all ecological zones it inhabits is the best way to ensure that the full spectrum of its genetic diversity is captured in *ex situ* collections (CPC, 2018; Hanson et al., 2017; Khoury et al., 2015). Using methods introduced by Khoury et al. (2019) and Beckman et al. (2019), we calculated geographic and ecological coverage by comparing two sets of geographic points: 1) known *in situ* occurrences, and 2) *ex situ* collection source localities (i.e., wild occurrences where seed was collected for *ex situ* preservation). To approximate potential suitable habitat, nearby populations, and/or gene flow, we placed a circular buffer around each *in situ* occurrence point and each *ex situ* collection source locality. When buffers around *ex situ* collection source localities overlap with buffers around *in situ* occurrence points, that area is considered 'conserved' by *ex situ* collections (Figures 3-5; Table 4). Because our calculations of geographic and ecological coverage are based on a rough estimation of the distribution of a species, the values reported here should be viewed as estimates that can be used to compare among species for prioritization rather than values reflecting the actual capture of genetic diversity (e.g., alleles or DNA sequence differences) in *ex situ* collections.

Carya cordiformis (Ed Hedborn, The Morton Arboretum)

Carya pallida (Susan McDougall)

In situ occurrence points for each target species were downloaded from a variety of publicly available data sources, including Biodiversity Information Serving Our Nation (BISON; USGS, 2019), Botanical Information and Ecology Network (BIEN; bien.nceas.ucsb.edu, 2020; Maitner, 2020), Forest Inventory and Analysis (FIA) Program of the USDA Forest Service (Forest Inventory and Analysis Database, 2019), Global Biodiversity Information Facility (GBIF.org, 2020; Chamberlain & Boettiger, 2017), Integrated Digitized Biocollections (iDigBio; idigbio.org, 2020; Michonneau & Collins, 2017), and U.S. herbarium consortia (e.g., SERNEC; Data Portal, 2020). To increase their reliability, these raw data points were automatically vetted using a set of common filters for biodiversity data (Zizka et al., 2019). Points were removed if they fell within 500 meters of a state centroid or 100 meters of a biodiversity institution, or if they were not within a county of native occurrence for the target species based on county-level data from Biota of North America (BONAP; Kartesz, 2018). Points were also removed if they were recorded before 1950, were missing a record year, were recorded as a living or fossil specimen, or were recorded as introduced, managed, or invasive. The final set of points was also manually vetted based on literature review, to remove any points clearly outside the species' native range.

Ex situ data were gathered during the 2018 survey described in the previous section, and records for target species with a wild source locality description were manually geolocated when latitude and longitude were missing. For target native U.S. *Carya* species (*C. floridana* and *C. myristiciformis*), about 17% of records with wild or unknown provenance were manually geolocated, while 32% had latitude and longitude provided by the institution and 51% contained too little locality information to geolocate to county-level or finer. To map wild provenance localities of *ex situ* individuals, accessions collected from wild localities near each other were grouped together based on latitude and longitude rounded to one digit after the decimal. All data processing and mapping were performed in R (R Core Team, 2020; Graul, 2016).

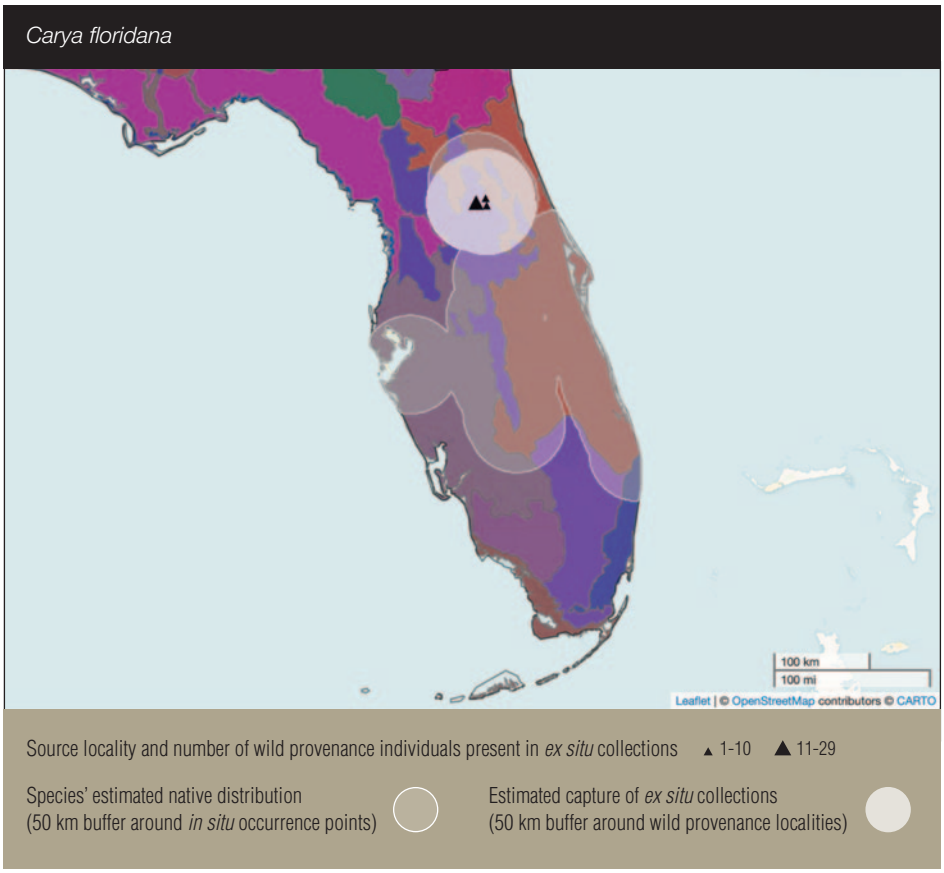


Figure 3. Native distribution and wild provenance localities of *ex situ* individuals for *Carya floridana*, based on 50 km buffers around *in situ* occurrence points and *ex situ* source localities. Background colors show EPA Level IV Ecoregions (U.S. EPA Office of Research & Development, 2013b). In addition to standard *in situ* occurrence point filters applied to all target species, *C. floridana* occurrence points were further refined by removing records outside native counties provided in the Atlas of Florida Plants (Wunderlin et al., 2020).

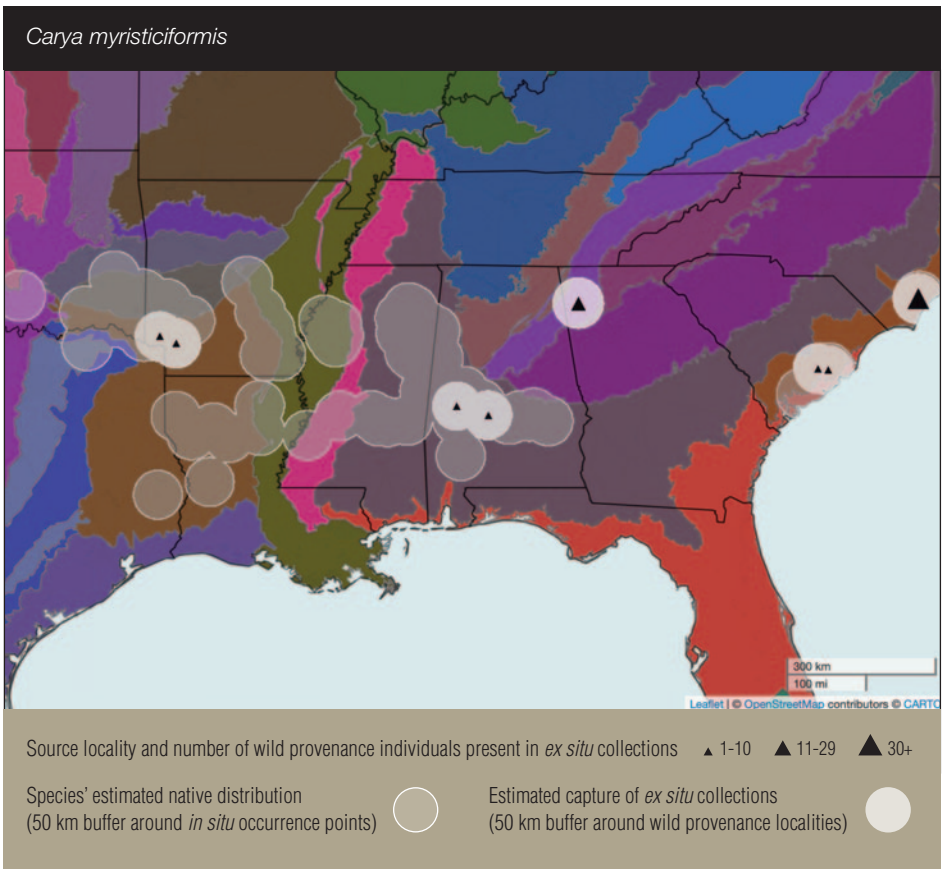


Figure 4. Native distribution and wild provenance localities of *ex situ* individuals for *Carya myristiciformis*, based on 50 km buffers around *in situ* occurrence points and *ex situ* source localities. Background colors show EPA Level III Ecoregions (U.S. EPA Office of Research & Development, 2013a). In addition to standard *in situ* occurrence point filters applied to all target species, *C. myristiciformis* occurrence points were further refined by removing records more than 200 km outside native counties provided in The PLANTS Database (USDA NRCS, 2018).

Table 4. Estimated geographic and ecological coverage of *ex situ* collections of priority native U.S. *Carya* species. Geographic coverage = area covered by buffers around *ex situ* wild provenance localities / area covered by buffers around *in situ* occurrence points (values are given in km^2). Ecological coverage = number of ecoregions under buffers around *ex situ* wild provenance localities / number of ecoregions under buffers around *in situ* occurrence points. U.S. EPA Level IV Ecoregions (2013b) were used for calculating ecological coverage. Buffer area falling outside the contiguous U.S. was removed for all calculations. Three different-sized buffers (radius of 20 km, 50 km, and 100 km) were used to show the variation in estimated *ex situ* genetic representation depending on assumptions regarding population size and gene flow.

Species	20 km buffers		50 km buffers		100 km buffers		Average of all three buffer sizes	
	Geographic coverage	Ecological coverage	Geographic coverage	Ecological coverage	Geographic coverage	Ecological coverage	Geographic coverage	Ecological coverage
Carya floridana	1,884 / 16,586 **(11%)**	2 / 5 **(40%)**	9,377 / 52,500 **(18%)**	3 / 6 **(50%)**	29,930 / 85,082 **(35%)**	6 / 11 **(55%)**	**21%**	**48%**
Carya myristiciformis	9,511 / 78,481 **(12%)**	19 / 52 **(37%)**	47,901 / 266,242 **(18%)**	28 / 74 **(38%)**	158,785 / 552,368 **(29%)**	46 / 97 **(47%)**	**20%**	**41%**

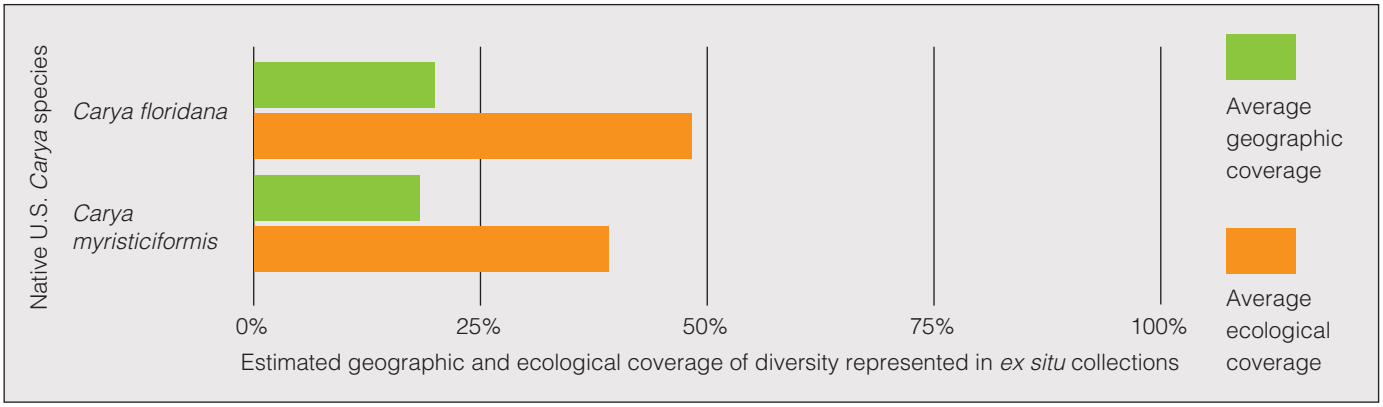


Figure 5. Average geographic and ecological coverage of *ex situ* collections for priority native U.S. *Carya* species (See Table 4 for details).


Juglans major (Whitney Cranshaw)


Carya tomentosa (Susan McDougall)

TREE CONSERVATION QUESTIONNAIRE RESULTS

In 2019, we conducted a Tree Conservation Action Questionnaire for priority native U.S. tree species within nine target genera: *Carya, Fagus, Gymnocladus, Juglans, Lindera, Persea, Pinus, Sassafras*, and *Taxus*. The questionnaire was designed primarily to gather information regarding current or future planned conservation activities, but also to provide a platform to ask experts their opinion regarding most urgent conservation actions and most significant threats for each target species (Figure 6). A subset of target species were chosen to be included in the questionnaire based on threat rankings (IUCN Red List Category and NatureServe Global Status), climate change vulnerability, impact from pests and diseases, and representation in *ex situ* collections.

The questionnaire was emailed directly to targeted *ex situ* collections, content experts, attendees of the 2016 "Gene Conservation of Forest Trees: Banking on the Future" workshop, native plant societies and The Nature Conservancy contacts (from states with 20 or more target species), NatureServe and Natural Heritage Program contacts (from states with ten or more target species), BLM field offices, the USDA Forest Service RNGR National Nursery and Seed Directory, and USFS geneticists, botanists, and pest/disease specialists. The questionnaire was also distributed via newsletters and social media through ArbNet, the American Public Gardens Association, Botanic Gardens Conservation International, the Center for Plant Conservation, the Plant Conservation Alliance, The Morton Arboretum, and the USDA Forest Service.

More than 200 institutions completed the questionnaire, including 15 institutions that provided input on conservation activities for priority native U.S. *Carya* species. Institutions reporting that they could "provide information regarding current conservation activities, most urgent conservation needs, and/or primary threats to wild populations" included eight for *C. floridana*, and 17 for *C. myristiciformis*. Respondents were given the opportunity to fill in other native U.S. *Carya* species that they considered of conservation concern; *C. illinoinensis, C. laciniosa* and *C. ovata* were listed by one respondent each. See Appendix A for a list of participants and Appendix B for a full summary of questionnaire responses, which can be used to identify potential collaborators, coordinate conservation efforts, and recognize possible gaps in current activities.

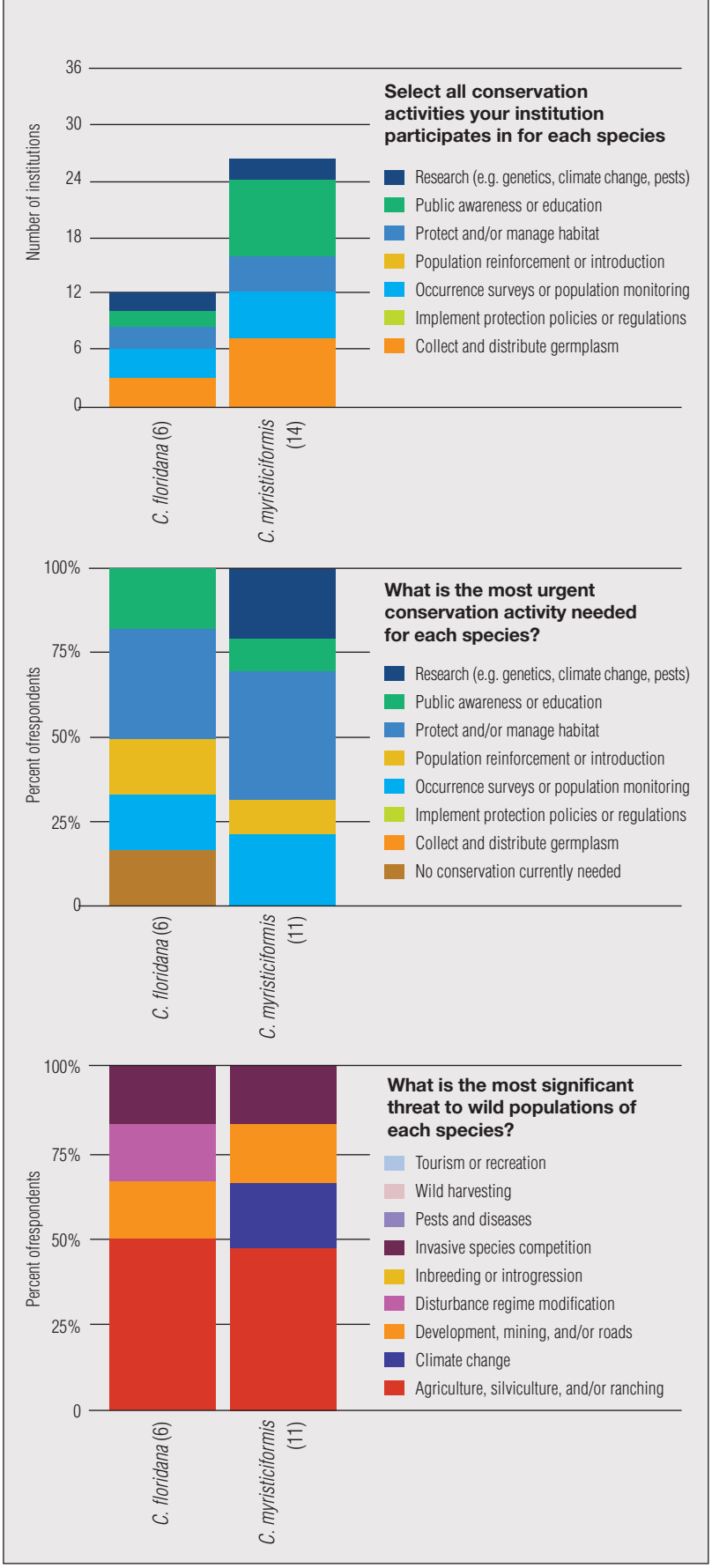


Figure 6. Results from the Tree Conservation Action Questionnaire for priority native U.S. *Carya* species. The number of institutions or respondents participating in each question is listed in parentheses after the species' name. See Appendix B for details regarding which institutions reported each conservation activity.

CONCLUSIONS & RECOMMENDATIONS

Species' distributions and threats: There are 11 *Carya* species native to the United States, and all are native to the eastern half of the country (Figure 1). Two species, *Carya floridana* and *C. myristiciformis*, are of conservation concern, based on their global NatureServe rank of Apparently Secure (G4), in combination with few plants in *ex situ* collections (*C. floridana*) or high vulnerability to climate change (*C. myristiciformis*). *Carya floridana* is endemic to Florida, found in scrubby, xeric communities concentrated in the center and eastern edge of the state. *Carya myristiciformis* has a wide but fragmented distribution across the southern U.S., from eastern Texas and Oklahoma to coastal South Carolina, with the densest populations in Mississippi and Arkansas. Native U.S. *Carya* species are susceptible to a variety of pests and diseases, though all pose little threat (Tables 1-2). The majority of native U.S. *Carya* species are predicted to have high vulnerability to climate change, but potential persistence; exceptions include *C. myristiciformis*, which is predicted to have high vulnerability and little adaptation or persistence potential, and *C. glabra* and *C. tomentosa*, which are predicted to have low threat exposure, low sensitivity, and high adaptive capacity (Table 3).

Conservation quality of *ex situ* collections: Based on data from 100 *ex situ* collections that submitted accessions data for native U.S. *Carya* species, *C. illinoinensis* is represented by the most *ex situ* individuals (6,248), but the majority (more than 80%) are of unknown or horticultural origin. This very high number of individuals in collections is associated with breeding and research focused on the economic value of *C. illinoinensis* (as the source of pecan nuts). *Carya cordiformis*, *C. glabra, C. laciniosa, C. ovata*, and *C. tomentosa* each have between 400 and 1,300 individuals in *ex situ* collections, with between 30 and 60% of individuals of wild origin. The five remaining species (*C. aquatica, C. floridana, C. myristiciformis, C. pallida,* and *C. texana*) have fewer individuals in *ex situ* collections (from 27 to 166), but a higher percent of wild origin individuals (between 65 and 78%). Geographic and ecological coverage of *ex situ* collections were calculated for two priority species of conservation concern: *Carya floridana* and *C. myristiciformis*. About 60% of the 100 wild origin individuals reported in *ex situ* collections for *C. myristiciformis* were able to be mapped, resulting in an estimated geographic coverage of 20% and ecological coverage of 41%. Of the 21 known wild origin individuals of *C. floridana*, 15 had enough information to be mapped to their wild origin locality, resulting in similar coverage to that of *C. myristiciformis* (21% geographic, 48% ecological). For the more common native U.S. *Carya* species, current *ex situ* collections are substantial. The two less-common *Carya* species would benefit from targeted *ex situ* collecting to capture populations not yet represented (Figures 2-5; Table 4).

Conservation actions: wo target native U.S. *Carya* species were included in the Tree Conservation Action Questionnaire. The most commonly reported conservation activities for *C. floridana* were collect and distribute germplasm and occurrence surveys or population monitoring. For *C. myristiciformis*, public awareness or education was the most common activity, followed by collect and distribute germplasm. The conservation activity most frequently identified as most urgent was to protect and/or manage habitat for both target *Carya* species in the questionnaire. Agriculture, silviculture, and/or ranching was most frequently identified as the most significant threat to both species (Figure 6). Target *Carya species* (*C. floridana* and *C. myristiciformis*) received relatively few responses in our questionnaire compared to species in other target genera, including *Fagus grandifolia* (52 institutions responding), *Gymnocladus dioicus* (44), *Juglans cinerea* (50), *Lindera benzoin* (50), *Sassafras albidum* (50), and *Pinus palustris* (24). But, compared to species with similar distribution size (moderate to small, rather than very large), the response rate and number of activities reported are reasonable.

Carya laciniosa (Susan McDougall)

Overall summary and recommendations: Native U.S. *Carya* species face little threat from pests or pathogens, though most are at least moderately vulnerable to climate change. Further monitoring and modeling should be carried out, as methods continue to improve. Based on the number of individuals and *ex situ* collections, most native U.S. *Carya* species are well-represented in collections; but, these collections may not represent the full wild distribution of each species, and species-by-species geolocation and analysis of wild provenance localities of *ex situ* accessions would be helpful in guiding future collecting efforts. Such analyses of living collections are especially important for exceptional species groups, such as *Carya*, since their seeds cannot be banked long-term and therefore must be held in living collections. This gap analysis was able to provide spatial analyses of wild-collected *ex situ* individuals of *C. floridana* and *C. myristiciformis*, though refined wild distribution maps for the species are needed based on a combination of further scouting and verification of herbarium specimens, perhaps leading to species distribution modelling. Due to their relative rarity, these two *Carya* species should be the first priority for further targeted collecting from wild populations not yet represented in *ex situ* collections. In addition to monitoring and modelling climate change, continued protection of habitat is vital to the thriving of this tree group.

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APPENDIX A. LIST OF PARTICIPANTS

Institutional participants in the 2018 *ex situ* collections survey:

Agro-Botanical Garden of USAMV Cluj-Napoca • Antony Woodland Garden • Arboretum Bramy Morawskiej w Raciborzu • Arboretum Bukovina • Arboretum Kirchberg, Musée national d'histoire naturelle • Arboretum National des Barres • Arboretum w Przelewicach • Arboretum Wespelaar, Foundation • Arboretum Wojslawice, University of Wroclaw • Arizona-Sonora Desert Museum • Arnold Arboretum of Harvard University, The • Atlanta Botanical Garden • Auckland Botanic Gardens • Bamboo Brook Outdoor Education Center • Bartlett Tree Research Laboratories Arboretum • Bayard Cutting Arboretum • Beal Botanical Gardens, W. J. • Bedgebury National Pinetum and Forest • Belmonte Arboretum • Bergius Botanic Garden, Stockholm University • Bessey Nursery, Nebraska National Forests and Grasslands • Boerner Botanical Gardens • Bok Tower Gardens • Botanic Garden Meise • Botanic garden of Le Havre, Ville du Havre • Botanic Garden of Smith College, The • Botanic Gardens of South Australia • Botanischer Garten der Philipps-Universität Marburg • Brenton Arboretum, The • Brookgreen Gardens • Brooklyn Botanic Garden • Bureau of Land Management, Prineville District • Cheryl Kearns, private garden • Chicago Botanic Garden • Cornell Botanic Gardens • Cox Arboretum • Darts Hill Garden Park • Davis Arboretum of Auburn University • Dawes Arboretum, The • Denver Botanic Gardens • Dunedin Botanic Garden • Eastwoodhill Arboretum • Eddy Arboretum, Pacific Southwest Research Station Placerville, The Institute of Forest Genetics (IFG) • Eden Project • Estancia San Miguel • Fairchild Tropical Botanic Garden • Finnish Museum of Natural History LUOMUS • Frelinghuysen Arboretum • Ghent University Botanical Garden • Green Bay Botanical Garden • Green Spring Gardens • GRIN Database, National Plant Germplasm System (NPGS) • Hackfalls Arboretum • Holden Forests & Gardens (Cleveland Botanical Garden and The Holden Arboretum) • Hollard Gardens • Honolulu Botanical Gardens System • Hørsholm Arboretum • Hoyt Arboretum • Huntington, The • Ioulia & Alexandros Diomidis Botanical Garden • Jardin Botanique de l'Université de Strasbourg • Jardin botanique de Montréal • JC Raulston Arboretum • Keith Arboretum, The Charles R. • Key West Tropical Forest and Botanical Garden • Linnaean Gardens of Uppsala, The • Longwood Gardens • Lovett Pinetum • Lyon Arboretum & Botanical Garden of the University of Hawaii • Marie Selby Botanical Gardens • Mercer Botanic Gardens • Millennium Seed Bank Partnership, Royal Botanic Gardens Kew • Missouri Botanical Garden • Montgomery Botanical Center • Morris Arboretum of the University of Pennsylvania, The • Morton Arboretum, The • Moscow State University Botanical Garden Arboretum • Mount Auburn Cemetery • Mt. Cuba Center, Inc. • Muséum national d'Histoire naturelle, Paris • Naples Botanic Garden • National Tropical Botanical Garden • NDSU Dale E. Herman Research Arboretum, Woody Plant Improvement Program • New York Botanical Garden • Norfolk Botanical Garden • North Carolina Arboretum, The • Orto Botanico dell'Università degli studi di Siena • Orto Botanico dell'Universita della Calabria • Peckerwood Garden • Pinetum Blijdenstein • Polly Hill Arboretum, The • Powell Gardens • Pukeiti • Pukekura Park • Rancho Santa Ana Botanic Garden • Real Jardín Botánico Juan Carlos I • Red Butte Garden, The University of Utah • Reiman Gardens, Iowa State University • Rogów Arboretum of Warsaw University of Life Sciences • Royal Botanic Garden Edinburgh • Royal Botanic Gardens Kew, Wakehurst Place • Royal Botanic Gardens Ontario • Royal Botanic Gardens Victoria • Royal Horticultural Society Garden, Wisley • Smale Riverfront Park • Starhill Forest Arboretum • State Botanical Garden of Georgia, University of Georgia • State Botanical Garden of Kentucky, The Arboretum • Stavanger Botanic Garden • Tasmanian Arboretum Inc., The • Timaru Botanic Garden • Tucson Botanical Gardens • Tyler Arboretum • U.S. National Arboretum • UBC Botanical Garden, The University of British Columbia • UC Davis Arboretum and Public Garden • University of California Botanical Garden at Berkeley • University of Connecticut Arboretum • University of Delaware Botanic Gardens • University of Florida/IFAS, North Florida Research and Education Center, Gardens of the Big Bend • University of Guelph Arboretum • University of Washington Botanic Gardens • USFS Brownwood Provenance Orchard • USFS western white pine, sugar pine, and whitebark pine seed orchards in OR and WA • Utrecht University Botanic Garden • Vallarta Botanical Gardens A. C. • VanDusen Botanical Garden • Village of Riverside, Illinois • Waimea Valley Botanical Garden • Wellington Botanical Gardens • Westonbirt, The National Arboretum • Willowwood Arboretum • Winona State University, The Landscape Arboretum at • Xishuangbanna Tropical Botanical Garden (XTBG) of Chinese Academy of Sciences (CAS) • Zoo and BG Plzen

Carya glabra (Susan McDougall)

Carya floridana (Susan McDougall)

Institutional participants in the 2019 Tree Conservation Action Questionnaire:

Adkins Arboretum • Agnes Scott College • Aldrich Berry Farm & Nursery, Inc • Alpha Nurseries, Inc • American Chestnut Foundation, The • American University • Arboretum des Grands Murcins • Arboretum Kalmthout • Arboretum San Miguel • Arboretum Wespelaar • Arkansas Natural Heritage Commission • Atlanta Botanical Garden • Auckland Botanic Gardens • Baker Arboretum • Bartlett Tree Research Lab & Arboretum • Bayard Cutting Arboretum • Bergius Botanic Garden • Bernheim Arboretum and Research Forest • Better Forest Tree Seeds • Blue Mountains Botanic Garden, The • Boehm's Garden Center • Boerner Botanical Gardens • Bok Tower Gardens • Borderlands Restoration Network • Botanic Garden of Smith College • Botanic Garden TU Delft • Botanical Garden of the University of Turku • Bowman's Hill Wildflower Preserve • Brenton Arboretum, The • Brookgreen Gardens • Brooklyn Botanic Garden • California Department of Fish and Wildlife • California Native Plant Society • Catawba Lands Conservancy • Chatham University Arboretum • Chicago Botanic Garden • Cincinnati Zoo & Botanical Garden • City of Columbia Stephens Lake Park Arboretum • City of Hamilton • City of Kansas City, Missouri • Colonial Williamsburg Foundation • Connecticut College Arboretum • Cowichan Lake Research Station • Cox Arboretum and Gardens • David Listerman & Associates, Inc • Dawes Arboretum, The • Delaware Division of Fish and Wildlife • Denver Botanic Gardens • Donald E. Davis Arboretum at Auburn University • Downtown Lincoln Association • Draves Arboretum • Dunedin Botanic Garden • Dunn School • Earth Tones Natives • Ed Leuck Louisiana Academic Arboretum, The • Eden Project • Elmhurst College • Evergreen Burial Park and Arboretum • Excelsior Wellness Center • Fairchild Tropical Botanic Garden • Farmingdale State College • Florida Fish and Wildlife Conservation Commission • Florida Forest Service • Florida Natural Areas Inventory • Folmer Botanical Gardens • Frostburg State University • Georgia Department of Natural Resources • Green Bay Botanical Garden • Growild, Inc • Hackfalls Arboretum • Hastings College • Hazel Crest Open Lands • Holden Forests and Gardens • Huntington, The • Illinois Department of Natural Resources Mason State Nursery • Indiana Native Plant Society • Jane E. Lytle Memorial Arboretum • Jardin Botanique de Paris, Arboretum de Paris • John F. Kennedy Arboretum • Johnson's Nursery, Inc. • Keefer Ecological Services Ltd. • L.E. Cooke Co • Lauritzen Gardens • Le Jardin du Lautaret de la Station alpine Joseph Fourier • Longfellow Arboretum • Longwood Gardens • Louisiana Department of Wildlife and Fisheries • Lovell Quinta Arboretum, The • Maryland Department of Natural Resources • McKeithen Growers, Inc. • Meadow Beauty Nursery • Michigan Natural Features Inventory • Mill Creek MetroParks, Fellows Riverside Gardens • Minnesota Department of Natural Resources • Minnesota Natural Resources Commission • Missouri Arboretum • Missouri Native Plant Society • Missouri State University • Montgomery Botanical Center • Morris Arboretum • Moscow State University Botanical Garden • Mt. Cuba Center • Mt. Desert Land & Garden Preserve • Muscatine Arboretum • Naples Botanical Garden • National Botanical Garden of Georgia • Native Plant Society of Oregon • Native Plant Trust • Natural Resources Canada • Nature Conservancy, The • New College of Florida • New Jersey Audubon • New York Botanical Garden, The • New York City Department of Parks & Recreation • New York Natural Heritage Program • Norfolk Botanical Garden • North Carolina Natural Heritage Program • North Dakota State University • Parque Botânico da Tapada da Ajuda • Peaceful Heritage Nursery • Peckerwood Garden • Pennsylvania Department of Conservation & Natural Resources • Pennsylvania Natural Heritage Program • Pizzo Group • Polly Hill Arboretum, The • Powell Gardens • Pronatura Veracruz • R.L. McGregor Herbarium • Rancho Santa Ana Botanic Garden • Reeseville Ridge Nursery • Regional Parks Botanic Garden • Reveg Edge, The • Rogów Arboretum of Warsaw University of Life Sciences • Royal Botanic Garden Edinburgh • Royal Botanic Gardens Victoria • San Diego Botanic Garden • Santa Barbara Botanic Garden • Sidmouth Civic Arboretum • Sister Mary Grace Burns Arboretum at Georgian Court University • Smith Gilbert • Smithsonian • Springfield-Greene County Parks • Starhill Forest Arboretum • State Botanical Garden of Kentucky, The Arboretum • Strasbourg University Botanic Garden • Tasmanian Arboretum, The • Tennessee Division of Natural Areas • Texas A&M Forest Service • Tower Grove Park • Town of Winthrop • Tree Musketeers • Tucson Botanical Gardens • Twin Peaks Native Plant Nursery • UC Davis Arboretum and Public Garden • United States Botanic Garden • United States Fish and Wildlife Service • United States National Arboretum • University of California • University of California Botanical Garden at Berkeley • University of Florida North Florida Research and Education Center • University of Guelph Arboretum • University of Leicester Botanic Garden • University of Maribor Botanic Garden • University of Minnesota • University of Notre Dame • University of Oklahoma • University of Washington Botanic Gardens • USDA Agricultural Research Service • USDA Forest Service • USDI Bureau of Land Management • VanDusen Botanical Garden • Vietnam National University of Forestry • Village of Bensenville • Village of Riverside • West Virginia Native Plant Society • West Virginia Wesleyan College • Westonbirt, The National Arboretum • Wilson Seed Farms, Inc • Woodland Park Zoo • WRD Environmental, Inc. • Wright Nursery Alberta • Yellowstone Arboretum

Carya ovata (Ed Hedborn, The Morton Arboretum)

Carya cordiformis (Ed Hedborn, The Morton Arboretum)

APPENDIX B. RESULTS FROM THE 2019 TREE CONSERVATION ACTION QUESTIONNAIRE

To receive contact information for a specific respondent and target species, please email treeconservation@mortonarb.org.

Species	Institution reporting conservation activities	Country (U.S. state)	Collect and distribute germplasm	Implement protection policies or regulations	Occurrence surveys or population monitoring	Population reinforcement or introduction	Protect and/or manage habitat	Public awareness or education	Research (e.g., genetics, climate change, pests)
Carya floridana	Donald E. Davis Arboretum at Auburn University[1]	United States (AL)	X					X	
	Louisiana Department of Wildlife and Fisheries[6]	United States (LA)			X		X		
	Peckerwood Garden[1]	United States (TX)	X		X			X	
	United States National Arboretum[3]	United States (DC)							X
	USDA Agricultural Research Service[3]	United States (TX)	X						X
	Wilson Seed Farms, Inc[8]	United States (IL)			X		X		
Carya myristiciformis	Arboretum Wespelaar[1]	Belgium						X	
	Arkansas Natural Heritage Commission[6]	United States (AR)					X	X	
	Blue Mountains Botanic Garden, The[1]	Australia	X						
	City of Columbia Stephens Lake Park Arboretum[2]	United States (MO)	X					X	
	Donald E. Davis Arboretum at Auburn University[1]	United States (AL)	X					X	
	Louisiana Department of Wildlife and Fisheries[6]	United States (LA)			X		X		
	North Carolina Natural Heritage Program[6]	United States (NC)			X		X	X	
	Peckerwood Garden[1]	United States (TX)	X		X			X	
	Polly Hill Arboretum, The[1]	United States (MA)	X						
	University of Oklahoma[9]	United States (OK)			X		X		
	USDA Agricultural Research Service[3]	United States (TX)	X						X
	Westonbirt, The National Arboretum[1]	United Kingdom					X	X	X
	Wilson Seed Farms, Inc[8]	United States (IL)			X				
	Name not shared[1]	United States (LA)	X					X	

Institution types

[1] Arboretum/botanical garden [2] Government (local) [3] Government (national) [4] Land conservancy [5] Native plant society [6] Natural heritage program [7] Other non-governmental organization [8] Private sector [9] University

List of state abbreviations used in Appendix B

U.S. State	Abbreviation	U.S. State	Abbreviation	U.S. State	Abbreviation
Alabama	AL	Kentucky	KY	New Mexico	NM
Arkansas	AR	Louisiana	LA	New York	NY
Arizona	AZ	Massachusetts	MA	Ohio	OH
California	CA	Maryland	MD	Oklahoma	OK
Colorado	CO	Michigan	MI	Oregon	OR
Florida	FL	Minnesota	MN	Pennsylvania	PA
Georgia	GA	Missouri	MO	South Carolina	SC
Iowa	IA	Mississippi	MS	Tennessee	TN
Illinois	IL	North Carolina	NC	Texas	TX
Indiana	IN	North Dakota	ND	Utah	UT
Kansas	KS	New Jersey	NJ	Washington	WA

Carya myristiciformis (Plant Image Library from Boston, USA)

Conservation Gap Analysis of Native

U.S. Hickories

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Front cover images:
Carya aquatica (John Bradford)
Carya cordiformis (Susan McDougall)
Carya floridana (Susan McDougall)
Carya glabra (Susan McDougall)
Carya illinoinensis (Susan McDougall)
Carya laciniosa (Deb Brown, The Morton Arboretum)
Carya myristiciformis (Susan McDougall)
Carya ovata (Deb Brown, The Morton Arboretum)
Carya pallida (Susan McDougall)
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