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Carya Species for Use in the Managed Landscape: Predicted Drought Tolerance

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Abstract. **Impressive ornamental features including exfoliating bark and golden fall color are among the reasons why hickories [*Carya* (Nutt.)] are sought after by horticulturists. Their potential for application in the green industry continues to grow as producers and consumers in the United States become more interested in adopting native plants; however, an absence of knowledge that defines which species are tolerant of abiotic stresses in the landscape limits their use. If production of stress-tolerant hickories increases, they could be used to diversify urban forests and may bolster the resiliency of managed landscapes. We examined the predicted leaf water potential at the turgor loss point to estimate drought tolerance among several species of hickories and pecans adapted to growing in northern climates in the United States. Our hypotheses were that because some bottomland habitats experience seasonal drought in addition to flooding, taxa adapted to these sites may be more drought tolerant than previously assumed, and that the degree of drought tolerance would be variable within species and populations. Predicted mean leaf turgor loss measured in summer across species was −3.38 MPa. Kingnut hickory [*Carya laciniosa* (F. Michx.) Loud.] exhibited the lowest mean summer leaf turgor loss point −3.64 MPa), whereas pignut hickory [*Carya glabra* (Mill.) Sweet.] exhibited the highest (−3.20 MPa). Provenance of trees studied influenced estimated drought tolerance of *C. laciniosa*. Variability between individual trees within each species was observed, suggesting clonal selections of each taxon can be made for drought-prone landscapes. The results of this work imply that all the species studied are at least moderately drought tolerant and should be considered for planting in managed landscapes. Further, species often associated with riparian habitats may exhibit substantial tolerance to drought and should not be excluded from use on drought-prone sites.**

The genus *Carya* comprises 20 taxa globally, with 14 species found in North America (Wood and Grauke, 2011). Divided into three subgenera, the "true hickories" (sect. Carya) and "pecan hickories" (sect. Apocarya) comprise the 14 species found in North America, and the remaining species (sect. Sinocarya) are restricted to Asia (Manos and Stone, 2001). Of the taxa endemic to North America, all but one, Mexican hickory (*Carya palmeri* Manning), are distributed across the eastern United States. Species belonging to this genus are commonly referred to as either "hickories" or "pecans." Naturally occurring interspecific hybrids are found for multiple species in overlapping ranges (Grauke, 2003). This genus consists of large, long-lived woody perennials, with all but one [scrub hickory (*Carya floridana* Sarg.)] exhibiting upright, tree-like habits and forms (Peattie, 1966). Diversity of adaptations to unique habitats and conditions abound within this genus ranging from species found on dry, upland sites to taxa encountered in seasonally inundated swamps, as well as those that fall in the middle of the spectrum, and those that appear adaptable to both extremes. Multiple species of *Carya* have potential for application throughout U.S. Department of Agriculture cold hardiness zones 4 to 10. Hickories and pecan are often sought after by horticulturists for their outstanding ornamental features. Some hickories, like shagbark hickory [*Carya ovata* (Mill.) K. Koch] or *C. laciniosa* exhibit large, exfoliating plates of bark, and others offer scaly and ridged or fissured bark. Coarse, upright habits and superior golden fall colors are typical of hickories and pecan. Although all species produce edible nuts, not all are desirable for nut production. Flavor, ease of cracking, and fruit size vary, leaving opportunity for selection of trees better suited to urban applications rather than orchards. In addition, reports indicate some interspecific hybrids may be sterile and therefore fruitless, a useful attribute for urban forest selections (Thompson and Grauke, 1991).

Although desirable for a variety of applications, some species belonging to the genus *Carya* are restricted by nursery production bottlenecks. Their potential for commercial horticulture is constrained by a lack of clonal selections and propagation techniques suited to trees grown for landscape application, minimal production in the nursery trade, and claims of difficulty transplanting (Dirr, 2009). These common generalized claims from the green industry suggest hickories are not well-suited to traditional nursery production systems. Yet some nurseries have shown interest in adopting these trees into production by trialing hickory crops to evaluate amenability to current production schemes. Recent research now partially addresses these issues by outlining alternative production techniques that support the use of hickories as nursery crops (Miller and Bassuk, 2022a, 2022b; Miller and Graves, 2019).

Given that hickories and pecan offer many desirable traits, their limitations in the nursery should not invalidate potential application for use in managed landscapes. In addition to their ornamental traits and their adaptability, Peattie (1950) suggests they may be excellent candidates for tolerating the conditions of urban environments; potentially bolstering urban forest resiliency via species diversification. Some riparian species belonging to the genus *Carya* are clearly suited to sites with periodic inundation of the root zone, and traditional thinking may suggest that only taxa adapted to upland sites will offer increased drought tolerance. However, many riparian habitats fluctuate between seasonal inundation and drought (Hodges, 1998; Kassahun and Renninger, 2021). This is true of habitats of which some bottomland species of *Carya* occur (Thompson and Grauke, 1991). Therefore, it is possible that some species adapted to riparian environments may be better able to acclimate in their responses to fluctuations between drought and flooding.

Trees planted and managed in urban environments are exposed to the stresses and conditions of those sites. Urban trees often experience limited soil volumes (Grabosky and Bassuk, 1995), soil compaction (Day and Bassuk, 1994), and high pH (Jim, 1998), as well as extreme fluctuations in temperature (Graves et al., 1991) and water availability (Whitlow and Bassuk, 1987). To ensure successful growth, these stresses must be accounted for when selecting trees for managed landscapes. These factors help focus selection criteria for practitioners and are useful for exploring and identifying underused taxa that may offer tolerances to a broad range of site conditions. To successfully match an appropriate plant for a set of specific site conditions, the tolerances of the species or cultivar should be well documented. In the case of drought, the leaf water potential at the turgor

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loss point (Ψ_{P0}) is a valuable measurement for characterizing the ability of a plant to tolerate water stress (Hirons and Thomas, 2018). Leaves of species with a more negative Ψ_{P0} will continue to function physiologically over a broader range of water deficits relative to those with a less negative Ψ_{P0}. Consequently, plants with more negative Ψ_{P0} are more likely to have the capacity to survive and maintain growth during and after periods of reduced soil moisture (Blackman et al., 2010; Mitchell et al., 2008).

A common misunderstanding among native plant enthusiasts is that because a taxon is endemic to a particular locale it is suitable for use in managed landscapes within that same region. However, this thinking does not acknowledge conditions plants encounter in the wild vs. the harsh site conditions typical of managed landscapes. As reported stress tolerance of hickories is often based solely on their habitats in situ and evidence for drought tolerance beyond observation is lacking without a relative scale, we evaluated leaf ψ_S at full turgor ($\Psi_{\pi 100}$) and predicted Ψ_{P0} of five species of *Carya*. Our objectives were to 1) quantify and characterize potential drought tolerance of species belonging to the genus *Carya* suitable for managed landscapes in the northern regions of the United States; 2) quantify and characterize the ability of these taxa to osmotically adjust throughout the growing season, and 3) determine if predicted drought tolerance is variable within populations as well as among trees that represent different provenances within the native range of a particular taxon.

Materials and Methods

This study was conducted in both 2019 and 2020 in late spring (June) once trees exhibited fully expanded growth and in late summer (August) after trees had adequately experienced summer growing conditions. Species and number of individuals assessed include the following: bitternut hickory [*Carya cordiformis* (Wangenh.) K. Koch] ($n = 10$), *C. glabra* ($n = 10$), *Carya illinoinensis* (2019, $n = 4$; 2020, $n = 5$), *C. laciniosa* (2019, $n = 10$; 2020, $n = 11$), and *C. ovata* ($n = 10$). All trees studied were well-established individuals in the landscape located in and around the Cornell University campus in Ithaca, NY (42°26'52.9″N, 76°28'38.0″W) with the exception of seven accessions of *C. laciniosa* at the Owasco Flats Nature Preserve in Moravia, NY (42°45'12.7″N, 76°27'48.2″W). Mean (°C) temperatures (Min.°C, Max. °C) for regions where the trees were sampled from June through August were 20° (3.8°, 32.2°) in 2019 and 21.5° (2.72°, 34.5°) in 2020 for Ithaca, NY. Trees in Moravia, NY, experienced ~20.4° (5.5°, 31.7°) and 21.8° (9.9°, 33.9°) in 2019 and 2020, respectively. From June through August in 2019 and 2020 the sites in Ithaca, NY, received ~33.5 cm and 28.7 cm total precipitation, whereas the site in Moravia, NY, received ~29.2 cm and 21.0 cm. Weather data were acquired from the nearest weather stations [Ithaca (CUAES: Cornell Orchards) and Aurora] in the Network for Environment and Weather Applications station network (Cornell University, updated 2021). All trees sampled were assumed to be of seed origin.

The evening before measurements were taken, samples were collected from the plants. Branches fully exposed to the sun and not afflicted by disease or exhibiting flower or fruit development were targeted (Bartlett et al., 2012a). Branches were removed with a pole pruner and the basal, cut ends were submerged under water in a bucket. Samples were quickly transported to the laboratory and recut under water to remove any embolisms in the branch vasculature that may have developed as a result of the initial severance. Once recut, branches were covered with an opaque material to exclude light and then left overnight at room temperature to equilibrate. The following day, three separate leaves were removed from each branch sequentially and leaves were wiped with a Kimwipe (Kimberly-Clark Professional, Roswell, GA) to ensure the lamina was clean. Using a 6-mm cork borer, a leaf disc was removed from the lamina between the largest veins. Each disc was wrapped singly in tin foil, labeled, then placed in a flask of liquid nitrogen for at least 2 min. In sequence, each disc was quickly removed from the liquid nitrogen, unwrapped, then pierced with sharp forceps (Kikuta and Richter, 1992) 15 times before loading into the 10-μL chamber of a Vapro 5600 Vapor Pressure Osmometer (Wescor, Logan, UT). Leaf discs were pierced with forceps to ensure proper evaporation of leaf solutes once loaded in the chamber. After sample loading, the chamber of the Vapro 5600 would equilibrate for 10 min followed by measurements of the solute concentration (C_s) of the leaf disc. Measurements of C_s were continuously taken (using process-delay mode on the Vapro 5600) until three measurements within 5 $\text{mmol}\cdot\text{kg}^{-1}$ of one another could be recorded. Three measurements were recorded per leaf leading to nine total observations ($n = 9$) made for each tree at each sampling period. The temperature of the Vapro 5600 was recorded for each measurement. Using Van't Hoff's relation [Eq. (1)]:

$$\Psi_{\pi 100} = -\text{RTCs},$$

where R is a gas constant, T equals the temperature measured in Kelvins, and C_s is the solute concentration of the sample at full turgor, C_s was first converted to the osmotic potential at full turgor ($\Psi_{\pi 100}$). The original relationship between osmotic potential at full turgor and the turgor loss point proposed by Bartlett et al. (2012b) can be used to predict the turgor loss point. However, Bartlett et al. (2012b) used a cosmopolitan meta-analysis for their work. Therefore, a temperate tree corrected equation published by Sjöman et al. (2015) [Eq. (2)]:

$$\Psi_{P0} = -0.2554 + 1.1243 \times \Psi_{\pi 100}$$

adapted from Bartlett et al. (2012b) was used to calculate Ψ_{P0} from the $\Psi_{\pi 100}$.

Statistical analysis. Data collected for all but two plants in both 2019 and 2020 were pooled and presented as averages across both years to better account for year-to-year variation. Plants represented with only 1 year of data were presented as is. Spring and summer datasets were subjected to one-way analysis of variance. Post hoc mean separations were performed using Tukey's honestly significant difference test. Osmotic adjustment, calculated as the difference between spring and summer measurements, was analyzed using a paired *t* test. Statistical analysis was conducted using JMP Pro 15 software (JMP Version 15; SAS Institute, Inc., Cary, NC).

Results

Osmotic potential at full turgor ($\Psi_{\pi 100}$). Mean $\Psi_{\pi 100}$ (±*SE*) across species was −2.20 (±0.01) MPa in spring and −2.78 (±0.02) MPa in summer. Differences across species in both spring and summer ($P < 0.0001$) were observed (Table 1). In spring, *C. illinoinensis* exhibited the highest $\Psi_{\pi 100}$, whereas the lowest $\Psi_{\pi 100}$ was observed with *C. laciniosa*. In summer, highest $\Psi_{\pi 100}$ was evident with *C. glabra* and the lowest $\Psi_{\pi 100}$ occurred with *C. laciniosa*. Significant seasonal osmotic adjustment was evident with each taxon (Table 1). The least and most seasonal osmotic adjustment occurred with *C. ovata* and *C. illinoinensis*, respectively (Table 1).

Predicted leaf turgor loss point (Ψ_{P0}). Overall spring and summer Ψ_{P0} means (±*SE*) across species were −2.72 (±0.01) MPa and −3.38 (±0.02) MPa, respectively. Differences across species ($P < 0.0001$) were detected in both seasonal groups (Fig. 1). Taxa exhibiting the highest and lowest Ψ_{P0} in spring and summer matched the aforementioned pattern

Table 1. Osmotic potential at full turgor [$\Psi\pi100$ (±*SE*)] and seasonal osmotic adjustment ($\Delta\Psi_{\pi 100}$) for five species of *Carya* evaluated in 2019 and 2020 using vapor pressure osmometry. Spring and summer means ($\Psi_{\pi 100}$) were subject to a one-way analysis of variance ($P < 0.0001$) indicating species differences.

Taxon	Spring $\Psi_{\pi 100}$ (MPa)	Summer $\Psi_{\pi 100}$ (MPa)	$\Delta\Psi_{\pi 100}$ (MPa)
C. cordiformis	−2.09 (± 0.02) b[i]	−2.77 (± 0.03) b	0.68***[ii]
C. glabra	−2.15 (± 0.02) b	−2.62 (± 0.03) a	0.47***
C. illinoinensis	−1.81 (± 0.03) a	−2.69 (± 0.05) ab	0.88***
C. laciniosa	−2.37 (± 0.02) c	−3.06 (± 0.03) c	0.67***
C. ovata	−2.34 (± 0.02) c	−2.69 (± 0.03) ab	0.35***

[i] Means within columns sharing a letter are not significantly different according to Tukey's honestly significant difference test ($P \geq 0.05$).

[ii] Differences between spring and summer data were determined by a paired *t* test; *** indicates significance at $P \leq 0.0001$.

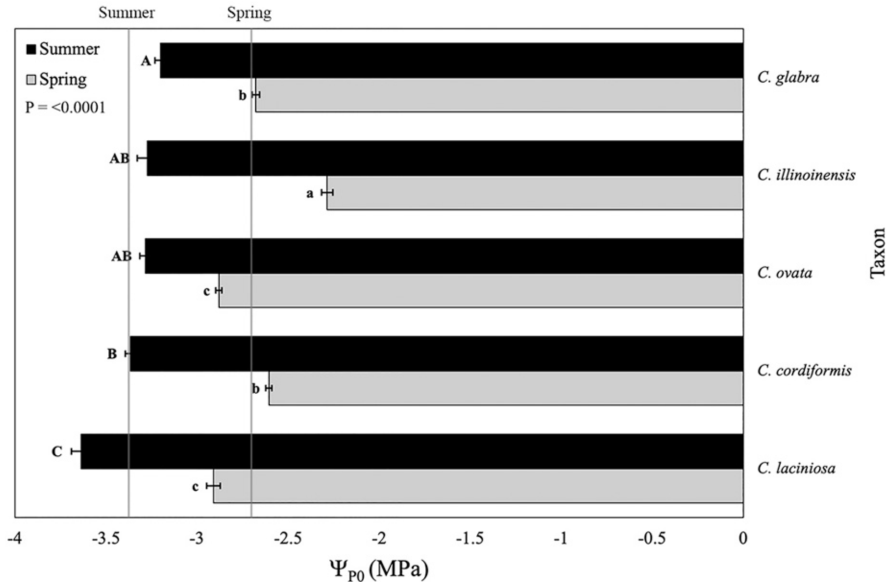

Fig. 1. Predicted leaf turgor loss point in spring and summer of species of *Carya* ranked by summer values. Seasonal means for summer and spring were compared separately. Means across species sharing a letter for summer (uppercase) or spring (lowercase) are not significantly different according to Tukey's honestly significant difference test ($P \leq 0.05$). Error bars represent the standard error of the mean. Vertical lines indicate the overall mean for spring and summer across taxa.

observed for $\Psi_{\pi 100}$ (Fig. 1). On the population scale, differences were observed for spring ($P < 0.0001$) and summer ($P = 0.0003$) (Fig. 2). For both seasons, higher mean Ψ_{P0} was observed with the cultivated plants in the arboretum and lower mean Ψ_{P0} with the wild population in the Owasco Flats Nature Preserve (Fig. 2). Marked variation was noted with spring and summer means ($P < 0.0001$) across individual trees within the sampled populations of *C. glabra* (Fig. 3) as well as *C. cordiformis*, *C. illinoinensis*, *C. laciniosa*, and *C. ovata*.

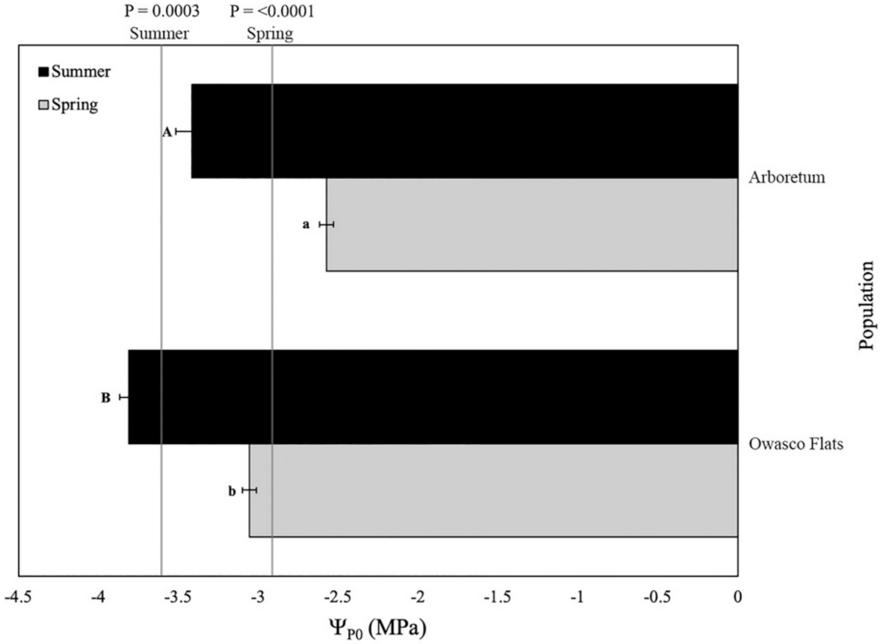

Fig. 2. Predicted leaf turgor loss points in spring and summer of two populations of *Carya laciniosa* of known provenance ranked by summer values. Seasonal means for summer and spring were compared separately. Means across populations sharing a letter for summer (uppercase) or spring (lowercase) are not significantly different according to Tukey's honestly significant difference test ($P \leq 0.05$). Error bars represent the standard error of the mean. Vertical lines indicate the overall mean for spring and summer across populations.

Discussion

Of the taxa involved in this study, *C. laciniosa* exhibited the most negative Ψ_{P0} and *C. glabra* had the highest Ψ_{P0} in summer (Fig. 1). Each taxon adjusted osmotically between late spring and late summer (Table 1). While the summer Ψ_{P0} for *C. illinoinensis* was not the lowest of the species studied (Fig. 1), this taxon exhibited the greatest capacity for osmotic adjustment (Table 1). The relative Ψ_{P0} ranking we observed directly contradicts rankings of water quantity requirements in the literature. Boisen and Newlin (1910) indicate water requirements in ascending order as follows: *C. glabra*, mockernut hickory [*Carya tomentosa* (Lam.) Nutt.], *C. ovata*, *C. cordiformis*, *C. laciniosa*, nutmeg hickory [*C. myristiciformis* (F. Michx.) Nutt.], *C. illinoinenis*, and water hickory [*C. aquatica* (F. Michx.) Nutt.]. In horticulture and related fields, species belonging to the genus *Carya* are often subject to generalizations and assumptions based on observations of familiar taxa and the most common habitat conditions of native stands in situ. These generalizations and assumptions underestimate the use and potential of *Carya* species in managed landscapes. Just as generalizations of root morphological development in response to nursery production techniques of seedling hickories have been shown to be inaccurate (Miller and Graves, 2019), the potential abilities of these species to tolerate drought are also likely to have been misrepresented (Fig. 1).

Based on mean summer $\Psi_{P0,}$ *C. cordiformis* and *C. laciniosa,* taxa typically found on bottomland sites and generally considered drought sensitive, were predicted to be more drought tolerant than *C. glabra*, a taxon referenced (Boisen and Newlin, 1910; Sparks, 2002) as one of the most tolerant of dry sites and requiring the least water (Fig. 1). Although counterintuitive to traditional site and habitat association, we believe that this pattern should be given greater attention. The literature often reflects site-related restrictions for most species, yet some hickories are frequently observed in a variety of habitats in the wild and sites in cultivation. *Carya laciniosa* and *C. cordiformis* are species that tend to dwell in or near riparian habitats; however, it is not uncommon to see these species and their relatives thriving across a broad array of site conditions. Schlesinger (1990) mentions that although *C. laciniosa* requires more water to survive than *C. glabra*, *C. tomentosa*, and *C. ovata,* and is usually found on deep, rich soils such as Alfisols, it can also be found on a broad range of sites including those with dry, sandy conditions and soils. Thompson and Grauke (1991) support the potential adaptability of *C. laciniosa* across both swampy and dry sites. Braun (1961), Elias (1980), and Thompson and Grauke (1991) describe *C. cordiformis* as often associated with swampy bottomlands, but also occurring naturally on mesic and dry sites. All-or-nothing assumptions based on typical habitat characteristics are problematic because they simply may not be accurate and do not account for outlier individuals and populations.

Some riparian habitats are subject to routine fluctuations between inundation and drought and taxa adapted to these sites must exhibit a degree of resilience to extremes of soil-moisture

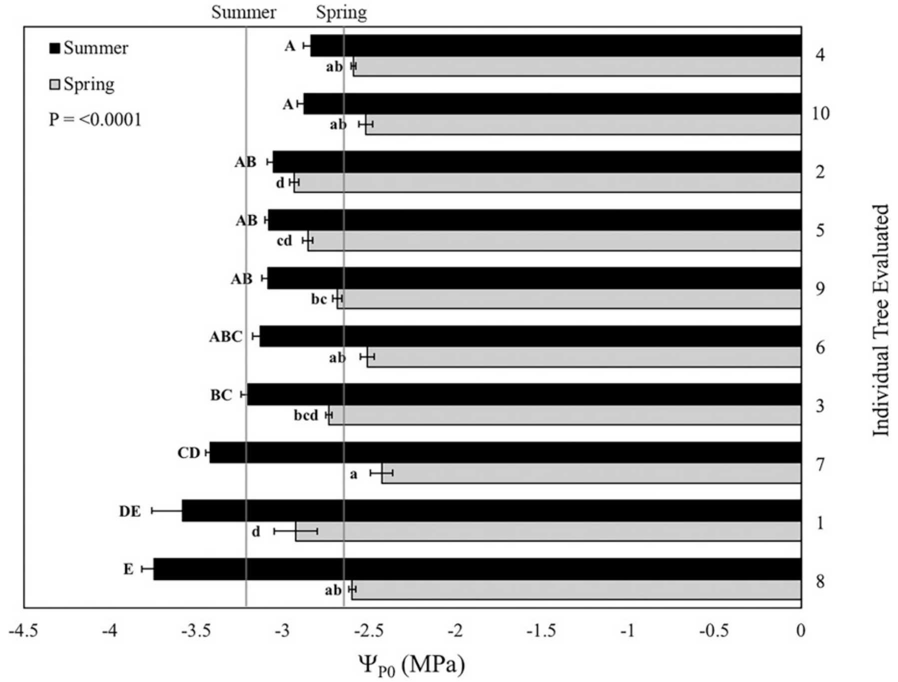

Fig. 3. Predicted leaf turgor loss point in spring and summer of 10 individuals of *Carya glabra* ranked by summer leaf turgor loss values. Seasonal means for summer and spring were compared separately. Means across individuals sharing a letter for summer (uppercase) or spring (lowercase) are not significantly different according to Tukey's honestly significant difference test ($P \leq 0.05$). Error bars represent the standard error of the mean. Vertical lines indicate the overall mean for spring and summer across individuals.

gradients (Devall and Parresol, 1998; Konings and Gentine, 2017). Indeed, a high degree of resiliency and plasticity to both drought and waterlogging is not the case for most bottomland-dwelling angiosperm species (Niinemets and Valladares, 2006a, 2006b). However, some examples of documented outliers include *Alnus maritima* (Marshall) Muhl. ex Nutt. (Schrader et al., 2005), *Pinkneya bracteata* (W. Bartram) Raf. (formerly *Pinkneya pubens*) (Stewart et al., 2007), *Taxodium distichum* (L.) Rich., and *Magnolia virginiana* L. (Nash and Graves, 1993). In their evaluation of drought tolerance of seven *Magnolia* L. species, Sjöman et al. (2018b) corroborated the ability of *M. virginiana* to tolerate drought better than its congeners. In the wild, *M. virginiana* is found almost exclusively in bottomland habitats (Preston, 1989) and the related taxa involved in their study are usually found inhabiting mesic sites, yet multiple reports have corroborated the ability of *M. virginiana* to surpass its congeners in drought tolerance.

Species that belong to the genus *Carya* exhibit strong taproots that persist beyond their juvenile development stages (Thompson and Grauke, 1991). Although in this study we have reported drought tolerance predictions, other studies recommend the potential for some *Carya* species to use drought avoidance strategies. Sparks (2002) suggests that *C. illinoinensis*, with its strong taproot, is phreatophytic, and will grow to the water table and that this taxon cannot be grown on dry sites (Sparks, 2005). Although all hickories are noted for the development of a taproot, it is unclear if all *Carya* species are accurately classified as phreatophytes. In their study of a population of oaks and hickory in central Missouri, Parker et al. (1982) provide evidence that *C. tomentosa*, a species common on mesic sites, may use drought avoidance strategies. Our study is focused on predicting drought tolerance in a few select species. We recognize that some species in this genus, such as *C. tomentosa*, may be better classified as drought avoiders. However, given the evidence we have provided for *C. illinoinensis*, we question if some species may be better classified as opportunistic, rooting into deep soil horizons when capable or enduring drought via seasonal osmotic adjustment when necessary. We also question whether generalizations of *C. illinoinensis* were made through the lens of prolific nut production rather than simple growth and survival.

Relative to taxa involved in other research (Hirons et al., 2021; Schwartz Sax et al., 2020; Sjöman et al., 2015; Sjöman et al., 2018a, 2018b), the species of *Carya* in our study appear to rank among moderately drought-tolerant taxa that are commonly found growing and thriving in urban environments. For example, mean summer Ψ_{P0} for all of the taxa we studied appear to have surpassed that of *Acer platanoides* L. (Sjöman et al., 2015), a taxon known for its ability to thrive under urban constraints. Our results for *C. ovata* align with findings of Sjöman et al. (2018a) who conducted a comparable study of underrepresented taxa with potential for use in urban forestry. Their research involved four specimens of *C. ovata* also located in Ithaca, NY. The corroborated results between the two studies are strongly aligned, not only supporting the reliability and repeatability of this evaluation method but also the conclusions we have drawn.

As would likely be expected for a species with a broad distribution that is not entirely continuous, we observed distinct variability between a wild population and population of cultivated trees of known provenance of *C. laciniosa* (Fig. 2). Trees for these populations were regionally close in proximity, yet slight variability in climatic conditions was observed between sites. The authors suspect these minor climatic differences were not enough to result in the response divergence measured between populations; however, future studies may consider further investigating this phenomenon, especially considering the ability of *C. laciniosa* to osmotically adjust (Table 1). It is widely known that provenance can contribute significantly to intraspecific variation for an assortment of traits and should be considered for making tree selections for the urban environment (Arnold et al., 2012). Sternberg and Wilson (2004) specifically mention the potential for using regionally adapted selections of *C. cordiformis* in cultivation given its extensive native range. This trend appears consistent with stress tolerance traits like drought tolerance and should be strongly considered by practitioners selecting nursery stock for planting. In addition to variability between distinct populations, our study also highlights marked intraspecific variation within a population. Relative to the other species involved in this study, *C. glabra* was predicted to be the most drought sensitive (Fig. 1). Comparatively, across the 10 individual trees of *C. glabra,* we found a significant amount of variation, with trees one and eight each exhibiting summer Ψ_{P0} values well below the population mean (Fig. 3). This trend was consistent across the taxa we evaluated. Similarly, Sjöman et al. (2015) observed comparable trends with cultivars of *Acer rubrum* L. and *Acer saccharum* Marshall, whereas Hannus et al. (2021) reported similar trends for *Betula pendula* Roth derived from different provenances, both emphasizing the importance of intraspecific variability for stress tolerance traits both within and between populations. This variation between individual trees suggests that clonal selections can be made that are better suited to placement in drought-prone landscapes. We recognize also, on a relative scale across the endemic distribution of the taxa included in our study, that additional variation likely exists. Therefore, until additional provenances are sampled and reported, our results should be leveraged by the number of trees and locales they represent.

As managed landscapes continue to be threatened by increasing abundance and frequency of abiotic and biotic stresses, further diversification of species composition will be necessary to bolster overall landscape resiliency (Hooper et al., 2005; Alvey, 2006). Expanded species diversity in managed landscapes and urban forests will likely be achieved by adding underused taxa into the landscape (Sjöman et al., 2018a). The process of selecting plants and matching them to individual sites should consider not only ornamental features, but the ability of those species to tolerate the stresses imposed by the site. The species belonging to the genus *Carya* that inhabit the United States can be found growing in many different environments and offer a wealth of biodiversity for use in horticulture. Their status as native plants (in the United States) does not necessarily imply that these species are capable of performing in managed landscapes; however, the species we studied exhibit useful drought-tolerance traits that qualify them for use in a broad array of landscape situations including urban plantings that may otherwise exclude drought-sensitive species. Their relatedness on the generic level does not imply that these species will perform equally, and each should be considered on a case-by-case basis to match the best-suited species to the site conditions. Further, outlying individual clones with superior drought tolerance should be identified and introduced specifically for use in drought-prone landscapes. Species that belong to the genus *Carya* are underused taxa that may offer both adaptability to a broad range of sites and stresses as well as superior ornamental traits for landscape application. In particular, this research supports the broader application of *C. laciniosa*, a species that is nearly nonexistent in the horticulture trade, but one that offers ornamental features like exfoliating bark and golden fall color and appears to be quite adaptable and tolerant of drought.

Studies have demonstrated that commonly referenced literature may offer conflicting information or recommendations of plant tolerances that can be interpreted subjectively (Sjöman et al., 2015, 2018a). Therefore, characterization and relative ranking of stress tolerances should be considered when selecting species and cultivars for use in the landscape. This study offers direction to landscape practitioners on selection of species of *Carya* suited to growing in northern climates within the United States to aid in matching taxa to appropriate site conditions. In addition, this work contributes to the larger knowledgebase of characterizing drought stress tolerance for more accurate species selection in managed landscapes and urban forests.

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