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Shade factors for 149 taxa of in-leaf urban trees in the USA

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ABSTRACT

Shade factors, defined as the percentage of sky covered by foliage and branches within the perimeter of individual tree crowns, have been used to model the effects of trees on air pollutant uptake, building energy use and rainfall interception. For the past 30 years the primary source of shade factors was a database containing values from 47 species. In most cases, values were obtained from measurements on a single tree in one location. To expand this database 11,024 shade factors were obtained for 149 urban tree species through a photometric process applied to the predominant species in 17 U.S. cities. Two digital images were taken of each tree, crowns were isolated, silhouette area defined and shade factors calculated as the ratio of shaded (i.e., foliage and woody material) pixels to total pixels within the crown silhouette area. The highly nonlinear relationship between both age and diameter at breast height (DBH), and shade factor was captured using generalized additive mixed models.

We found that shade factors increased with age until trees reached about 20 years or 30 cm DBH. Using a single shade factor from a mature tree for a young tree can overestimate actual crown density. Also, in many cases, shade factors were found to vary considerably for the same species growing in different climate zones. We provide a set of tables that contain the necessary values to compute shade factors from DBH or age with species and climate effects accounted for. This new information expands the scope of urban species with measured shade factors and allows researchers and urban foresters to more accurately predict their values across time and space.

1. Introduction

Growing interest in the ecosystem services provided by urban trees, such as energy effects, rainfall interception, carbon storage, and air pollutant uptake, is driving new investments in urban forests as green infrastructure (Berland and Hopton, 2014; Livesley et al., 2016; Zölch et al., 2017). Biometric research is measuring and modeling the characteristics of different tree species that influence their performance, such as diameter at breast height (DBH), crown size, and leaf area (Dahlhausen et al., 2016; McPherson and Peper, 2012; Semenzato et al., 2011; Yoon et al., 2013). One trait that has received relatively little study is the crown density of urban trees. Shade factor, defined as the percentage of sky covered by foliage and branches within the perimeter of individual tree crowns, can vary by species from about 60% to 95% when trees are in-leaf (McPherson, 1984). Shade factors are an important parameter in numerical models of urban forest biometrics and benefits. They are applied with crown parameters in regression equations to estimate tree leaf area, which is used to model air pollutant uptake (Nowak et al., 2008). Shade factors are used for modeling effects of tree shade on energy use by buildings and the efficiency of roof-mounted solar systems (Heisler, 1982; Thayer and Maeda, 1985). They are proxies for crown gap fraction, a variable used to model the amount of precipitation that falls unimpeded through the tree crown (Xiao et al., 2000).

Foresters have long studied the manner in which forests absorb, radiate, reflect, and transmit radiant energy and its effects on ecophysiological processes such as photosynthesis, evapotranspiration, and growth (Reifsnyder and Lull, 1965). Urban forest canopies can reduce the risk of heat stress to city dwellers by regulating the thermal environment (Kong et al., 2014). Tree crowns attenuate solar radiation and increase latent heat flux through evapotranspiration, which reduces air temperature (Thom et al., 2016). Their cooling effectiveness varies

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by species and depends on crown size and density (e.g., leaf area index) growth rate, and stress tolerance (Rahman et al., 2015, 2017). Recent research has been identifying the thermal impact of trees in cities, with particular interest on the effects of evapotranspiration on air temperatures (Kong et al., 2016).

The authors are not aware of studies that have measured differences in attenuation of solar radiation among species during the past few decades. That work was prompted by the US oil crisis of 1979, which led to increased use of solar hot water systems and the need for solar access (Erley and Jaffe, 1979). Researchers began studying attenuation of sunlight in urban forests to select and locate trees for summer shade without blocking light to solar collectors (Heisler, 1986b). The techniques they used to measure crown density have changed as the technology evolved. Irradiance reductions by open growing city trees were first measured with pyranometers and light meters (Canton et al., 1993; Erley and Jaffe, 1979; Heisler, 1986a; Wilkinson et al., 1991). With the advent of portable computers, photographic approaches were adopted because large numbers of trees could be easily measured (Wagar and Heisler, 1986; Wilkinson et al., 1991). Photographs of tree crowns were taken, then scanned to measure relative transmission, or shading coefficient, a term first used in the building engineering literature (ASHRAE, 1989). Wilkinson (1991) found that there was no significant difference between shade factors for trees in full-leaf derived from photographic and photometric means. The photographic approach is used in this study.

Although photographic methods are quick and allow large numbers of trees to be studied, they have their limitations. Because these images are recording gaps in crowns, they are not a good measure of radiant energy reduction by trees (Heisler, 1982). Much of the radiation in shade is in a diffuse form rather than direct beam because of reflection off leaves and branches. Shade factors obtained from measuring gaps can underestimate the amount of radiation under a tree because the diffuse component is not included.

Patterson et al. (2011) found that side view photos offer a robust method for estimating shade factor. However, while a photograph of a crown taken at an angle of approximately 30° above the horizon captures the horizontal density of the crown in one direction, this value may not accurately capture the crown's density in other directions, or its vertical density. For example, closely spaced street trees can have crown's that are wider perpendicular to the street, and narrower parallel to the street due to competition from adjacent street trees. Shade factors recorded for only the widest dimension are likely to be greater than values for the narrowest dimension. Inaccuracies in measurements of horizontal density can influence modeling of tree shade on building energy performance when solar elevation angles are very high or low. Similarly, shade factors from horizontal images of species with high ratios of crown height to width (i.e., tall, narrow crowns) might underestimate their vertical densities. This issue could impact modeling rainfall interception when precipitation falls from above.

Shade factors typically range from 70% to 90% among species in-leaf. Results of 73 in-leaf measurements of shade factors were compiled for 47 different tree species located throughout the U.S. (McPherson, 1984). Values ranged from 62% for honey locust (*Gleditsia triacanthos inermis*) to 93% for littleleaf linden (*Tilia cordata*). But do differences in shade factors among species substantially effect their functional performance?

In a sensitivity analysis of tree shade effects on residential buildings in Tucson, AZ a 10% difference in shade factor (75%–85%) increased annual cooling savings by 2% (75–150 kWh) depending on building size and type of construction (McPherson and Dougherty, 1989). Overall savings were proportional to the amount of area shaded based on crown size and shape, as well as the shade factor of each species. Shade factors ranged from 70% to 90% for a simulation of species planted for building shade in Sacramento, CA (Simpson and McPherson, 1998). The simulations assumed a constant shade factor for each mature species. These studies indicate that shade factor can have a substantial influence on building cooling savings. Unfortunately, these studies did not measure effects for the full 30% range in shade factors among species, or for changes in density that might occur as trees mature.

A sensitivity analysis of factors influencing rainfall interception by individual trees found that interception loss was sensitive to gap fraction, where gap fraction is defined as the percentage of crown area normal to the direction of rainfall that allows rain drops to reach the ground unimpeded (Xiao et al., 2000). The amount of unimpeded throughfall was directly proportional to the gap fraction. Keeping other factors constant, a three-fold increase in gap fraction was estimated to decrease interception loss (i.e., evaporation) from 12.1 to 4.3%. Interception estimates were highly sensitive to gap fraction, along with leaf area index and surface storage capacity. Shade factor was used as a proxy for gap fraction in modeling rainfall interception by Sacramento's urban forest (Xiao et al., 1998). In their measurements of interception by two eucalypt species (*Eucalyptus* sp.), Livesley et al. (2014) measured gap fraction using four upward-looking digital images for each tree. Gap fraction varied between species (14% and 20%).

In i-Tree, a software package widely used to model air pollutant uptake by trees, leaf area estimates from the i-Tree regression equation (Nowak, 1996) are very sensitive to the shade factor value (Fig. 1). The average shade factor from the literature for hackberry (*Celtis occidentalis*) is 88% (McPherson, 1984). Given variability of ± 10% among individual hackberry trees, shade factors can range from 78% to 98%. The i-Tree equation predicts that leaf area is 374 m^2 with the 88% shade factor at 20 years. Leaf areas for the dense (98%) and open (78%) hackberry are estimated to be 633 m^2 and 221 m^2, respectively. The ± 10% change in shade factors results in a nearly three-fold difference in estimated leaf area.

In summary, shade factors are used to model tree leaf area and functions such as effects of tree shade on building energy performance and rainfall interception. The most extensive database of shade factors is over 30 years old and contains values for only 47 species (McPherson, 1984). Most urban forests contain many more taxa than this. Presumably, values for other species must be assigned to those missing based on taxonomic or structural similarity. The current modeling assumptions are that shade factors remain static over the tree's lifetime and do not change within a species due to effects of management practices and different climates. If differences within species and across tree ages and climate zones are insignificant, a single shade factor per species can be justified for modeling purposes. If differences exist as trees of the same species age, or for trees of the same species located in different climate zones, accurate modeling of shade factors for the same species may need to incorporate changes in crown density across time and space. Hence, the goal of this research is to develop a process for calculating shade factors based on user inputs, such as species, size, age, and climate zone. To achieve this goal we answer the following

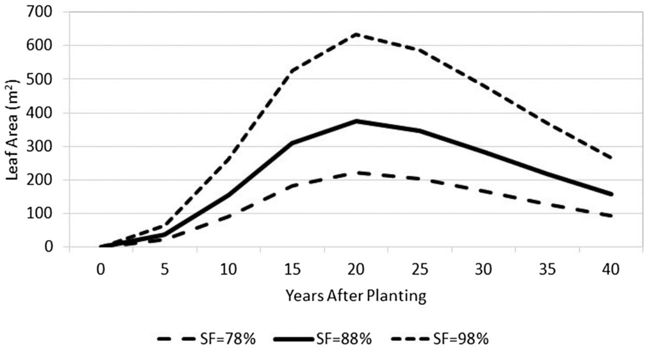

Fig. 1. Modeled leaf area of hackberry (*Celtis occidentalis*) using i-Tree's logarithmic regression equation (Nowak, 1996) and crown dimensions (height and diameter) from the Urban Tree Database (UTD) growth equations (McPherson et al., 2016). The sensitivity of leaf area to shade factors (SF) is illustrated using values that are ± 10% of the species average for hackberry (88%).