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

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ABSTRACT

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.

1. 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, 2014). 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, 2014). 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

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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-Dadeís 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.

2. Methods

2.1. 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 three cities in Florida, plots were installed randomly across varied urban land uses, such as residential, institutional, and commercial (for Pensacola, Gainesville, and Miami-Dade County, respectively; see: Escobedo et al 2010; Lawrence et al., 2012; 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), as well as east Orlando, Florida were