Resolving uncertainties in predictive equations for urban tree crown characteristics of the southeastern United States: Local and general equations for common and widespread species

A. BLOOD¹, G. STARR², F. J. ESCOBEDO³, A. CHAPPELKA⁴, P. E. WISEMAN⁵, R. SIVAKUMAR⁶, and C.L. STAUDHAMMER^{7*}

¹ Department of Biological Sciences, University of Alabama. Email: amymblood@gmail.com

² Department of Biological Sciences, University of Alabama. Email: gstarr@ua.edu

³ Universidad del Rosario, Faculty of Natural Sciences and Mathematics, Biology Program, Functional and Ecosystem Ecology Unit, Colombia. Email:

franciscoj.escobedo@urosario.edu.co

⁴ School of Forestry and Wildlife Sciences, Auburn University. Email: chappah@auburn.edu

⁵ The Department of Forest Resources and Environmental Conservation, Virginia Tech. Email: pwiseman@vt.edu

⁶ Center for Geographic Information Systems, College of Architecture, Georgia Tech. Email: siva@coa.gatech.edu

⁷ Department of Biological Sciences, Box 870344, University of Alabama, Tuscaloosa, AL. Email: cstaudhammer@ua.edu

*corresponding author

Urban forest research and management requires improved methods for quantifying ecosystem structure and function. Regional equations for urban tree crown width and height can accordingly improve predictions of urban tree structure. Using a large regional dataset with 12 locations in the southeastern US, we developed diameter-based equations for 97 urban tree species. Whereas previously published urban equations have almost exclusively been developed with one location on public or commercial land, our data included both public and private land uses. For 5 widespread, common urban tree species (*Acer rubrum*, *Cornus florida*, *Pinus taeda*, *Quercus nigra* and *Lagerstroemia* spp.), we also assessed the inclusion of additional variables such as crown light exposure, land cover, basal area, and location. Overall, height and crown width models were improved when including additional predictors, although competition and location effects varied by species. Study city was a significant predictor of tree height in all species except *C. florida*, and a significant predictor of crown width for all species except *C. florida* and *Q. nigra*. This indicates that anthropogenically-influenced variation among cities can lead to significant differences in both tree form and structure and that future model development should utilize data encompassing multiple cities. Our predictive equations for urban tree crown characteristics provide an improved method for planning, management, and estimating the provision of ecosystem services to improve quality of life in cities.

Keywords: urban tree allometry; urban forest sampling; tree inventory; crown width, tree height

Introduction

Understanding urban forest structure is of growing concern given that over 66% of the world's population will live in urban areas by 2050 (UN, 2015). Central to sustainable urbanization is the conservation of natural resources and the development of green infrastructure and associated policies that equitably provide benefits and protect the environment (UN, 2015). Urban forests are an element of green infrastructure that provide a variety of essential ecosystem services including decreasing air, water, and noise pollution, mitigating flood risk, and providing recreational areas (Escobedo et al., 2011; Roy et al., 2012). Urban trees also help mitigate climate change by sequestering carbon and reducing the urban heat island effect (Kleerekoper et al., 2012). Additionally, urban forests are aesthetically pleasing and provide habitat for wildlife (Melles et al., 2003). Proper planning and management of these forests are essential for the overall optimization of a community's greenspace benefits as well as for reducing ecosystem disservices and associated costs (Escobedo et al., 2011; Roy et al., 2012).

Information on urban forest structure can be used to inform management activities, determine ecosystem services, characterize diversity, and quantify pest resistance and/or damage (Keller and Konijnendijk, 2012; Martin et al., 2011; Nielsen et al., 2014). In particular, tree height and crown width determine the amount of shade cast by trees, which reduces surface and atmospheric temperatures in cities and thereby conserves energy used for cooling buildings (McPherson, 1994; McPherson and Simpson, 1999; Shashua-Bar and Hoffman, 2000). Height and crown width are also strongly related to total tree biomass and leaf area, which influence the amount of carbon dioxide and pollutants that trees remove from the atmosphere (Nowak et al., 2008).

Unfortunately, tree height and crown width measurements, although necessary for quantifying biomass and ecosystem services, may be omitted from urban forest inventories due to the labor-intensive nature of these measurements (Bechtold et al., 2002; Nielsen et al., 2014; Nowak, 2008). Alternatives to taking these measurements, such as allometric or empirical predictive equations, free up labor to document other relevant tree attributes during an inventory (Bechtold et al., 1998, 2002). Because the various physical attributes of trees are highly correlated, an easy-to-measure variable, such as trunk diameter at breast height (DBH), can be used to predict tree height and crown width. Although an abundance of predictive equations have been developed for trees in natural forests (Bechtold, 2003a; McHale et al., 2009; Zhang, 1997), very few equations have been developed for urban trees.

Trees in urban forests experience different growing conditions and management regimes than their counterparts in natural forests. They tend to be open-grown (affording more crown space and light exposure), yet often occupy a very small volume of low-quality soil. Moreover, their crown forms may differ from natural forest trees, as they often grow in more open conditions, and pruning is common for aesthetic or safety reasons (e.g., to prevent encroachment on roadways, sidewalks, buildings, and power lines). Differing growing conditions and crown forms make predictive equations for natural forest trees unsuitable for trees in urban forests (McHale et al., 2009; Rust, 2013; Troxel et al., 2013). Additionally, due to the variability of site types, environmental constraints, and need to ensure species diversification (Bassuk, 1990), a broad species palette is often used in urban environments. Therefore, many commonly occurring species in urban regions are uncommon in natural forests and thus have never been modeled.

Urban tree height and crown width models using DBH as an independent variable have been developed for many areas of the world, but equations specifically describing height and

crown width of urban trees are far less common than those for natural forests. In traditional forestry applications, site-specific models are often complemented with regional models to enable estimation of crown attributes. For example, large-scale, regional crown width models were produced for 87 stand-grown species across the eastern United States (Bechtold, 2003a) and 53 stand-grown species across the western United States (Bechtold, 2004). However, there are few regional models for urban tree attributes comprising data from more than one locality. Community tree guides are publicly available (McPherson et al., 2007, 2002), allowing users to quantify benefits and costs of regionally specific tree planting projects. These guides give basic growth curves (using years since planting) for predominant species in many regions, but generally only use one city to represent a region. Because maintenance practices, climate, and soils are quite variable across geographic regions, city-specific models are not widely applicable for a region (McPherson and Peper, 2012). Yet tree height and crown width, modeled using height–DBH relationships from a single reference city, are regularly used in applications such as i-Tree to predict and estimate ecosystem services (air quality improvement and energy conservation) of urban forests across regions (McPherson and Peper, 2012; Nowak et al., 2008).

Measures of stress and competition are not commonly incorporated into predictive equations for urban tree height or crown width, despite evidence this has a significant effect on urban trees. For example, relative crown radius and trunk size was found to relate to size of planting space in parking lots (Day and Amateis, 2011; Grabosky and Gilman, 2004; Sanders and Grabosky, 2014). Urban tree size was also found to be positively correlated to an urban soil quality index, based on soil organic matter, pH, and texture (Scharenbroch and Catania, 2012). Thus, competition, resource limitation, and environmental stressors are significant predictors of crown attributes in forests (Bragg, 2001; Uzoh and Oliver, 2006).

An investigation into what factors may influence differential height or crown form for urban trees will increase our understanding of urban forest structure and function. To date, most of the published predictive equations for urban trees in the international literature have been based on publicly-owned and maintained trees (Frelich, 1992; Martin et al., 2012; North, 2013; Peper et al., 2014; Rust, 2013; Semenzato et al., 2011); other studies have used nursery trees (Larsen and Kristoffersen, 2002) or those found in parking lots (Grabosky and Gilman, 2004; Sanders and Grabosky, 2014; Stoffberg et al., 2008). However, privately owned and residential trees make up a substantial portion of the urban forest; over 60% of Miami-Dade's tree population were located on private lands (Zhao et al., 2010). Thus, equations for private, non-street trees are essential to understand the entire urban forest and the ecosystem services they provide.

Given this lack of information, the aim of our study was to create species-level, trunk diameter-based regional equations for urban tree crown characteristics using a large regional dataset for the southeastern United States (SEUS). Our first objective was to develop tree height and crown width models based on DBH for common species in the SEUS. Our second objective was to investigate the explanatory power of additional predictors in these equations to determine how factors such as light availability, tree density, local basal area, and geographic location may influence urban tree attributes. We hypothesized that additional variables would increase the explanatory power and precision of predictions when compared with models that only included DBH measurements. We expected that crown light exposure would be a strong predictor in the models due to its incorporation of anthropogenic competition (e.g., buildings) for light and that local tree density and basal area would also increase the explanatory power of models. Lastly, location variables including land cover and municipality were included in this study to determine

if there were significant differences among cities and land use types that affect these relationships. We hypothesized that due to variability in and between urban forests, models would differ significantly with land cover and municipality. Understanding inaccuracies within and limits to models will help city foresters better quantify the benefits and costs of their urban forests.

Methods

Data Acquisition

Tree inventory data were collected by independent research groups in 12 cities between 2008 and 2014 (Table 1). In 2015, the data were compiled into the Southeastern Urban Tree Database, as part of a collaborative project sponsored by the Southern Research Station of the USDA Forest Service and several universities, and maintained by the University of Alabama. Trees in nine localities (five in Virginia, four in Florida) were inventoried using randomly sampled 0.04 ha plots. In four cities in Florida, plots were installed randomly across varied urban land uses, such as residential, institutional, and commercial (for Gainesville, Miami-Dade County, and Pensacola, respectively; see: Escobedo et al., 2015; Lawrence et al., 2012; Timilsina et al., 2014; Zhao et al., 2010). One location in Virginia (Falls Church) was sampled using a randomized grid, whereas the other four Virginia locations (Charlottesville, Abingdon, Winchester, and Roanoke City; Wiseman, 2012), as well as east Orlando, Florida were sampled using stratified random sampling, stratifying by land use (Horn et al., 2015). Additionally, complete censuses were conducted for the maintained trees on three college campuses: Auburn University (Auburn, AL; Martin et al., 2011), the University of Georgia (UGA, Athens, GA), and the Georgia Institute of Technology (Georgia Tech, Atlanta, GA).

- 1 Table 1. Site descriptions for urban tree data collection locations. Climate data were obtained from Arguez et al. (2012); elevation data
2 were obtained from USGS (2015). Ecological section and province were defined by USDA Forest Service ecozones (Bailey, 1998).
3 *Location data comes from a nearby city.

Location (Study area)	# Plots measured	# Plots containing Trees	# Trees	Avg Rainfall (cm)	Avg Min Temp (°C)	Avg Max Temp (°C)	Avg Elevation (m)	Ecological Section	Ecological Province
Winchester (WIN): Winchester city limits	88	56	336	97	6.6	17.7	233	Northern Ridge & Valley (NRV)	Central Appalachian Broadleaf Forest-Coniferous Forest- Meadow (CABF)
Falls Church (FC): Falls Church city limits*	38	31	178	113	7	17.6	101	Southern Appalachian Piedmont (SAP)	Southeastern Mixed Forest (SMF)
Charlottesville (CHA): Charlottesville city limits	74	59	409	108	7.1	19.2	137	Blue Ridge Mountains	CABF
Roanoke (ROA): Roanoke city limits	171	114	1627	105	8.1	19.6	337	NRV	CABF
Abingdon (AB): Abingdon town limits	73	39	279	116	5.7	18.7	641	NRV	CABF
UGA: University of Georgia	Census	Census	8063	118	10.8	23.2	206	SAP	SMF
Georgia Tech (GT): Georgia Institute of Technology	Census	Census	11307	126	11.8	22.2	288	SAP	SMF
Auburn (AU): Maintained areas of Auburn University	Census	Census	8533	136	11.3	23.8	201	SAP	SMF
Pensacola (PEN): The greater Pensacola area	78	60	658	166	15.1	24.8	16	Florida Coastal Lowlands	Outer Coastal Plain Mixed Forest (OCP)
Gainesville (GNV): Gainesville city limits	65	51	689	120	14.3	26.7	42	CPF	OCP
East Orlando (ORL): 200 km ² around an Eddy flux tower centered at 28° 35' 33.54" N and 81° 12'0.34" W	96	78	732	129	17.1	28.2	18	Coastal Plains & Flatwoods (CPF)	OCP
Miami-Dade (MIA): Miami- Dade county	229	135	1202	157	21.2	29.1	2	Everglades	Everglades

- 4 Avg, Average; Min, Minimum; Max, Maximum

All data were collected using the i-Tree Eco protocol (Nowak et al., 2008), a standard sampling and inventory protocol that has been used extensively in urban forests throughout the world (<https://www.itreetools.org/about.php>). Each tree or palm with DBH greater than 2.5 cm was measured and its species name recorded. In cases where trunk diameter was measured at a height other than 1.37 m above ground level, the measurement height was recorded. The six largest diameters were recorded for multi-stemmed individuals such as *Lagerstroemia*. Height was measured with a clinometer, hypsometer, or tree height pole, depending on the location. Crown width was measured in two cardinal directions and averaged. Following the i-Tree Eco protocol, crown light exposure (CLE) was estimated using the methods of Bechtold (2003b) to account for the effects of shading from competing trees and non-tree objects (e.g., buildings). A value of 0 indicated that a tree would receive no sunlight when the sun was directly overhead, and a value of 5 indicated that the tree would have sunlight on all five sides of the tree, including the top.

Land use was also recorded, but due to the user-defined nature of these measurements, it was not included in these analyses. Instead, land cover (LC) was extracted from the 2011 National Land Cover Database (Homer et al., 2015) based on plot or tree-level location. We grouped these into five LC classifications: high-intensity developed, medium-intensity developed, low-intensity developed, open space developed, and non-developed. Due to low numbers of observations, the non-developed class included all other classifications such as forests, shrubland, and herbaceous. Additionally, plot and tree locations were used to calculate Hopkin's bioclimatic index (HI) following Bechtold (2003a, 2004). This variable expresses the delay in spring relative to the average among sampling locations (Hopkins, 1938). The average

latitude, longitude, and elevation were used in the calculation of HI; therefore, the index is relative to the average of the tree locations encompassed by the data:

$$HI = \frac{(Elevation - 222)}{30.5} + (Latitude - 33.3148) * 4 + (-84.2870 - Longitude) * 1.25$$

Thus, spring is delayed four days for every degree of longitude west of -84.2870, 1.25 days for every degree latitude north of 33.3148, and one day for every 30.5 m (100 ft) in elevation greater than 222 m.

Tree-level variables included in models were: DBH, local tree density, and local basal area. In cases where a tree had multiple stems, the quadratic mean diameter was used as DBH. Local basal area (BA; m²/ha) and tree density (TPH; stems/ha) were calculated using trees and palms recorded in each 0.04 ha plot. For census (i.e. non-plot) data, BA and TPH were calculated using a 0.04 ha plot constructed from a spatial dataset with each tree as the center.

At the time of analysis, the database contained measurements on 34,013 trees from more than 400 unique species across twelve localities in the SEUS (Figure S.1; Table S.1-S.2). The database included 202 species with at least 10 individuals measured; 35% of these species had >100 individuals measured (Table S.1).

Data Analysis

Regional Equations

Trunk-diameter-based models of crown width and tree height were estimated at the species-level. However, not all 400+ species in the database had sufficient data, both in total number of trees and in number of locations represented across the region. So, species were selected for model estimation if they met the following requirements:

1. At least 30 trees were present in the database with non-missing measurements for height, crown width, and DBH;
2. Measurements were present in at least two locations;
3. Stem diameter was measured between 1.2 and 1.5 m from the ground;
4. At least 10% of trees measured were greater than 6 m in height;
5. The tree species was not a monocot (e.g., palms).

An arbitrary cutoff of 30 trees was based on the common statistical rule for stability, while including a minimum of two locations ensured that species were regionally relevant and mitigated bias related to any single location's management practices. Although adjustments can be made for non-standard DBH height measurements, taper equations required to do this do not exist for most urban tree species; thus, using only measurements made at a standard DBH height minimized the impact of taper. The tree height cutoff prevented inclusion of shrub-like species, whereas exclusion of monocots limited our selection to woody species. Palms were excluded because they exhibit diffuse secondary growth and have distinctly different relationships between trunk diameter, height, and crown spread, all of which introduce error into models.

Of the 34,013 trees in the database, the vast majority (93%) were identified to the species level and remaining trees (7%) were identified to the genus level. In all but one case, we utilized only data from trees with species-specific identification. Because of difficulty differentiating among species in the genera *Lagerstroemia* (crapemyrtle), about half of these trees were only identified to the genus level. Therefore, we consolidated all trees identified as *Lagerstroemia* spp. and *Lagerstroemia indica* (the most common species) into *Lagerstroemia* spp..

We excluded 300 species which had fewer than 30 individuals measured. Several species had large numbers of individuals but were only present in one location and were also excluded

from analyses. For example, *Melaleuca quinquenervia* occurred in very high numbers in the dataset; however, since all observations occurred on a single plot at a single location (Miami-Dade), models for this species were not estimated. In total, eleven species were excluded due to a lack of sufficient locations. The exclusion of shrub-like species precluded six species of small woody plants from being modeled, whereas the exclusion of palms prevented two species of cycads, mostly in Miami-Dade from being modeled. In sum, height and crown width equations were developed for 97 woody tree species.

Based on published literature (Table 2), seven model forms were selected and tested to predict height and crown width of each species, using DBH as the independent variable (Peper et al., 2014; Sit and Poulin-Costello, 1994; Troxel et al., 2013; Zhang, 1997). All forms were evaluated with a natural log-transformed dependent variable in order to meet the assumptions of non-linear regression. Model coefficients for each species were estimated via non-linear least squares using the SAS procedure PROC NLIN (version 9.3). Equations were estimated for each species and tested to ensure that models met the assumptions of normality and homoscedasticity of the residuals. We validated model parameter estimates using a leave-one-out cross-validation approach (Picard and Cook, 1984). Models were evaluated and compared in terms of average absolute residuals, root mean square error (RMSE), and Akaike Information Criteria for small sample sizes (AICc; Akaike, 1981).

Effects of Location, Land Cover, and Competition Metrics

To investigate the influence of competition metrics and location on tree crown characteristics, we utilized a subset of five tree species, with data that were extensive across locations and land cover classes. The species *Acer rubrum*, *Cornus florida*, *Lagerstroemia* spp., *Pinus taeda*, and *Quercus nigra* all had >750 observations, with ≥ 5 trees in at least 6 of the 12

locations (Table 3) to ensure that the trees modeled were representative of the region. Locations where we found <5 individuals for a particular species were excluded for that species (e.g., *Q. nigra* in Miami-Dade). To facilitate comparisons, we utilized the logarithmic model form, since it was the best (or nearly best) predictive model for each of these five species. Utilizing a linear model with natural log-transformed dependent variables, we assumed that tree height and crown width would track linearly with ln(DBH), HI, TPH, and BA. CLE, LC, and City were included as class variables, and the interactions between variables and ln(DBH) were also investigated as possible parameters.

Table 2. Model forms, names, and sources for tested models of tree height and crown width (DBH=diameter at breast height; measured 1.37 m from the ground; Y=tree height or crown width). For Gompertz, Exponential, and Weibull height models, *a* was held constant at ln(DBH) height (0.315 m) to enable model convergence. Sources: ¹Zhang 1997; ²Sit and Poulin-Costello 1994; ³Peper et al. 2014; ⁴Troxel et al. 2013.

Model Form	Model Name	Model Source
[1] $\ln(Y) = a + b * e^{(-c * e^{(-d * DBH)})}$	Gompertz	1, 2
[2] $\ln(Y) = a + b * e^{\frac{-c}{DBH+d}}$	Exponential	1
[3] $\ln(Y) = a + b * [1 - e^{(-c * DBH^d)}]$	Weibull	1, 2
[4] $\ln(Y) = a + b * \ln(\ln(DBH + 1))$	Loglog	3
[5] $\ln(Y) = a + b * \ln(DBH) + c * DBH^2$	Quadratic	4
[6] $\ln(Y) = a + \frac{DBH}{b + c * DBH}$	First Degree Inverse Polynomial (FDIP)	2
[7] $\ln(Y) = a + b * \ln(DBH)$	Logarithmic	2
[8] $\ln(Y) = a + b * e^{c/DBH}$	Type III Exponential (T3 Exp)	2

The parameters in the best-fit models for each species were determined via the SAS procedure PROC MIXED using a manual step-wise procedure. Variables with the highest p-values (most non-significant; $p > 0.05$) were removed until further removals increased the AICc value by more than two points. Where significant, the effects of variables on tree height and crown diameter were investigated. Least square (marginal) means were generated for each

significant variable, holding all other variables in the model at their average values, to facilitate comparisons, especially where interactive effects were indicated. For categorical variables, effect levels were further compared with post-hoc comparisons via Tukey's HSD test at $\alpha=0.05$ level.

Table 3. Descriptive statistics for five tree species selected for modeling height and crown width using additional effects for location, land cover, and competition metrics.

Species	# of Locations (≥ 5 trees)	<i>n</i>	Hopkin's Bioclimatic Index			Tree Density (stems/ha)			Local Basal Area (m ² /ha)		
			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
<i>Acer rubrum</i>	11	1358	0.74	-29.84	25.57	249	25	3800	7.8	0.01	69.6
<i>Cornus florida</i>	10	807	3.96	-23.32	25.51	286	25	1475	14.2	0.01	61.6
<i>Lagerstroemia</i> spp.	8	2801	-0.53	-29.52	24.40	139	25	1600	5.4	0.04	43.0
<i>Pinus taeda</i>	6	1691	-0.54	-29.65	4.65	572	25	2600	21.2	0.03	81.5
<i>Quercus nigra</i>	6	1220	-1.52	-42.37	4.80	348	25	2675	21.6	0.04	72.3

Results

Tree height in the database ranged from 1.0 m to 45.7 m (Table S.1). The average crown width of urban trees in the database was 6 m, but exceeded 30 m in several *Quercus* and *Ulmus* species. Tree species with the largest diameter ranges were *Populus deltoides*, *Quercus phellos*, and *Q. nigra* (Table S.1). *Pinus taeda* had the greatest height range, followed by *Liriodendron tulipifera*. The species with the largest range in crown widths was *Quercus nigra*. On average, the largest trees were found in Falls Church (in terms of DBH and crown width) and Gainesville (in terms of height), while the smallest trees by every metric were found in coastal Miami-Dade, although the average DBH in Miami-Dade was the same as in coastal Pensacola (Table S.2).

Regional Height and Crown Width Equations

The best-fit model form varied considerably among species (Figure 1; Table 4). The logarithmic form was the most common model for crown width and tree height, chosen for 27 and 19 species, respectively. There was no consensus in model form at the genus level. For instance, of the 19 *Quercus* height models estimated, the most common best-fit models were logarithmic and Weibull (4 species), followed by T3 Exponential (3 species). Gompertz and FDIP were each selected for just one species of *Quercus*. Whereas Weibull was common for *Quercus* height, no crown width models for the genus were best described with the Weibull equation; most *Quercus* best-fit crown width models were logarithmic (6), quadratic (5), and FDIP (5). For many species, there was more than one model for height (73 species) and crown width (79 species) that could be considered “best”, as determined by AICc with values within two points (e.g., crown width for *Cornus kousa*). In these cases, the chosen model had the lowest RMSE value, indicating better precision for the given data.

Figure 1. Best-fitting model forms for height and crown width for 97 urban tree species in the southeastern United States. Model equation form and sources are listed in Table 2.

146 Table 4. Best-fit equations and their corresponding model parameter estimates for height and crown width for 97 common urban tree
 147 species in the Southeastern US. Model equations and sources are listed in Table 2.

Species	Crown Width (m)						Tree Height (m)					
	Best Equation	Parameter estimates				RMSE	Best Equation	Parameter estimates				RMSE
		<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>			<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	
<i>Acer barbatum</i>	T3 Exponential	0.77	3.64	-24.93		0.26	Quadratic	1.09	0.26	9.2E-04		0.22
<i>Acer buergerianum</i>	Logarithmic	-0.26	0.71			0.18	Logarithmic	0.71	0.48			0.20
<i>Acer negundo</i>	Logarithmic	-0.12	0.67			0.35	Loglog	0.73	1.39			0.27
<i>Acer palmatum</i>	Loglog	-0.11	1.71			0.31	Loglog	0.32	1.17			0.27
<i>Acer platanoides</i>	Logarithmic	0.45	0.48			0.36	Weibull	0.32	2.17	0.31	0.69	0.25
<i>Acer rubrum</i>	FDIP	5.0E-3	4.08	0.32		0.24	Quadratic	0.71	0.52	-1.9E-5		0.23
<i>Acer saccharinum</i>	Quadratic	-0.20	0.71	-3.0E-5		0.15	Loglog	0.64	1.50			0.24
<i>Acer saccharum</i>	Loglog	-0.56	2.25			0.23	T3 Exponential	1.18	1.86	-12.1		0.18
<i>Acer x freemanii</i>	Loglog	-0.54	2.16			0.18	T3 Exponential	1.67	1.66	-23.3		0.13
<i>Ailanthus altissima</i>	Logarithmic	-0.18	0.66			0.35	Gompertz	0.32	2.52	1.27	0.10	0.26
<i>Betula nigra</i>	Exponential	0.66	2.74	18.4	4.36	0.23	Gompertz	0.32	2.35	1.11	0.10	0.25
<i>Carpinus betulus</i>	Quadratic	-1.98	1.46	-3.6E-3		0.31	Exponential	0.32	2.03	2.29	-0.70	0.17
<i>Carpinus caroliniana</i>	Weibull	0.70	1.59	3.5E-4		0.34	T3 Exponential	1.36	1.78	-15.5		0.16
<i>Carya alba</i>	Logarithmic	0.19	0.59			0.21	Logarithmic	0.67	0.61			0.22
<i>Carya glabra</i>	Quadratic	0.29	0.51	8.6E-5		0.21	Loglog	0.52	1.89			0.22
<i>Carya illinoensis</i>	FDIP	0.78	11.2	0.31		0.21	FDIP	1.22	9.82	0.41		0.22
<i>Carya ovata</i>	Loglog	0.34	1.48			0.32	Loglog	0.63	1.83			0.18
<i>Cedrus deodara</i>	FDIP	-0.13	5.08	0.28		0.20	Exponential	0.32	2.78	6.06	-0.06	0.22
<i>Celtis laevigata</i>	Logarithmic	0.35	0.56			0.31	Logarithmic	1.01	0.45			0.29
<i>Celtis occidentalis</i>	Logarithmic	0.26	0.56			0.25	Logarithmic	0.44	0.61			0.25
<i>Cercis canadensis</i>	T3 Exponential	0.38	1.91	-4.82		0.27	Gompertz	0.32	1.61	1.87	0.22	0.27
<i>Cinnamomum camphora</i>	Logarithmic	0.10	0.58			0.33	Gompertz	0.32	2.07	12.30	0.49	0.30
<i>Cornus florida</i>	Loglog	0.16	1.53			0.32	Loglog	0.67	1.09			0.27
<i>Cornus kousa</i>	Loglog	0.11	1.54			0.37	Quadratic	0.16	0.66	-1.1E-3		0.21
<i>Cryptomeria japonica</i>	Quadratic	3.0E-2	0.44	4.0E-4		0.17	FDIP	0.68	6.66	0.32		0.15
<i>Cupressocyparis leylandii</i>	FDIP	0.50	19.6	0.26		0.25	Gompertz	0.32	2.34	1.46	0.10	0.24
<i>Fagus grandifolia</i>	Logarithmic	0.36	0.59			0.27	Logarithmic	0.60	0.55			0.26
<i>Fraxinus pennsylvanica</i>	Quadratic	-0.27	0.75	-5.0E-5		0.27	Weibull	0.32	4.16	0.19	0.41	0.22
<i>Ginkgo biloba</i>	T3 Exponential	0.33	2.76	-12.4		0.29	T3 Exponential	1.05	2.13	-11.1		0.22
<i>Gordonia lasianthus</i>	Loglog	-9.5E-2	1.42			0.32	Logarithmic	0.59	0.59			0.32
<i>Ilex cassine</i>	FDIP	0.79	18.9	0.28		0.21	T3 Exponential	1.62	3.68	-44.0		0.29

<i>Ilex cornuta</i>	T3 Exponential	0.78	1.78	-17.2	0.24	Gompertz	0.32	1.87	1.21	7.8E-2	0.31
<i>Ilex opaca</i>	T3 Exponential	0.50	2.16	-14.1	0.29	FDIP	0.59	6.29	0.41		0.29
<i>Ilex vomitoria</i>	Loglog	-0.47	1.99		0.28	Loglog	0.35	1.31			0.32
<i>Ilex x attenuata</i>	T3 Exponential	0.39	1.90	-11.6	0.22	T3 Exponential	0.88	2.10	-12.0		0.24
<i>Juglans nigra</i>	FDIP	0.63	8.64	0.32	0.29	Gompertz	0.32	2.51	1.67	0.13	0.30
<i>Juniperus virginiana</i>	T3 Exponential	0.31	2.33	-12.2	0.26	Weibull	0.32	2.76	0.16	0.62	0.25
<i>Lagerstroemia</i> spp.	FDIP	1.4E-2	4.63	0.35	0.24	Gompertz	0.32	1.75	1.24	9.4E-2	0.25
<i>Ligustrum japonicum</i>	Quadratic	0.19	0.38	0.00	0.30	Quadratic	1.12	0.00	1.0E-3		0.34
<i>Liquidambar styraciflua</i>	FDIP	0.58	12.27	0.31	0.22	Weibull	0.32	2.98	0.19	0.65	0.25
<i>Liriodendron tulipifera</i>	FDIP	1.5e-2	4.33	0.33	0.29	Weibull	0.32	3.14	0.17	0.65	0.21
<i>Magnolia grandiflora</i>	FDIP	-0.24	3.59	0.31	0.23	Exponential	0.32	2.89	13.6	7.03	0.23
<i>Magnolia virginiana</i>	FDIP	-0.33	3.74	0.30	0.30	T3 Exponential	1.17	2.37	-14.4		0.33
<i>Magnolia x soulangiana</i>	Logarithmic	-0.26	0.67		0.23	Gompertz	0.32	1.95	1.44	8.7E-2	0.24
<i>Melia azedarach</i>	Logarithmic	-0.66	0.82		0.32	Loglog	0.53	1.58			0.28
<i>Metasequoia glyptostroboides</i>	Logarithmic	-0.75	0.78		0.28	Gompertz	0.32	2.94	1.40	5.2E-2	0.20
<i>Morella cerifera</i>	Logarithmic	0.17	0.48		0.27	FDIP	1.03	26.6	3.1E-2		0.28
<i>Morus alba</i>	Logarithmic	-2.2E-2	0.65		0.30	T3 Exponential	0.82	1.79	-5.34		0.27
<i>Morus rubra</i>	Loglog	0.46	1.40		0.34	Logarithmic	0.77	0.46			0.34
<i>Nyssa biflora</i>	T3 Exponential	0.78	2.31	-19.3	0.26	Logarithmic	0.64	0.63			0.38
<i>Nyssa ogeche</i>	Loglog	-0.74	2.46		0.16	Gompertz	0.32	2.15	1.27	8.7E-2	0.17
<i>Nyssa sylvatica</i>	Logarithmic	6.6E-2	0.62		0.29	Gompertz	0.32	2.49	1.36	9.4E-2	0.25
<i>Oxydendrum arboreum</i>	Logarithmic	9.2E-3	0.60		0.42	Loglog	0.44	1.72			0.32
<i>Pinus echinata</i>	Loglog	-0.70	2.18		0.17	Weibull	0.32	2.88	3.9E-2	1.17	0.25
<i>Pinus elliotii</i>	FDIP	5.6E-2	9.30	0.23	0.24	Gompertz	0.32	2.73	1.82	0.12	0.30
<i>Pinus palustris</i>	Logarithmic	-0.97	0.83		0.29	Quadratic	-0.32	0.97	-1.9E-4		0.31
<i>Pinus strobus</i>	FDIP	0.25	8.52	0.32	0.24	Quadratic	0.08	0.75	-6.3E-5		0.28
<i>Pinus taeda</i>	Quadratic	-0.66	0.74	1.9E-5	0.23	Loglog	0.25	2.06			0.25
<i>Pinus thunbergiana</i>	T3 Exponential	0.38	2.49	-14.4	0.21	Gompertz	0.32	1.43	47.5	0.83	0.19
<i>Pinus virginiana</i>	Logarithmic	-0.26	0.65		0.25	Gompertz	0.32	2.46	1.12	7.6E-2	0.30
<i>Pistacia chinensis</i>	Weibull	0.37	2.26	0.02	1.39	Quadratic	0.79	0.33	1.7E-4		0.15
<i>Platanus occidentalis</i>	T3 Exponential	1.35	2.26	-29.4	0.19	Gompertz	0.32	2.90	0.91	4.3E-2	0.22
<i>Prunus caroliniana</i>	Loglog	2.0E-2	1.59		0.30	Loglog	0.99	0.99			0.30
<i>Prunus serotina</i>	FDIP	0.64	8.58	0.40	0.32	Gompertz	0.32	2.48	1.32	0.11	0.26
<i>Prunus serrulata</i>	Loglog	-0.47	2.13		0.20	Logarithmic	0.64	0.40			0.17
<i>Prunus yedoensis</i>	Loglog	0.11	1.64		0.18	Weibull	0.32	1.73	0.17	0.82	0.23
<i>Pyrus calleryana</i>	Logarithmic	-0.14	0.65		0.23	Logarithmic	1.00	0.35			0.23

<i>Quercus acutissima</i>	Loglog	-1.24	2.81		0.15	T3 Exponential	1.24	1.74	-13.1		0.17
<i>Quercus alba</i>	Quadratic	-0.36	0.73	8.7E-6	0.24	Gompertz	0.32	2.91	1.16	5.0E-2	0.25
<i>Quercus bicolor</i>	Quadratic	-0.28	0.69	4.6E-5	0.18	T3 Exponential	1.29	1.90	-15.3		0.11
<i>Quercus coccinea</i>	Logarithmic	-0.44	0.78		0.18	Logarithmic	0.37	0.64			0.20
<i>Quercus falcata</i>	Quadratic	-0.19	0.69	9.6E-6	0.18	Weibull	0.32	2.96	0.16	0.66	0.20
<i>Quercus laceyi</i>	FDIP	0.15	5.94	0.29	0.16	Logarithmic	0.50	0.53			0.24
<i>Quercus laurifolia</i>	FDIP	0.23	7.90	0.30	0.34	T3 Exponential	1.15	1.97	-7.99		0.32
<i>Quercus lyrata</i>	T3 Exponential	0.55	2.88	-15.0	0.18	Exponential	0.32	3.31	23.1	17.3	0.15
<i>Quercus macrocarpa</i>	FDIP	-1.0E-2	4.93	0.28	0.12	Logarithmic	0.52	0.49			0.14
<i>Quercus nigra</i>	Quadratic	-0.29	0.73	-4.0E-6	0.22	FDIP	0.42	2.90	0.35		0.23
<i>Quercus palustris</i>	Logarithmic	-0.39	0.76		0.17	Quadratic	0.78	0.47	1.4E-5		0.21
<i>Quercus phellos</i>	T3 Exponential	0.49	2.72	-13.3	0.23	Exponential	0.32	3.32	16.9	11.1	0.16
<i>Quercus prinus</i>	Logarithmic	6.8E-2	0.62		0.26	Loglog	0.47	1.86			0.29
<i>Quercus rubra</i>	FDIP	-0.16	3.75	0.29	0.23	Loglog	0.35	1.79			0.23
<i>Quercus shumardii</i>	Logarithmic	-0.16	0.70		0.18	Quadratic	0.77	0.48	2.2E-5		0.17
<i>Quercus stellata</i>	Logarithmic	-0.57	0.79		0.21	Weibull	0.32	2.85	0.07	0.94	0.18
<i>Quercus texana</i>	Quadratic	-0.50	0.81	-6.0E-5	0.20	Weibull	0.32	2.45	0.21	0.65	0.15
<i>Quercus velutina</i>	Logarithmic	6.0E-2	0.63		0.22	Weibull	0.32	2.84	0.15	0.76	0.25
<i>Quercus virginiana</i>	FDIP	0.19	7.60	0.29	0.29	Logarithmic	0.42	0.54			0.39
<i>Robinia pseudoacacia</i>	Logarithmic	0.28	0.50		0.36	Gompertz	0.32	2.38	1.41	0.14	0.26
<i>Sassafras albidum</i>	Loglog	0.22	1.46		0.16	Logarithmic	0.75	0.55			0.28
<i>Taxodium distichum</i>	Quadratic	-0.39	0.63	4.4E-5	0.27	Quadratic	0.01	0.79	-6.4E-5		0.28
<i>Triadica sebifera</i>	Logarithmic	-0.19	0.62		0.22	Logarithmic	0.54	0.49			0.32
<i>Ulmus alata</i>	FDIP	0.43	6.76	0.30	0.22	T3 Exponential	1.32	2.02	-11.5		0.18
<i>Ulmus americana</i>	T3 Exponential	-0.14	3.41	-9.46	0.33	FDIP	0.46	2.89	0.38		0.17
<i>Ulmus parvifolia</i>	T3 Exponential	-0.08	3.02	-6.37	0.21	Logarithmic	0.43	0.58			0.17
<i>Ulmus pumila</i>	Quadratic	-0.38	0.76	-5.0E-5	0.34	Loglog	0.83	1.35			0.30
<i>Ulmus rubra</i>	FDIP	0.90	13.3	0.29	0.25	Logarithmic	0.83	0.49			0.21
<i>Vitex agnus-castus</i>	Quadratic	-0.81	0.99	-5.0E-4	0.28	Loglog	0.12	1.37			0.21
<i>Zelkova serrata</i>	FDIP	-3.20	0.52	0.17	0.24	Logarithmic	0.76	0.43			0.18

Predictive Equations Utilizing Additional Parameters

For all five of the selected common species, DBH was the most important predictor of tree height and crown width in each model, as indicated by its much larger F-values (Table 5). However, the addition of further parameters improved the accuracy and precision of model estimates. In general, RMSE was reduced when including location and/or competition metrics, although the amount of model improvement varied by species. An increase in BA and TPH (where significant) resulted in greater height. Increases in BA (where significant) resulted in smaller crown width, unless there was an interaction with DBH (as was the case for two species). In these cases, wider crowns associated with higher DBH were amplified with greater BA for larger trees and dampened for smaller trees. At least one location-specific metric (City, HI, and LC) was significant in all of the height models and most of the crown width models, although LC was not significant in any of the crown models. Increased HI resulted in increased height and crown width. The effects of city and LC, where significant, varied by species.

Acer rubrum

In addition to DBH, the variables HI, City, CLE, BA, and TPH were significant predictors in models of *A. rubrum* height (Table 5; Table S.3). DBH interacted significantly with CLE such that height increases associated with increased DBH were significantly different among CLE values when trees were small, and when trees were large (Figure 2A). For the smallest DBH values, trees with a CLE of 3 were significantly taller than those in all other classes except CLE 4. Trees <33 cm DBH that received no direct sunlight (CLE=0) were significantly shorter than all but the trees with CLE of 1. When trees were very large (>54 cm DBH), height increases associated with increased DBH were significantly different by CLE; at the largest values of DBH, trees with a CLE of 3 were significantly shorter than all others, and

171 Table 5. Type 3 tests of fixed effects for models of tree height and crown width for five selected urban tree species in the
172 Southeastern US. Null values in the table indicate non-significant model effects.

		<i>Acer rubrum</i> (n= 1358)		<i>Cornus florida</i> (n=806)		<i>Lagerstroemia</i> spp. (n=2798)		<i>Pinus taeda</i> (n=1691)		<i>Quercus nigra</i> (n=1220)	
Model	Effect	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Height	ln(DBH)	1676	<.001	1193	<.001	50.5	<.001	1456	<.001	677.4	<.0001
	TPH	39.0	<.001					26.4	<.001		
	BA	18.1	<.001			28.3	<.001	31.7	<.001	37.3	<.0001
	CLE	10.3	<.001	16.0	<.001	23.1	<.001	7.0	<.001		
	HI	9.2	0.003			14.3	<.001				
	LC			17.3	<.001	5.4	<.001	4.4	0.002	14.1	<.0001
	City	9.1	<.001			3.7	<.001	26.0	<.001	18.1	<.0001
	ln(DBH) x CLE	8.2	<.001								
	ln(DBH) x BA							9.2	0.002	20.6	<.0001
	ln(DBH) x City					5.0	<.001			12.3	<.0001
	ln(DBH) x LC							5.5	<.001		
Crown width	ln(DBH)	3236	<.001	1400	<.001	122.2	<.001	3818	<.001	6226	<.001
	TPH					23.0	<.001			30.6	<.001
	BA	54.1	<.001			16.6	<.001	46.8	<.001		
	CLE	7.0	<.001	14.8	<.001			13.7	<.001		
	HI					9.5	0.002				
	City	8.1	<.001			16.9	<.001	16.9	<.001		
	ln(DBH) x CLE							10.8	<.001		
	ln(DBH) x BA	46.5	<.001			18.5	<.001				
	ln(DBH) x City					12.6	<.001				

173 TPH, local stem density in trees/ha; BA, local basal area in m²/ha; CLE, crown light exposure; HI, Hopkin's Bioclimatic Index; LC,
174 land cover; City, name of location

Figure 2. Marginal mean of *Acer rubrum* for (A) height versus Diameter at Breast Height (DBH) by crown light exposure (CLE) class, (B) height by Location, (C) crown width by crown light exposure (CLE) class, and (D) crown width by Location (see Table 1). All other variables in the model were at their average values. Values denoted with different letters are significantly different ($\alpha=0.05$) using Tukey's HSD test. Location abbreviations are annotated in Table 1.

those that received no direct sunlight were significantly taller (Figure 2A). City was also a significant predictor of height for this species; trees in Gainesville were on average significantly taller than those in many other cities, and trees in Pensacola and Auburn were on average shorter than those in other cities (Figure 2B).

For models of *A. rubrum* crown width, significant predictor variables were DBH, City, CLE, and BA (Table 5; Table S.4). Falls Church had the largest crown widths, which were significantly different from those of East Orlando and Gainesville, which had the smallest. Lower values for CLE (less direct sunlight) were associated with larger crown widths for *A. rubrum*. BA interacted significantly with DBH in predicting crown width such that increases in

crown width associated with increased DBH were reduced when BA was larger. Trees with higher local BA values had smaller crown widths when trees were larger (>20 cm), but the opposite was true when trees were small (Table S.3 and Table S.4).

Cornus florida

DBH, CLE, and LC were significant predictors of *C. florida* height (Table 5; Table S.3). Trees with near complete shading (CLE=1) were on average tallest, but were only significantly taller than those with complete or near-complete sunlight (CLE=4 or 5; Figure 3A). Trees in non-developed and open space developed classifications were on average significantly taller than those in low and medium intensity developed (Figure 3B). DBH and CLE were the only significant predictors of *C. florida* crown width (Table 5; Table S.4). Similar to *A. rubrum*, crown width was larger with larger DBH, and smaller with direct sunlight (CLE).

Figure 3. Marginal mean of height for *Cornus florida* by (A) crown light exposure (CLE) class, and (B) Land Cover (LC) class (High, Med, and Low=High, Medium, and Low-intensity developed, Open=Open space developed, and Non=Non-developed). All other variables in the model were at their average values. Values denoted with different letters are significantly different ($\alpha=0.05$) using Tukey's HSD test.

Lagerstroemia spp.

DBH, HI, LC, City, CLE, and BA were significant predictors for *Lagerstroemia spp.* height (Table 5; Table S.3). The only significant differences among LC classes were between medium-intensity developed and high- and low-intensity developed (Figure 4A). Intermediate

CLE values were associated with the greatest height values (Figure 4B). There was a significant interaction between DBH and City in predicting height, with the two Virginia locations displaying very little height increase with DBH. At smaller DBH values, *Lagerstroemia* was shortest in Gainesville and tallest in Roanoke, although the only significant difference in height was between Auburn and Georgia Tech. However, for larger DBH trees, those at UGA were significantly taller than in Auburn, Charlottesville, Georgia Tech, and Pensacola (Figure 4C).

Figure 4. Marginal mean of *Lagerstroemia* spp. for (A) height by crown light exposure (CLE) class, (B) height by Land Cover (LC) class (High, Med, and Low=High, Medium, and Low-intensity developed, Open=Open space developed, and Non=Non-developed), (C) height versus DBH by Location; and (D) crown width by Location. All other variables in the model were at their average values. Values denoted with different letters are significantly different ($\alpha=0.05$) using Tukey's HSD test. Location abbreviations are annotated in Table 1.

Lagerstroemia crown width was also significantly predicted by DBH, City, BA, TPH, and HI (Table 5; Table S.4). BA and City both interacted with DBH in predicting crown width. As was the case with *A. rubrum*, the relationship between crown width and DBH was weaker with an increase in BA, and this relationship was more pronounced where DBH > 15 cm. At

smaller DBH values, East Orlando's *Lagerstroemia* had the greatest crown width, which was significantly different from the crown widths of trees in Gainesville and Auburn, where the narrowest *Lagerstroemia* trees were found (Figure 4D). However, as DBH increased, the crown widths of *Lagerstroemia* in East Orlando remained relatively constant, indicating a lack of a significant relationship between crown width and DBH at this location. Increased DBH in Pensacola resulted in only moderate increases in crown for *Lagerstroemia* compared to the other locations. At average DBH values (~25 cm), there were very similar crown widths for Roanoke, Auburn, Georgia Tech, Charlottesville, and UGA. At the greatest DBH values, Roanoke had the largest tree crowns (although not significantly different from any other location) and East Orlando had the smallest. East Orlando's crown widths were significantly narrower than those in the college campuses (Auburn, Georgia Tech, and UGA).

Pinus taeda

DBH, TPH, BA, CLE, City, and LC were significant predictors for *Pinus taeda* height (Table 5; Table S.3). Similar to *Lagerstroemia*, *P. taeda* was tallest with intermediate CLE values. The effect of City was especially strong in Gainesville, where *P. taeda* achieved a height significantly greater than in the other locations investigated (Figure 5A). Pensacola and East Orlando had the shortest *P. taeda*. LC and BA interacted with DBH. At the smallest DBH values, increases in height associated with DBH were similar across LC. Height increases associated with DBH increases were highest in open space developed, followed by non-developed (Figure 5B). At the largest DBH values (>90 cm), trees in low-, medium-, and high-intensity developed were shortest and were not significantly different from one another. Increases in *P. taeda* height associated with increases in DBH were greater when BA was larger (data not shown).

Figure 5. Marginal mean of *Pinus taeda* for (A) height by Location, (B) height versus DBH by Land Cover (LC) class (High, Med, and Low=High, Medium, and Low-intensity developed, Open=Open space developed, and Non=Non-developed), (C) crown width versus DBH by crown light exposure (CLE) class and (D) crown width by Location. All other variables in the model were at their average values. Values denoted with different letters are significantly different ($\alpha=0.05$) using Tukey's HSD test. Location abbreviations are annotated in Table 1.

Significant predictors of *P. taeda* crown width included DBH, City, CLE, and BA (Table 5). *P. taeda* in Georgia Tech had the greatest crown width, but on average, these crown widths were not significantly different from those in Auburn or Pensacola. Gainesville had the narrowest crowns, which were significantly different from all but nearby East Orlando (Figure 5A). There was a significant interaction between CLE and DBH. At smaller DBH values, *P. taeda* with CLE values of 0 and 5 had significantly greater crown width than those with CLE values of 1, 2, and 3 (Figure 5B). For trees with DBH larger than 33 cm, completely shaded *P. taeda* (CLE=0) were significantly narrower than those with more direct sun (CLE ≥ 1).

Quercus nigra

DBH, LC, City, and BA were significant predictors of *Q. nigra* height (Table 5), and City and BA interacted with DBH. Similar to *P. taeda*, increases in BA resulted in increased height, which was more prominent with greater DBH. The open-space developed and non-developed LCs contained the tallest trees. High-intensity developed contained the shortest trees, which were not significantly different from those of medium- and low-intensity developed (data not shown). When DBH was smallest, *Q. nigra* trees in all locations were similar. When DBH was > 50 cm, *Q. nigra* trees were significantly taller in Gainesville. DBH and TPH were the only significant predictors of crown width for *Q. nigra*; increases in TPH were associated with narrower crowns.

Discussion

For a large number of the species, all models produced adequate fit for the data, indicating that the chosen models approximate urban crown characteristics well. However, three of the eight model forms (Exponential, Gompertz, and Weibull) failed to converge for many species when modeling crown width. For some species (e.g. *Carpinus betulus*), this was likely due to the variety of sampled cultivars with differing growth habits (Gilman and Watson, 1993).

As expected, the strongest predictor of height and crown width for all species was DBH, indicating that relationships between crown characteristics and diameter for trees in urban environments are similar to those in natural forests. HI was significant for the height of two species (*Lagerstroemia* spp. and *A. rubrum*) and the crown width of one (*Lagerstroemia* spp.); however, it was only significant when City was in the model. Therefore, HI may account for plot-level differences in elevation and site type throughout a location (Uzoh and Oliver, 2006).

We expected BA and TPH to have similar effects on urban tree height and crown width as in natural forest trees. This held true for tree height; higher TPH and BA were associated with greater height. Increased TPH also resulted in larger crown width for *Lagerstroemia* spp, and increased BA resulted in larger crown width for smaller (<15-20 cm) *Lagerstroemia* spp. and *A. rubrum* individuals, consistent with previous investigations (Bragg, 2001). However, *Q. nigra* crown widths were smaller with increased TPH, while larger (>15-20 cm) *Lagerstroemia* spp. and *A. rubrum* individuals had smaller crown widths with increased BA. TPH and BA are not often jointly included in models due to their multicollinearity. However, we found no such significant confounding effects of these variables. The lack of collinearity may be in part due to the high degree of heterogeneity in urban areas, especially among small (0.04 ha) sample plots or to differences in sampling protocols. In traditional forestry, each tree stem is counted as its own tree (if branching occurs below DBH). However, the i-Tree Eco protocol counts multi-stemmed trees as one tree (Nowak et al., 2008). On the other hand, this could be due to the tree size distribution of highly managed, diverse, private urban forests. Diverse forests often do not have highly correlated TPH and BA due to crown overlap, relationships between bole and crown, and the shape of their diameter distributions (Bechtold, 2004; Cade, 1997). Moreover, the relatively small average tree size found in this study may have also contributed to our findings. Crown development of smaller trees may be more affected by pathogens, spacing, or the planting regimes of the cities under study.

LC was a significant predictor for four of the five height models, but was not significant for any crown width models. For all species where LC was significant, those with LC classifications of non-developed and open space developed were generally the tallest, although that depended on DBH for *P. taeda* (at larger DBH values, this held true). Briber et al. (2015)

found that conversion from forest to urban land uses resulted in significant increases in basal area increment for *Q. rubra*. A rapid increase in DBH growth—beyond that provided by the logarithmic function—at the time of land development and release from vegetation competition may explain the weaker height-diameter relationship for trees in developed areas. Additionally, lesser-developed LC's are likely to have less soil degradation and anthropogenic structures that may inhibit tree growth (Grabosky and Gilman, 2004).

CLE was significant for the height of four species and the crown width of three species. Where the CLE was 5 (i.e., open-grown trees), trees were shortest for *Lagerstroemia* spp., *C. florida*, and *P. taeda*. This was expected, as open-grown trees are usually wider and shorter than their more shaded counterparts (Bechtold, 2004). A CLE of 0 (i.e., full shade) resulted in taller *Lagerstroemia* spp. and *C. florida*, but shorter *P. taeda*. Since *Lagerstroemia* spp. is tolerant of varied sun exposure, *C. florida* is a shade-loving species, and *P. taeda* is intolerant of shade, these results are expected; *P. taeda* height growth was likely suppressed due to its shade intolerance. This could also be a result of past disturbance events such as hurricanes affecting crown characteristics in Pensacola and East Orlando; both of which had the shortest *P. taeda*. On the other hand, with smaller DBH values for shade-tolerant *A. rubrum*, completely shaded trees (CLE of 0) resulted in shorter trees. As DBH increased, however, *A. rubrum* with a CLE of 0 became the tallest. Like *Lagerstroemia* spp., *A. rubrum* tolerates varied conditions well. It is likely that fully shaded *A. rubrum* allocate their resources to greater height growth so that they may potentially receive more sunlight. Complete shading resulted in greater crown widths, whereas full sun resulted in smaller width for *A. rubrum* and *C. florida*. The results for the effect of CLE on crown width of *C. florida* can be explained best as a result of shade preference. Trees with greater competition for light tend to have more competition for space and must allocate

resources to height growth rather than crown spread. However, the pattern for *A. rubrum* is the opposite. This could be an artifact of landscape placement, whereby trees in open spaces are pruned more frequently or are cultivars with narrow crown form (as opposed to natural genotypes that might be encountered in shadier natural areas). Due to an interaction between DBH and CLE, *P. taeda* with smaller DBH values had the widest crowns at CLEs of 0 and 5 and the narrowest at 1, 2, and 3. As DBH increased for *P. taeda*, a CLE of 0 resulted in the narrowest crowns. These results were expected for larger trees; for smaller trees, a low sample size may have led to this unusual result.

City was a significant variable for all species besides *C. florida*, and its interaction with DBH was significant for *Lagerstroemia* spp. and *Q. nigra*. The significance of City is indicative of something that could not be tested given the available data. This may be an effect of maintenance or planting practices or past disturbance events (e.g. hurricanes and pest outbreaks). For example, the differences in height for *Lagerstroemia* could be a result of “topping,” a controversial tree trimming technique where trees are shortened to a uniform height. The college campuses (Auburn, UGA, and Georgia Tech) all have taller *Lagerstroemia* than the other locations. Homeowners and business owners may be more likely to top their *Lagerstroemia* because of different ornamental objectives from those of grounds professionals on college campuses. We would have expected the height–diameter relationship to be the same for trees in Auburn and UGA; they are both college campuses in the same ecozones, are geographically close, and are at very similar elevations. However, *A. rubrum* trees in Auburn were significantly shorter than those in UGA, despite having the same crown width–diameter relationship. This could be due to cultural differences such as pruning or fertilizing, or may be due to the planting of different cultivars as a result of preference or availability. Additionally, *A. rubrum* was also

shorter in Pensacola. We note that Pensacola is coastal and has been impacted by past hurricanes, and this has affected urban forest structure (Escobedo et al., 2015). Regardless of the reason for significant differences, our results show that a model developed in one location may be inaccurate in another (McPherson and Peper, 2012), demonstrating the need for regional models.

Many previous studies have utilized data from more homogeneous sources. For example, some studies have focused on trees with no evidence of pruning (Pretzsch et al., 2015); these may provide a more accurate representation of a tree's potential given the particular environment. However, our vast dataset included and did not distinguish between trees that had undergone varied levels of pruning typical within the region, that were different cultivars, and that were in diverse land uses. These metrics are not typically collected as part of the i-Tree protocol and would be difficult to discern depending on the season and how recently a tree had been pruned. Although representative of the urban forest, this may have resulted in unstable models (such as for *Carpinus betulus*). Given the origin of these data and for the sake of consistency in the database, there was no specification regarding which trees were heavily pruned or which were unique cultivars with vastly different form. Pruning practices and cultivar selection vary with geographic area and with different levels of management intensity; therefore, our more in-depth investigation of the five species allowed us to take some of these factors into account, by including variables for land cover and city. In addition, bias may have resulted from the use of different measurement tools and procedures by research groups. For example, DBH at UGA was measured to the nearest inch (2.54 cm). Lastly, the results of this study may contrast from others due to the inclusion of remnant forest patches within the dataset. While these data may be more similar to those of natural forests, they represent the wide range of environmental conditions in which urban forests occur across the SEUS.

Conclusions

To our knowledge, our assemblage of models for 97 species of commonly occurring urban trees in the SEUS is the most comprehensive synthesis of predictive equations for urban trees in the world thus far. Additionally, many of the species in this study have never been modeled previously, despite their regular occurrence in SEUS urban forests. Due to the large sample sizes and variation across tree and location parameters, the regional models developed in this study are very robust. These models encompass diverse urban forests of the SEUS, varying in land use, ownership (both public and private), management regime, and municipality size. Our findings should enable urban forest managers and researchers in the SEUS and similar geographic settings to measure fewer tree attributes when conducting inventories while still being able to accurately quantify the structure of their urban forests in a cost-effective manner. Furthermore, our predictive equations, due to their regional basis, should allow for more efficient and accurate estimates of ecosystem services and disservices. Finally, this study provides an initial starting point for making comparisons between urban and natural forests, in terms of the relationship between trunk diameter and crown attributes.

The addition of site variables to the predictive equations has definite management, maintenance, and planting implications. Understanding which urban site factors may dampen (or, conversely, enhance) tree height or crown width growth could allow urban foresters to better plan the placement of trees within the urban landscape. Importantly, this study demonstrated that models developed for urban trees in a single location might not accurately predict tree dimensions in another location, even though the climatic zone or region is the same. Further studies aimed at determining between-city differences in tree form as a result of anthropogenic

pressures, as well as those that compare urban versus non-urban relationships between trunk diameter and crown attributes, could help answer questions about the effect of management and provide information about how management practices interact with other factors to influence tree height and crown width.

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