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Crown size and growing space requirement of common tree species in urban centres, parks, and forests

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ABSTRACT

Tree crown size determines among others tree's growth, carbon sequestration, shading, filtering of fine air particulates, and risk of wind-breaking. The dependence of crown size on species, resource supply, and tree age complicates an accurate evaluation of a tree's space requirement, and its size-dependent functions and services in urban as well as in forested areas.

Based on a world-wide dataset of tree crown measurements of 22 common urban tree species we first derived species-specific crown radius–stem diameter relationships for open grown conditions. By cluster analysis we then assigned the 22 species to 5 crown extension types and developed mean relationships of tree height, crown radius, crown projection area, and crown volume depending on tree diameter for each type. This allometric analysis yielded auxiliary relationships which can be used for estimating the species-specific crown size and dynamics at a given tree dimension. We discuss how the results can support the choice and initial spacing of particular species and the assessment and prognosis of their functions and services.

Introduction

Urban forests, i.e. the stock of trees in urban areas, can improve environmental conditions and quality of life in cities by providing multiple ecosystem services. They have not only important aesthetic and cultural values but urban trees can, for instance, increase biodiversity, mitigate the heat island effect, reduce storm water runoff, sequester carbon, and filter pollutants from the air (e.g. McPherson et al., 1997; Nowak and Crane, 2002; Tyrväinen et al., 2005). Urban forests and trees can also have detriments, though, such as blocking out sunlight, generating leaf litter, being hosts to pests, producing allergenic pollen and volatile organic compounds as precursors to ozone, or being a hazard during storms. Benefits and disadvantages of the urban forest are influenced by its planning and management such as location and configuration of tree plantings, density of tree stands, species selection, and more.

In the general literature, there is an ever increasing body of evidence on the benefits and detriments of urban forests. However, urban tree managers need to be enabled to assess the particular performance of the urban forest in their respective cities in relation to enhancing or limiting factors, so that they can devise locally adapted strategies for the planning and management of their urban trees and forests. Ultimately, effective urban tree planning and management aiming at promoting ecosystem services depend on intimate knowledge of the growth behaviour of trees in the urban environment. Which crown size will a tree of a particular species attain in a particular location and point of time, and hence, what are its space requirements? How much can that tree be expected

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to cool a certain area by shading and evapotranspiration? What will be the annual stem increment and how much carbon will the tree sequester and store over time? What is the difference between tree species in this regard? Despite a long history of the use of trees in urban areas, surprisingly little is known on their structure and growth.

The scarcity of such data is a limitation to accurate assessment of ecosystem services provided by the urban forest, for instance via modelling tools such as i-Trees from the USDA Forest service (http://www.itreetools.org/). The quality of the output from such models critically depends on the quality of the input data from field surveys and the functions by which relationships between, e.g. tree variables such as the leaf area index and regulating services such as temperature moderation are expressed. The latter requires detailed information on structure and growth of the large variety of urban trees and related characteristics such as tree height, crown width, and crown volume.

Tree crown size is a key variable in this context as it correlates with the space a tree occupies as well as with the physiological tree functions mentioned above. Crown projection area and crown volume, e.g., can be used as proxy variables for leaf area and leaf biomass (Binkley et al., 2013; Forrester, 2013). However, knowledge about crown size and allometry of open-grown trees, as typically found in urban areas, is still rather limited. Because of the relevance of the forest canopy structure for stand productivity and biodiversity many studies deal with canopy closure (Jennings et al., 1999; Ishii et al., 2004), crown shyness (Putz et al., 1984), or gap dynamics (Choi et al., 2001) at forest stand level. Much less studies focus on the shape and allometry of the individual trees that form a stand (Bayer et al., 2013; Pretzsch and Schütze, 2005; Pretzsch, 2014). And even less is known about the shape, structure and structural dynamics of open-grown trees, as they play a minor role in forestry and rather serve as a reference for understanding tree behaviour under competition.

Tree growth experiments covering different density and competition levels show, that tree height growth is rather stable within a broad range of stand density levels from solitary to dense stand conditions. Tree crown and tree stem diameter growth in contrast are very sensitive to competition. So, especially in the case of the allometry between tree diameter and crown dimensions a transfer of size relationships and dynamics from forest trees to open-grown trees in urban areas (e.g., along boulevards, in parks, places) must take into account those forest trees which exhibit maximum crown size at a given diameter i.e. which grew up under very low competition.

We use a rather unique dataset from urban trees worldwide and suitable trees from long term experimental plots comprising 22 species in order to scrutinize their stem diameter–crown width allometry. In more detail we

(i) derive species-specific allometric relationships between stem diameter and crown width,
(ii) assign the 22 different species to 5 crown extension types by cluster analysis of their allometric traits,
(iii) derive mean allometric relationships of tree height, crown radius, crown projection area, and crown volume depending on tree diameter for each crown extension type,
(iv) present how the resulting relationships can support the choice and initial spacing of particular species and the assessment and prognosis of their functions and services.

Materials and methods

Material

Our data cover in total 39,057 single tree observations with information about crown size. We pooled data from urban trees of 9 metropolises worldwide (Table 1), comprising solitary street trees, as well as trees from city parks and urban forests. When collecting data from city trees we paid attention to have a balanced sample size of trees from city centres, from suburban, and from rural areas. By this, sampled trees followed an urban climatic gradient. The investigated metropolises represent different climates ranging from boreal to subtropical conditions. We further pooled data from long term forest research plots mainly located in Southern Germany (Table 1), where trees grew under different competition conditions ranging from solitary situations to strong canopy closure. This combination results in a coverage of 22 different tree species which are internationally important in urban greening. In case of sampling solitary grown trees we tried to exclude pruned trees in order to get reliable values of the species-specific maximum reach of the crown.

As all measurements followed internationally concerted standards, the quality of the data is comparable independent of the data source. For all trees, – among other variables – diameter at breast height, *d*, and crown radii, *r* in the eight subcardinal directions (N, NW,. . ., NE) were measured. Diameters at breast height were recorded using diameter measurement tapes. For determining crown radii and crown projection area, there are two frequently applied methods both determining crown radius as the distance from the centre of the trunk to the perimeter of the crown (Fig. 1, Röhle, 1986). The vertical sighting method (Preuhsler, 1979) is quick, though, rather inaccurate compared to the projection method, which uses a plummet and is very accurate but time consuming (Röhle and Huber, 1985; Röhle, 1986). The measurements behind our data were mostly done using the vertical sighting method whereas in about 10% of each days' measurements the plummet was used to continuously train the measuring person and minimize his/her personal bias. The mean crown radius cr is to be understood as the quadratic mean, $\mathrm{cr} = \sqrt{(r_N^2 + r_{\mathrm{NW}}^2 + \ldots + r_{\mathrm{NE}}^2)/8}$ ensuring a bias-free transition between crown radius to crown projection area, $\mathrm{cpa} = \mathrm{cr}^2 \times \pi$, which expresses the area occupied by a tree. For most species, our data cover a diameter at breast height range from 5 up to more than 60 cm, and a crown radius range from 1 to more than 5 m (Table 1). The tree ages start at about 20 years and end with more than 100, in some cases even with more than 200 years. For urban trees, information about tree age was derived from tree cores, for trees from long-term plots tree age is known from plot documentation.

Allometry

In the early 1930s, Huxley (1932) and Teissier (1934) formulated a 'relative growth equation' that is today widely accepted as the allometric equation. Supposing *x* and *y* quantify the size of plant organs or a total plant, their growth (d*x*/d*t* and d*y*/d*t*) is related to the size *x* and *y* as

$$\frac{\mathrm{d}y}{y} = \frac{\alpha \mathrm{d}x}{x}. \tag{1}$$

Better known are the integrated and logarithmic representations that include a scaling constant *b*.

$$y = bx^{\alpha} \tag{1a}$$

$$\ln y = \ln b + \alpha \ln x \quad (\text{equivalent to} \quad \ln y = a + \alpha \ln x \quad \text{for} \quad a = \ln b) \tag{1b}$$

Thus, allometry is the relative change of one plant dimension, d*y*/*y* (e.g. the relative height growth if *y* is height) in relation to the relative change of a second plant dimension d*x*/*x* (e.g. the relative diameter growth if *x* is diameter).The ratio between the relative changes of the plant dimensions *y* and *x* is constant and equal