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RESEARCH ARTICLE

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urban & community forestry

Performance Metrics for Street and Park Trees in Urban Forests

Eric A. North, Anthony W. D'Amato, and Matthew B. Russell

Tree performance in urban forests is difficult to evaluate, because there is not a unified metric such as wood volume to determine the highest performers. This study evaluated tree performance metrics for street and park trees in Minneapolis and Saint Paul, Minnesota. Metrics included: diameter at breast height (dbh), canopy projection area (CPA), a growth rate ratio (BRATIO), and a tree performance index (TPI). The BRATIO and TPI incorporated size and growth rate and were developed as quantitative metrics for evaluation of urban trees. Increased pervious surface area under the canopy had a positive influence on all metrics investigated. Metric comparisons showed larger mean dbh and CPA for street trees and higher mean values of BRATIO and TPI for park trees after controlling for tree age. Study results suggest that tree performance evaluated with size metrics (dbh and CPA) versus composite metrics (BRATIO and TPI) may prioritize faster growth over sustained longer-term growth.

Keywords: tree performance, urban tree growth, tree ring, growth metrics, urban forestry

Assessing the capacity of a site to support tree growth has long been a central element of traditional forest management and has generally quantified site productivity via estimates of wood volume or site indices based on tree height and volume predictions (Skovsgaard and Vanclay 2008). Urban forest productivity has been more complicated to assess, given the diverse range of values derived from urban trees. Clark et al. (1997) make the case that for urban forests to remain productive, they must provide a variety of net environmental and societal benefits through time. The myriad environmental and social benefits of urban trees have been well established in the literature (Dwyer et al. 2000, Brack 2002, McPherson 2003, Cappiella et al. 2005, Sanders et al. 2010). In an urban context, forest productivity can be assessed via tree performance, where performance is the growth capacity of trees for the provision of environmental and societal benefits through time.

Tree performance in urban environments has been evaluated in various contexts such as establishment success (Levinsson et al. 2017), tree mortality or survival (Roman et al. 2015, Vogt et al. 2015), tree condition (Kulhavy et al. 2014, Scharenbroch et al. 2017), public perception (Lee at al. 2009), infrastructure conflicts (Hauer et al. 1994, Koeser et al. 2013, North et al. 2017), and storm response (Lopes et al. 2009, Moore 2014) to list a few. Urban tree condition, canopy size, vigor, growth, and longevity have been used to demonstrate the performance and value of landscape trees (Morales 1980, McPherson 2003, Sanders et al. 2010, Dimke et al. 2013). Condition assessments are part of evaluations and appraisals for urban trees (Kulhavy 2014, Komen and Hodel 2015, Ponco-Donoso et al. 2017, Scharenbroch et al. 2017), and whereas tree condition is likely related to tree performance, condition and health may be more difficult to quantify accurately (Bond 2010). The subjective nature of tree condition and health assessments demonstrated in previous studies (Watson 2002, Komen and Hodel 2015, Ponco-Donoso et al. 2017) suggests that quantitative measures of tree growth may be better indicators of site quality and tree performance.

Scharenbroch et al. (2017) used 15 different factors and parameters including climate, urban infrastructure, and soil characteristics to establish the rapid urban site index (RUSI) to quantify tree performance in terms of tree condition and health as well as through the use of tree rings as a growth metric. The authors found that higher-quality urban sites were correlated with trees in better health and condition, but that noted

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tree health and condition assessments were subjective and may have biased their results (Scharenbroch et al. 2017). The RUSI was not significantly correlated with tree growth metrics of diameter at breast height (dbh)/age and mean annual ring width increment, but showed a significant correlation with the average annual increment over the last 10 years (Scharenbroch et al. 2017). A simpler technique to assess tree performance in terms of growth used available soil surface area and produced consistent results whereby increased soil surface area was correlated with increased tree size (Sanders et al. 2013, Sanders and Grabosky 2014, Dahlhausen et al. 2016). However, there is little evidence available in the literature regarding the future performance trend of urban trees, in terms of growth, based on site characteristics.

Manion (2001) provided a framework for assessing tree performance in terms of tree decline, whereby trees predisposed to stress often have symptoms of canopy decline with reduced photosynthetic ability. Reduction in basal area increment for trees under environmental stress has been linked with increased tree mortality (Dobbertin 2005, Das et al. 2007). Voelker et al. (2008) created a tree vigor index (TVI) to assess scarlet oak (*Quercus coccinea* Münchh.) and black oak (*Quercus velutina* Lam.) because tree size alone was not a good indicator of future tree performance. The TVI is the ratio of canopy surface area to trunk surface area used to assess tree vigor and predict future growth and mortality (Voelker et al. 2008, Lee et al. 2014). Although there have been no applications of TVI to urban forests, it stands to reason that urban trees operate on the same biological principle of growth as their counterparts growing in rural forests, although the magnitudes of growth response may differ. Development of a quantitative tree performance metric, similar to annual increment or TVI, capable of showing growth trends based on simple site characteristics, could assist urban forest managers in prioritizing urban sites based on the tree performance in terms of potential growth trends.

The objectives of this study were: (1) to adapt TVI as a metric to assess urban tree performance; (2) to investigate how diameter growth, crown size, annual growth increment, and adapted TVI are influenced by tree and urban site characteristics; and (3) to compare diameter growth, crown size, annual growth increment, and adapted TVI as tree performance metrics.

Methods

Research was conducted on municipally managed park and street trees in the cities of Minneapolis (44.9778° N, 93.2650° W) and Saint Paul (44.9537° N, 93.0900° W), Minnesota, USA. Live trees were selected from inventories provided by the Forestry Department of the Minneapolis Park and Recreation Board and the Forestry Department of the City of Saint Paul. Using the combined inventory data of both cities, Norway maple (*Acer platanoides* L.), hackberry (*Celtis occidentalis* L.), and honeylocust (*Gleditsia triacanthos* L.) were selected as tree species common throughout both cities. Linden (*Tilia* L.) was only identified to genus because of the similarities in growth rate, form, and mature size of linden species (Hardin et al. 2001, Dirr 2009) and inconsistencies in identification of hybrid and cultivated varieties in the inventory data. Genus and species were field-verified by researchers.

Park trees included in the study were growing in managed municipal parks where there was evidence of tree and landscape maintenance (i.e., pruning and lawn mowing), and impervious surfaces were a minimum of 1 m from the canopy dripline. Street trees included in the study were growing in municipally managed boulevard planting strips between sidewalk and curb on residential non-arterial streets. All sampled trees were a minimum dbh of 25 cm, which assumed that trees were a minimum age of 20 years (Frelich 1992) and established in their environments (Sherman et al. 2016). Both street trees and park trees were similar distances to neighboring trees (~9–20 m).

The urban forests of Minneapolis and Saint Paul are divided into management districts, and the districts were used to stratify each city as a proxy for ensuring geographic distribution of sampled trees. Forty street trees and 40 park trees for each species meeting study criteria were randomly selected from each district. A total of 320 trees were sampled. In cases where a tree listed in the inventory was not the same as the tree encountered in the field, a tree of the same species on the same city block or in the same park and meeting study criteria was selected. All data were collected between the months of June and August in 2014 and 2015.

Tree Variables

An increment core was obtained from each tree at 0.5 m from the ground to incorporate as many years of annual growth as physically possible. Cores were dried, mounted on wood mounts, and sanded with increasingly finer sandpaper to produce a smooth, flat surface. Each core was examined, dated, and aged by two researchers by counting the annual rings between bark and pith. Where pith was not visible, tree age was estimated using a series of concentric circles to approximate the number of nonvisible rings (Applequist 1958). Tree cores lacking a visible pith and with insufficient ring curvature (e.g., short or decayed cores) to provide a reasonable approximation of age were not

Management and Policy Implications

Urban forest managers typically seek to maximize tree performance, yet unfortunately, there is no single urban tree performance metric, such as wood volume, by which to evaluate urban trees. Our study evaluated the performance of urban trees based on diameter at breast height (dbh), canopy projection area (CPA), relative recent growth rate (BRATIO), and a tree performance index (TPI). The composite metrics of BRATIO and TPI were developed as quantitative tools to assess urban tree performance based on the potential of sustained future growth. Street and park tree performance improved with increased available soil surface area regardless of tree age or performance metric assessed. This highlights the importance of adequate soil resources to ensure a high level of urban tree performance. Our assessment of size metrics (dbh and CPA) favored street trees growing in spaces that are more restricted than park trees, after accounting for age. However, sustainable urban forests benefit from tree longevity, and the composite metrics (BRATIO and TPI) favored trees growing in less restricted or unrestricted spaces. The composite metrics BRATIO and TPI provide managers with new quantitative methods for assessing urban sites and tree species to maximize benefits and minimize costs of urban forests.

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used in the analysis. Individual ring widths were measured to the nearest 0.001 mm using a slide-stage micrometer (Velmex, Inc., Bloomfield, NY) and recorded via computer software (Measure J2X, VoorTech Consulting, Holderness, NH). Of the 320 trees sampled, 292 had cores sufficiently intact to include in the final analysis.

Trunk flare diameter at ground line (TFD), diameter at coring height (DCH), and dbh were measured to the nearest millimeter using a diameter tape. Four-crown radii were measured in the cardinal directions from the canopy dripline to the trunk and recorded to the nearest centimeter using a Bosch DLR130K laser distance measurer (Bosch, Stuttgart, Germany). Canopy projection area (CPA) was calculated from the measured crown radii using Equation 1:

$$\mathrm{CPA} = \left(\sum \mathrm{cr}_i / 4\right)^2 \times \pi \qquad (1)$$

where cr_i is the measured value of the crown radii in four directions.

Tree height and crown height were measured using a Suunto M-5/360PC clinometer (Suunto Co., Helsinki, Finland) and laser distance measurer. The trunk height from ground level to the base of the crown was determined by subtracting the crown height from the total tree height.

Trunk damage was visually assessed when decay, cankers, cracks, or ribs (Shigo 1983) were present on the trunk below the crown base and recorded as present or absent. The presence of stem girdling roots was determined via a visual assessment and recorded as either present or absent. Stem girdling roots are roots contacting the trunk causing compression or deformation in the trunk issue typically at or near ground line (Johnson and Hauer 2000), and reduce tree growth by restricting the flow of water and nutrients (Hulder and Beale 1981, Johnson and Hauer 2000, Wells et al. 2006).

Site Variables

Soil compaction was measured using an Eijkelkamp hand penetrometer (Eijkelkamp, Geisbeek, Netherlands) (Randrup 2001, Duiker 2002) to a depth of 25 cm and recorded in MPa. Soil moisture was not measured at each site; however, in the event of precipitation, data collection was stopped and resumed 48 h after precipitation ceased. The Palmer Drought Severity Index for June through August of 2014 and 2015 varied from midrange moisture to very moist conditions in Minneapolis and Saint Paul (National Centers for Environmental Information 2016). Pervious surface area under the canopy was measured as the contiguously open soil surface area under the canopy in meters to the nearest centimeter.

Data Analysis

A comparison of raw ring-width increment and Basal area increment (BAI) showed BAI as a more robust measure of long-term growth trends for comparison of species and age classes (Johnson and Abrams 2009). BAI was calculated from tree-ring measurements using R (R Core Team 2016) with the dplR package (Bunn 2010). A BAI ratio (BRATIO) was calculated via Equation 2:

$$\mathrm{BRATIO} = \mathrm{avgBAI}_{10} / \mathrm{avgBAI}_{T} \qquad (2)$$

where avgBAI_{10} is the average BAI over the last 10 years of growth, and avgBAI_{T} is the average BAI over the life of the tree.

A tree performance index (TPI) was calculated using field measurements of trunk and crown to create a modified form of the TVI (Voelker et al. 2008, Lee et al. 2014) multiplied by BRATIO Equation 4:

$$\mathrm{TVI} = \frac{\mathrm{CSA}}{\mathrm{SSA}} \qquad (3)$$

where CSA is the crown surface area calculated as the surface area of a cone or the surface area of the sphere based on the approximate crown form of a species. Determination of crown form by species was based on Wandell (1989) and field observations. Norway maple and hackberry most closely resembled spherical forms, whereas honeylocust and linden forms were viewed as inverse conical and conical, respectively. The SSA is the stem surface area calculated as the lateral surface area of a tapered cylinder using the TFD as the base of the cylinder. The top diameter of the cylinder was the trunk diameter at the base of the crown estimated using linear regression to find the mean decrease in diameter over the distance between DCH and dbh by tree species.

$$\mathrm{TPI} = \sqrt{\mathrm{TVI} \times \mathrm{BRATIO}} \qquad (4)$$

Two-way factorial ANCOVAs were conducted to examine the influence of site (street and park), species, and their interaction on mean dbh, CPA, BRATIO, and TPI controlling for age. Tukey's honestly significant difference test was conducted, and the significance level was set at .05.

Ordinary least-squares regression models were employed to assess differences in tree growth and performance of dbh, CPA, BRATIO, and TPI and their relationships to site and tree characteristics. Independent variables included pervious surface area, soil compaction, site (street or park), stem girdling roots, trunk damage, tree age, and tree species. Independent variables included in the final models were selected based on the corrected Akaike Information Criterion (Montgomery et al 2012). The final models for each response variable are presented in Table 3. The models were fit using the lm function in R (R Core Team 2016). All statistical analyses were conducted in R (R Core Team 2016).

Results

Table 1 provides descriptive statistics for age and pervious surface area, and sample size for species by site.

The effect of species and site interaction on mean dbh and mean CPA, controlling for tree age, was statistically significant ($P = .004$, $P = .001$ respectively). Park and street trees differed statistically in mean dbh and mean CPA ($P < .001$, $P = .001$ respectively) with street trees having a larger dbh and CPA on average (Table 2). However, for within-species comparisons, only honeylocust had a statistical difference in mean dbh or mean CPA ($P < .001$), with street trees having a larger dbh and CPA on average than park trees (Table 2). All other within-species differences between park and street trees for dbh and CPA were not statistically different (Table 2).

Statistical differences were detected between park and street trees for mean BRATIO and TPI ($P < .001$). Within-species comparisons between park and street trees, Norway maple and honeylocust park trees had a statistically higher BRATIO ($P < .001$, $P = .001$ respectively; Table 2). Neither hackberry nor linden showed statistical differences for BRATIO within-species comparisons between park and street trees ($P = .386$, $P = .131$ respectively; Table 2). Comparisons within species between park and street trees for mean TPI were statistically larger for park versus street trees for all species (Norway maple $P = .045$, hackberry

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Table 1. Sample size, mean age in years, and mean contiguously available pervious soil surface area in square meters by species and site (street or park).

	n		Age		Pervious surface area (m²)	
Species	Street	Park	Street	Park	Street	Park
Norway maple	37	37	38 (5)	38 (11)	26.8 (8.9)	97.5 (36.6)
Hackberry	37	35	36 (7)	64 (29)	22.0 (8.2)	133.5 (62.2)
Honeylocust	38	37	37 (6)	41 (17)	30.7 (12.9)	119.8 (48.2)
Linden	37	34	34 (8)	36 (14)	24.5 (11.0)	87.4 (32.7)

Note: Standard deviations are shown in parentheses.

P = .040, honeylocust P = .003, and linden P = .009; Table 2). Age was a statistically significant covariate for mean dbh, CPA, and BRATIO ($P < .001$, $P < .001$, $P = .018$ respectively), and was not significant for mean TPI ($P = .322$).

Contiguously available pervious surface area under the canopy was a statistically significant factor explaining variation observed in dbh, CPA, and TPI ($P < .001$; Table 3). The final model for BRATIO showed an inverse relationship with soil compaction; however, soil compaction was not statistically significant ($P = .191$; Table 3). Tree age was included in the final models for dbh, BRATIO, and TPI (Table 3) with a positive influence on dbh and BRATIO (Table 3). However, age was not a statistically significant factor for BRATIO ($P = .242$). The presence of stem girdling roots had a negative influence on both BRATIO and TPI ($P = .049$ and $P = .070$, respectively; Table 3). Trunk damage was included in dbh, BRATIO, and TPI models, but was only statistically significant for TPI ($P = .006$; Table 3). In the model for dbh, trunk damage had a positive though nonsignificant influence on dbh ($P = .089$; Table 3). Tree location (street) had a statistically significant positive influence on dbh and CPA ($P < .001$) and a statistically significant negative influence on BRATIO ($P < .001$; Table 3). In terms of R^2 values, the CPA model explained the most amount of observed variation, approximately 66%, and the BRATIO model explained the least amount of variation, approximately 18% (Table 3).

The effect of species differed in significance and magnitude depending on the response variable under investigation. Mean TPI and mean CPA were highest for honeylocust and lowest for linden as pervious surface area increased (Figure 1b and d). Hackberry had the largest mean dbh when pervious surface area was approximately 100 m² or greater (Figure 1a), whereas linden had the highest BRATIO compared with other species at the same levels of pervious surface area (Figure 1c). Pervious surface area under the canopy had the steepest slope for Norway maple and linden in terms of BRATIO (Figure 1c).

Discussion

Influence of Site Factors on Tree Performance

Urban tree performance has previously been evaluated using measures of canopy, dbh, or growth increment (Iakovoglou et al. 2001, Day and Amateis 2011, Sanders et al. 2013, Sanders and Grabosky 2014, Dahlhausen et al. 2016, Sherman et al. 2016). Here, we used linear models to assess tree performance through analysis and comparison of dbh, CPA, BRATIO, and TPI. Variables important in explaining tree performance differed across the metrics evaluated (Table 3). Pervious surface area was statistically significant and positively related to increased dbh, CPA, and TPI (Table 3, Figure 1). Although pervious surface area did not add to the explanatory power in the final model of BRATIO, park trees had a larger pervious surface area on average (Table 1) than street trees, and the mean BRATIO was higher for park trees than for street trees (Table 3), suggesting that increased pervious surface area improved BRATIO.

Even though the pervious surface area under the canopy for street trees was substantially smaller than for park trees (Table 1), street trees had a statistically larger mean dbh, after controlling for age, and a larger mean CPA than park trees (Table 3). This was unexpected and contrary to previous studies where trees in unrestricted growing spaces were larger on average (Iakovoglou et al. 2001, Day & Amateis 2011, Sanders et al. 2013, Sanders and Grabosky 2014, Dahlhausen et al. 2016, Sherman et al. 2016). Potential explanations for the observed difference in size are discussed in the section "Tree Performance Metrics."

In our models, soil compaction had a negative influence on dbh, CPA, BRATIO, and TPI (data not shown), but only improved the explanatory power for the final model of BRATIO, although soil compaction was not statistically significant (Table 3). Soil compaction above 2.3 MPa has been shown to negatively impact root growth (Day and Bassuk 1994), and water infiltration into compacted soils is limited

Table 2. Results of two-way factorial ANCOVA for the influence of site, species, and their interaction, controlling for age, on mean diameter at breast height (dbh), canopy projection area (CPA), ratio of the average basal area increment (BAI) over the last 10 years of growth divided by the average BAI over the life of a tree (BRATIO), and tree performance index (TPI).

	dbh (cm)		CPA (m²)		BRATIO		TPI	
Species	Street	Park	Street	Park	Street	Park	Street	Park
Norway maple	45.0(a)	43.3(a)	88.6(a)	82.4(a)	1.1(a)	1.4(b)	1.0(a)	1.1(b)
Hackberry	46.0(a)	42.3(a)	107.5(a)	99.3(a)	1.3(a)	1.4(a)	1.0(a)	1.2(b)
Honeylocust	48.4(a)	38.2(b)	147.6(a)	101.4(b)	1.3(a)	1.6(b)	1.1(a)	1.3(b)
Linden	46.8(a)	46.4(a)	75.5(a)	74.7(a)	1.5(a)	1.6(a)	0.9(a)	1.0(b)
All species	46.6(a)	42.6(b)	104.8(a)	89.5(b)	1.3(a)	1.5(b)	1.0(a)	1.1(b)

Note: Different letters in parentheses in a row under a growth metric column (e.g., dbh) indicate statistical differences between street and park trees for within a species. Tukey's honestly significant difference test with $\alpha = 0.05$. $N = 292$.

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Table 3. Final linear models examining the influence of pervious soil surface area, soil compaction, tree age, present of stem girdling roots, present of trunk damage, trees species, and site on canopy projection area (CPA), ratio of the average basal area increment (BAI) over the last 10 years of growth divided by the average BAI over the life of a tree (BRATIO), and tree performance index (TPI).

	Tree performance metrics			
Variables	dbh (cm)	CPA (m^2)	BRATIO	TPI
Intercept	16.92 (1.92)***	−14.50 (5.87)*	1.445 (0.104)***	1.1779 (0.0463)***
Pervious surface area (m^2)	0.15 (0.01)***	0.90(0.05)***		0.0017 (0.0002)***
Soil compaction (MPa)			−0.025 (0.019)	
Tree age	0.22 (0.03)***		0.002 (0.001)	−0.0039 (0.0009)***
Stem girdling roots			−0.093 (0.047)*	−0.0509 (0.0286)
Trunk damage	2.45 (1.43)		−0.094 (0.068)	−0.1163 (0.0413)**
Hackberry	−0.56 (1.31)	11.56 (4.46)*	0.069 (0.065)	−0.0233 (0.0393)
Honeylocust	−1.89 (1.28)	28.18 (4.40)***	0.155 (0.064)*	0.0388 (0.0393)
Linden	3.46 (1.25)**	−7.37 (4.43)	0.274 (0.059)***	−0.1441 (0.0364)***
Site: street tree	15.97 (1.35)***	85.45 (4.93)***	−0.341 (0.063)***	
Adjusted R^2	0.48	0.66	0.18	0.26

Note: Standard errors presented in parentheses. $N = 292$.
*** $P < .001$.
** $P < .01$.
* $P < .05$.

(Gilman et al. 1987, Gregory et al. 2006, Bartens et al. 2008); however, the influence of soil compaction on aboveground metrics of tree growth has been more difficult to demonstrate statistically. Other studies have used bulk density to assess soil compaction with varying statistical significance (Hodge and Boswell 1993, Iakovoglou et al. 2001, Day and Amateis 2011), although most studies suggest that increased compaction or bulk density has a negative influence on growth. Soil compaction in our study sites had a relatively uniform distribution and may not have had enough variability to detect statistical differences. Soil moisture was only coarsely accounted for, and compaction measurements would likely have improved if paired with soil moisture measurements at each site.

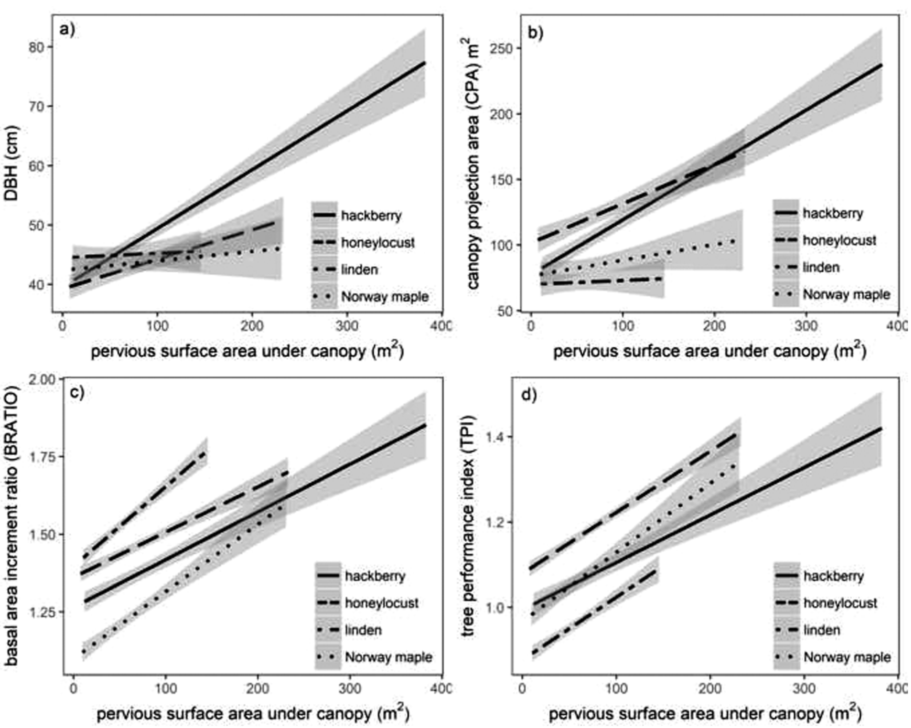

Figure 1. Final model output of mean diameter at breast height (DBH), canopy projection area (CPA), basal areas increment ratio (BRATIO), and tree performance index (TPI) for available pervious surface area by species, based on model results presented in Table 3. Gray bands represent a 95% confidence interval. $N = 292$.

Influence of Tree Factors on Tree Performance

The negative influence of stem girdling roots on BRATIO and TPI (Table 3) is consistent with existing research that has shown a reduction in aboveground growth when stem girdling roots are present (Hulder and Beale 1981, Wells et al. 2006). Trunk damage was included in the final models for dbh, BRATIO, and TPI (Table 3). Not surprisingly, trunk damage had a negative influence on BRATIO and TPI, consistent with previous findings where damage to or loss of cambium resulted in reduced tree growth and stability (Hauer et al. 1994, Shortle et al. 2003). Unexpectedly, trunk damage was positively associated with mean dbh (Table 3). A plausible explanation for the positive relationship between trunk damage and dbh is an increase in diameter from the formation of callus tissue and reaction wood produced by trees to remain mechanically stable following an environmental stress (Shigo 1983, Du and Yamamoto 2007). Another possible explanation for the positive trunk damage and dbh relationship is the removal of severely damage trees, leaving only the most vigorous trees.

Species results varied based on the performance metric assessed. Honeylocust had the highest performance in CPA and TPI, and the second highest performance in BRATIO, but the lowest performance in dbh models (Table 3, Figure 1c). This suggests that honeylocust has a high potential to

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sustain growth in a variety of environments and maintain a large canopy, both excellent characteristics for providing benefits in urban environments. High performance of honeylocust in urban environments has been noted by other researchers (Koeser et al. 2013, Swoczyna et al. 2015). Linden showed the highest performance in models of dbh and BRATIO, but the lowest in terms of CPA and TPI. Lower performance of linden in CPA is likely due to the oval or pyramidal canopy morphology (Wandell 1989, Sullivan 1994) reducing the CPA in comparison with other species. Although differences in performance between species were observed, within-species differences between sites may be more relevant for urban forest managers seeking to maintain diversity, whereas selecting appropriate planting sites for specific species as species diversity in urban forests is a desirable management object to limit the impact of exotic pests (Ball et al. 2007, Vecht and Conway 2015). An example of the value in species-specific site selection is the steep increase in BRATIO for both linden and Norway maple as pervious surface area under the canopy increased (Figure 1c), suggesting that both species are highly sensitive to restrictive growing spaces in terms of potential sustained growth.

The positive influence of age on dbh and BRATIO (Table 3) was consistent with expectations as dbh and BAI increase with age (Johnson and Abrams 2009). In the TPI model, age had an inverse but small influence as younger trees outperformed older trees on average (Table 3), which may indicate a slight decline in the balance of photosynthetic area to nonphotosynthetic area as trees age or are pruned. Incorporating measures of canopy density may help to improve the utility and explanatory power of TPI models.

Tree Performance Metrics

In the model of dbh, pervious surface area and age were positively related to larger mean dbh (Table 3 and Figure 1a). This initially appears consistent with Sanders et al. (2013) where they showed a positive relationship between available soil surface area and dbh. However, results from Table 3 also show that street trees had a larger mean dbh than park trees of the same age, even though street trees had less available pervious surface area than park trees (Table 1), which contradicts the results in Sanders et al. (2013). Street trees also outperformed park trees in mean CPA (Table 3) counter to previous studies that have shown that trees growing in restricted spaces have smaller canopies on average (Day and Amateis 2011, Sanders and Grabosky 2014). A limitation of our results is that the study area only included street trees planted in residential areas where soil filled the space between sidewalk and curb (e.g., no grates or tree pits), and there were no overhead obstructions (e.g., utility lines), which may not reflect planting conditions in other cities. Our observed size differences may not be found where street trees are in more restrictive environments with a variety of stressors not encountered in the study area. Also, no consideration was given to potential growth differences between cultivars used along streets versus those used in parks.

While our data cannot be used to directly determine why street trees had a larger mean dbh and mean CPA than park trees, a possible causal mechanism could be increased stormwater or irrigation runoff infiltrating into street planting trips under tree canopies. Impervious surfaces (e.g., sidewalks and buildings) can increase the amount of surface runoff from precipitation directed to a city's stormwater drainage system (Han and Burian 2005, Yao et al. 2016). Historically, the majority of growing-season precipitation events occurring in Minneapolis and Saint Paul are less than 3 cm (Fisk 2017), much of which may be intercepted by a tree's canopy and not infiltrate into soils directly beneath the canopy. For low-volume precipitation events at a park, a significant portion of precipitation that reaches the ground is absorbed and transpired by turf grass (Peters et al. 2001), resulting in less precipitation reaching the root zone of park trees. Further research in urban hydrology is required to verify this hypothesis.

Crown raising is another possible explanation for the observed larger CPA in street trees as carbon accumulation is temporarily diverted from the trunk to support expansion of the canopy in response to pruning. Minneapolis and Saint Paul street trees have their crowns raised to a minimum height of approximately 5 m to accommodate traffic, whereas park trees were observed with crowns lower than 5 m (data not presented). Pinkard et al. (1998) found that canopies increased in size for *Eucalyptus nitens* (H. Deane & Maiden) 2 years after their crowns were raised if at least 50% of the canopy was maintained. Carbon diverted from the trunk to canopy for street trees could also help to explain the statistically higher mean values for BRATIO and TPI of park trees than street trees (Table 2). Additional research on the effects of crown raising on the development of canopy in terms of size and condition would improve our understanding of the impacts of pruning approaches on urban tree performance.

Park trees significantly outperformed street trees for BRATIO and TPI (Table 2 and 3). Both BRATIO and TPI metrics incorporate growth trends, which suggests that whereas street trees are larger, park trees have a greater potential for increased longevity, which is consistent with previous studies investigating growth trends (Dobbertin 2005, Das et al 2007). Our results were also consistent with Scharenbroch et al. (2017) who found a statistically significant relationship between reduced recent annual increment (RAI) and lower site quality, although only ~3% of the variation in RAI was explained using the RUSI model. Both BRATIO and TPI incorporated measures of recent growth relative to past growth with models accounting for 18% and 26% of the observed variation, respectively (Table 3). Poor-quality sites and unfavorable environmental conditions can predispose trees to greater stress (Manion 2001), and trees under stress have been shown to have reduced-diameter growth and increased mortality (Waring 1987, Dobbertin 2005, Das et al. 2007, Drobyshev et al. 2007, Voelker et al 2008), which provides a biological explanation for the final models for BRATIO and TPI. Voelker et al. (2008) found that lower values of TVI indicated poor tree vigor, and lower relative values of BRATIO and TPI may indicate future tree performance similar to TVI. A meaningful management threshold of BRATIO might be a value of 1, as values below 1 would indicate that recent growth is declining relative to past growth. Future research should consider long-term monitoring to confirm the predictive value of BRATIO and TPI. Additional research is also needed to establish a minimum acceptable threshold for TPI and test the utility of TPI and BRATIO in a broader range of urban environments.

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Conclusion

Understanding urban tree growth is an important tool not only for managers of urban forests, but also for designers of urban infrastructure as the built environment often contains highly variable sites. The ability to anticipate the growth response of trees over time in different sites can assist urban foresters and natural resource managers to select and manage trees more effectively to meet objectives. A growing number of studies investigating urban tree performance based on site characteristics using different tree performance metrics (Hauer et al. 1994, Iakovoglou et al. 2001, Sanders et al. 2010, Day and Amateis 2011, Dahlhausen et al. 2016, Sherman et al. 2016, Scharenbroch et al. 2017) indicate the value in urban site assessments and highlight a need for a standardized tree performance metric. The adaptation of TPI from TVI (Voelker et al. 2008) was our attempt to create a unified performance metric capable of quantifying tree performance in urban environments by incorporating tree architecture and growth rate. However, BRATIO is perhaps a simpler metric for assessment of tree performance that could be combined with a tree condition assessment for similar results as TPI. Our models incorporating simple site characteristics provide evidence that BRATIO and TPI predicted tree performance consistent with the findings of previous research (Iakovoglou et al. 2001, Day & Amateis 2011, Sanders et al. 2013, Sanders & Grabosky 2014, Dahlhausen et al. 2016, Sherman et al. 2016, Scharenbroch et al. 2017). For urban site assessments to provide meaningful and broadly applicable results, a standardized tree performance metric should be combined with a standard set of site factors. The RUSI model developed by Scharenbroch et al. (2017) established excellent criteria for a standard set of site factors. Combining site factors proposed in the RUSI model (Scharenbroch et al. 2017) with TPI or BRATIO may provide a more complete picture of urban tree performance.

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