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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

Table 1
Data used in this study. The main data sources are Southern German long term research plots (LTP). Where data was sourced from city trees, the city's name and country are mentioned. Sample size is specified by indicating the origin of data from forests (*f*), parks in cities (*p*) and streets (*s*). *n*: total sample size, *d*: diameter in breast height (1.3 m), cr: crown radius.

Species	Data source	*n*			*d* [cm]			cr [m]			Age [yr]		
		f	*p*	*s*	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Abies alba Mill.	LTP	1079			3.8	29.9	97.8	0.6	2.6	5.7	42	201	283
Abies sachalinensis Mast.	Sapporo, Japan	36	74		20.0	33.4	77.5	1.2	2.9	6.9	24	42	119
Acer pseudoplatanus L.	LTP	942			4.7	17.6	56.7	0.3	2.0	5.6	20	59	283
Aesculus hippocastanum L.	Munich, Germany		67	163	27.2	63.5	116.9	2.9	5.5	9.0			
Alnus nigra Gilib.	LTP	51			6.5	15.2	47.0	1.1	1.9	3.8	36	44	88
Araucaria cunninghamii Aiton ex D.Don	Brisbane, Australia		46	80	15.7	40.7	129.5	1.3	1.8	3.4			
Betula pendula	LTP	31			5.0	12.8	38.7	0.7	1.6	4.1	16	30	88
Carpinus betulus Roth	LTP	778			4.3	13.9	39.5	0.4	2.5	6.4	18	97	176
Fagus sylvatica L.	LTP	14,963			2.9	23.1	191.4	0.1	3.0	14.3	16	97	283
Fraxinus excelsior L.	LTP	541			4.9	17.2	57.8	0.3	1.6	5.2	20	47	183
Khaya senegalensis (Desr.) A.Juss.	Hanoi, Vietnam			163	44.1	73.4	123.1	3.1	6.5	11.7			
Larix decidua Mill.	LTP	340			4.9	29.9	80.4	0.6	2.2	5.7	16	61	185
Picea abies (L.) H.Karst.	LTP	10,775			2.2	27.7	98.9	0.2	1.9	5.9	16	98	283
Picea glauca (Moench) Voss	Prince George, Canada	87	48	10	27.7	40.6	56.5	1.2	2.6	4.4	43	87	167
Pinus sylvestris L.	LTP	1609			5.3	23.4	76.2	0.2	2.0	5.6	16	81	200
Platanus × hispanica Münchh.	Paris, France		17	154	40.3	64.8	144.0	2.7	6.6	14.8			
Pseudotsuga menziesii (Mirbel) Franco	LTP	1613			10.8	32.7	64.4	1.0	3.1	6.9	40	43	51
Quercus robur L.	LTP,	4768			3.6	35.2	196.1	0.2	3.1	13.8	16	104	220
	Cape Town, South Africa		27	44									
Robinia pseudoacacia L.	Santiago de Chile, Chile		16	119	19.8	41.4	56.1	1.4	4.1	7.9	11	49	105
Sorbus aucuparia L.	LTP	19			4.0	14.0	25.5	0.7	1.7	2.7	21	44	57
Tilia cordata Mill.	LTP,	152			5.1	36.6	81.1	0.8	4.2	9.5	20	70	184
	Berlin, Germany	25	10	149									
Ulmus glabra Huds.	LTP	46			5.2	9.3	16.6	1.3	2.2	3.5	35	46	79

to α, which is the allometric exponent in Eq. (1a). The allometric exponent α can be understood as a distribution coefficient for the growth resources between organs y and x: when x increases by 1%, y increases by α %.

E.g. an individual tree diameter (d) – crown radius (cr) allometry with $\mathrm{cr} = \mathrm{b}d^{\alpha_{\mathrm{cr},d}}$ and $\alpha_{\mathrm{cr},d} = 0.5$ means that the crown radius increases by 0.5% when the tree diameter increases by 1%. The exponent α describes the slope when we plot $\ln(\mathrm{cr})$ versus $\ln(d)$. General allometric theory assumes $\alpha_{\mathrm{cr},d} = 2/3$ for the allometric ideal plant (West et al., 2009), i.e., when tree diameter increases by 1% crown radius should expand by 0.67%. However, recent publications stress that overarching scaling factors oversimplify plant allometry (Niklas, 2004) and that allometric exponent and factor may vary with species (Pretzsch, 2014), competition (Dieler and Pretzsch, 2013; Price et al., 2010; Purves et al., 2007), and age (Genet et al., 2011).

Determining upper, middle and low allometric relationships – Quantile regression

The crown radius–stem diameter allometry of open grown trees is most important for urban forestry. At a given stem diameter they exhibit the largest crown radii. For determining their allometry, the equation

$$\ln(\mathrm{cr}) = a + \alpha \times \ln(d) \tag{2}$$

therefore has to be fitted to the upper edge of the data cloud obtained when plotting $\ln(\mathrm{cr})$ against $\ln(d)$ with the former on the vertical and the latter on the horizontal axis.

For achieving this, we chose quantile regression (Koenker, 2013; Koenker and Hallock, 2001, see Rust, 2014, for an application to urban trees). This method allows fitting regression models to any desired conditional quantile of the dependent variable's distribution. In the context of our study this offered several advantages: We were not mainly interested in quantifying the conditional central tendency of the crown radius which would be the domain of the usual ordinary least squares (OLS) regression. Rather, quantifying the upper boundary relationship, i.e. the allometry of trees with a very broad crown at a given diameter, represent open-grown trees which are most typical for urban areas. Evidently, quantile regression also allows us to explore the lower boundary relationship which covers cramped trees with a very slender crown. We fitted Eq. (2) for the 95%-quantile (5% from above) in order to represent the open grown trees. In addition, we also fitted it for the 50%-quantile (the median) and the 5%-quantile in order to cover average and suppressed trees, respectively.

Another important benefit is that models fitted with quantile regression are invariant to monotone transformations. This means that there is no estimation bias when using the untransformed equation $\mathrm{cr} = e^{a} \times d^{\alpha}$ with the parameters a and α as obtained from fitting its logarithmic form which is technically much more convenient due to its linearity. It also means that the allometric relationship estimated for cr as the goal variable can be transformed bias-free into the allometric relationship for crown projection area cpa. Moreover, compared to OLS regression, quantile regression is robust against outliers.

Species grouping – Cluster analysis

For supporting practical applications we grouped the species-specific allometric relationships into a manageable number of allometric types. This grouping was based on two variables. The first

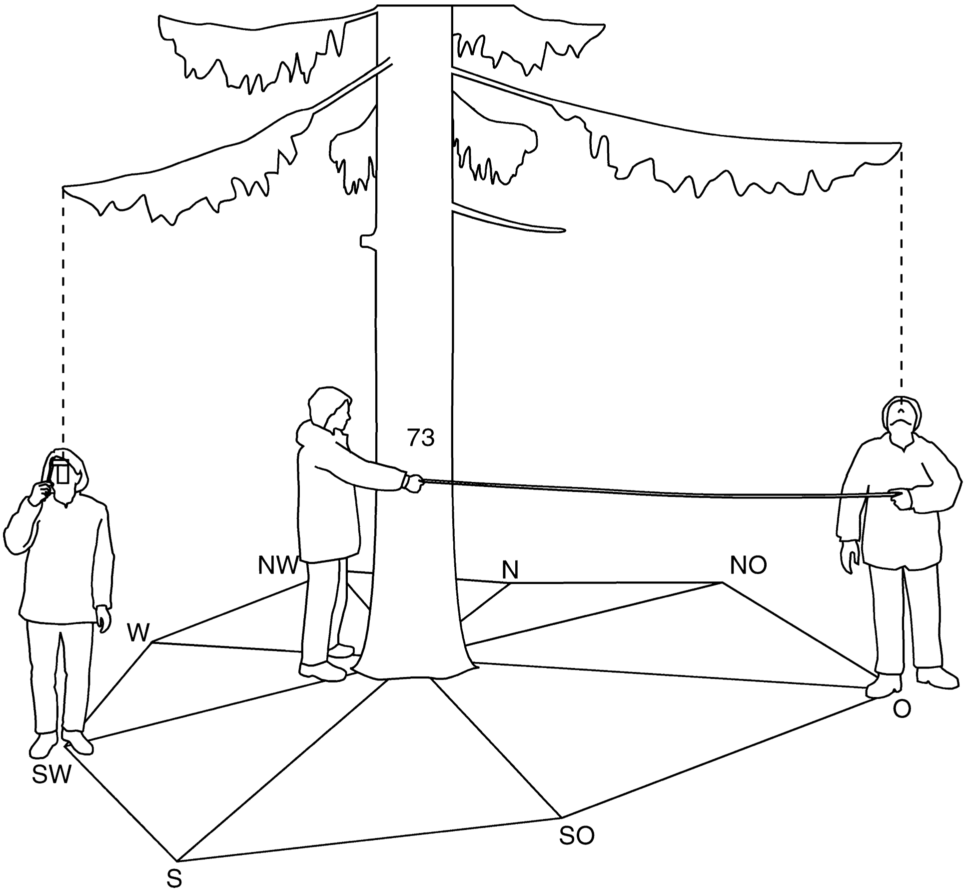

Fig. 1. Measuring crown radii and crown projection area via vertical sighting method (right person) (Preuhsler, 1979), or using a plummet according to Röhle (1986) (left person).

was cr_{25}, the species specific expected open-grown crown radius at a stem diameter of 25 cm, as estimated from the fitted allometric equation for the 95%-quantile. The second is α, the species-specific allometric slope for open-grown trees. The former introduces an absolute size measure, while the latter informs about how much the crown radius changes at a given diameter change.

Both variables were subjected to a k-means cluster analysis based on the algorithm by Hartigan and Wong (1979) which is recommended (R Core Team, 2014) as being generally more efficient than classic methods like MacQueen (1967), Forgy (1965), and Lloyd (1957/1982). Both variables, cr_{25} and α, taken as x in the following equation, were studentized before clustering by substracting their arithmetic mean and dividing by their sample standard deviation: $z_i = \frac{x_i - \bar{x}}{\sqrt{1/(n-1)\sum_k (x_k - \bar{x})^2}}$. This standardisation procedure ensured equal weighting of cr_{25} and α in the clustering process.

The optimal number of clusters was identified graphically by plotting the within group square sums against the corresponding number of clusters (Scree Plot). A bend in the resulting curve suggests an appropriate count of clusters (Everitt and Hothorn, 2009, p. 251).

By averaging the allometric slope α and cr_{25} per allometric type we obtained the mean determinants of the typical allometric relationship between crown radius and stem diameter. For application purposes we graphed and tabulated the resulting curves.

Additional relationships

While the typical cr–d-curves give an intuitive impression of intra-tree size relationships and should be used to identify allometric types with empirical data for tree species not covered in this study, we transformed them also into crown projection area (cpa)–stem diameter curves, simply based on the equation $cpa = cr^2 \times \pi$. This results in the allometric model

$$\ln(\mathrm{cpa}) = a' + \alpha' \times \ln(d) \qquad (3)$$

with $a' = \ln \pi + 2 \times a$ and $\alpha' = 2 \times \alpha$ when a and α are taken from Eq. (2). The cpa–d-curves show the diameter dependent growing space requirement for each allometric type. In addition, we took all data where tree heights h were measured and fitted the allometric model

$$\ln(h) = a + \alpha \times \ln(d) \qquad (4)$$

for describing the relationship between diameter and tree height. In order to cover open-grown trees, which have lowest heights at a given diameter, we fitted the model at the 5% conditional quantile. For the trees where crown length (cl) measurements were available, we fitted the following model with the crown volume cv (proxied by $cv = cpa \times cl$) as the goal variable at the 95% conditional quantile:

$$\ln(\mathrm{cv}) = a + \alpha \times \ln(d) \qquad (5)$$

By averaging, per allometric type, α from Eqs. (4) and (5) as well as h_{25}, and cv_{25}, the height and the crown volume estimated for a diameter of 25 cm, we obtained typical h–d, and cv–d-curves. The results were visualised in relation to the previously defined allometric types. As, in addition to crown radius, crown projection area, tree height and crown volumes are prominent proxy variables for photosynthesis rate, particle filtering potential, and shading in urban forestry (e.g. Berry et al., 2013), these outcomes provide useful information for practice.

Results

Inter-specific variation of the crown radius–stem diameter relationship

In Fig. 2a–d we show for all 22 included species the 95%, 50% and 5% quantile crown radius–stem diameter allometric regression lines (Eq. (2)). The 95% regression model reflects the species' radius under open grown conditions which might be relevant for e.g. spacing, distance-keeping and assessment of shading effects to buildings, recreational spaces, etc. Although the different species are covered with considerably different amounts of data (Table 1), the regression models, when plotted against the data, show intuitively plausible fits (Fig. 2a–d), the 50% quantile regression for *Sorbus aucuparia* (Fig. 2d) being the only exception.

Table 2 reflects the characteristics of the 95% quantile regression analysis for the crown radius–stem diameter relationship. The scaling parameter a did not significantly deviate from zero in some cases (e.g. *Aesculus hippocastanum*, *Fagus sylvatica*). This simply means that the factor e^a in the untransformed allometric relationship $\mathrm{cr} = e^a \times d^\alpha$ might be 1 in reality. In the context of this study, however, there is no reason not to use the original estimate. For the investigated species, factor a covers a range of approximately -1.8 up to 0.0 with values between -1.0 and -0.5 occurring most frequently (Fig. 3, left).

The allometric exponent α was always different from zero on a significance level of $p < 1/10{,}000$ (except for *Robinia pseudoacacia* where $p = 0.056$), and varied between $\alpha = 0.3899$ for *Araucaria cunninghamii* and $\alpha = 0.8276$ for *Picea glauca*. Species with low α-values expand their crowns only moderately with increasing stem diameter, values of 0.8 reflect wide-ranging cr with increases of stem size. As predicted by the allometric scaling theory (West et al., 2009) the estimates of α concentrate around 2/3 (Fig. 3, middle), but the scaling relationship between tree diameter and crown extension can also become much shallower (*A. cunninghamii, S. aucuparia*) or much steeper (*Quercus robur, P. glauca*) which shows that an overarching cr–d scaling of α=2/3 is an oversimplification.

A broad range can also be observed for the crown radius estimates that result from the presented values for factor a and exponent α and diameter $d = 25$ cm. The minimum and the maximum are 1.8 m (*A. cunninghamii*) and 5.2 m (*Ulmus glabra*), respectively, while values slightly greater than 3 m seem most probable (Fig. 3, right).

Species grouping by allometric properties

Graphical inspection of within group square sums against cluster count, suggested to form six clusters based on cr_{25} and α. These are visualised in Fig. 4, where each tree species is represented by a dot in the cr_{25}–α-plain. Each group of dots with the same colour represents a cluster. Each cluster was interpreted as a distinct allometric type, with the exception of clusters 1a (*Platanus* × *hispanica*, *Khaya senegalensis*, *A. hippocastanum*, *R. pseudoacacia*, *Tilia cordata*) and 1b (*U. glabra*, *Carpinus betulus*, *F. sylvatica*). Considering both neighbouring groups' range of cr_{25} and α values, we deemed them close enough for both clusters to be considered one common allometric type for the purpose of practical application.

Fig. 4 shows the result of the cluster analysis as well as the allometric types we assigned. Allometric type 1 "Large Crown Size–Moderate Allometric Slope" comprises *Platanus* × *hispanica*, *K. senegalensis*, *A. hippocastanum*, *R. pseudoacacia*, *T. cordata*, *U. glabra*, *C. betulus*, and *F. sylvatica*. Allometric type 2 "Medium Crown Size–Medium Allometric Slope" comprises *Larix decidua*, *Abies sachalinensis*, *Betula pendula*, *Pinus sylvestris*, *Alnus nigra*, and *Fraxinus excelsior*. Allometric type 3 "Medium Crown Size–Steep Allometric Slope" comprises *P. glauca*, *Q. robur*, and *Pseudotsuga menziesii*. Allometric type 4 "Medium Crown Size–Flat Allometric Slope" comprises *Acer pseudoplatanus*, *Picea abies*, *S. aucuparia*, and *Abies alba*. *A. cunninghamii* was distinctly discerned from all other clusters. This species seems to be a special case where a flat allometric slope is combined with small crown sizes.

For practical purposes we calculated species-overarching mean cr–d allometric lines for each allometric type that are shown in Fig. 5 (Table 3 for the parameters). If a species not covered by this study shall be attributed to one of these allometric types we suggest measuring several trees, preferably along a broad range of diameters. The cr–d pairs of values can then be charted in the diagrams. The typical allometric-type line they are nearest to would indicate which of the allometric types the species belongs to. The coloured areas around each line represent the allometric-type wise standard errors calculated from each species' predicted crown radius at any given diameter. Note, that allometric type 1 (large size, moderate slope) can be easily distinguished from all other allometric types. The medium-sized allometric types (2, 3, 4), however are hard to tell apart inside a diameter range of 20–50 cm. For smaller trees, the logarithmic representation (Fig. 5, left) offers a better distinction, while the standard scale (Fig. 5, right) works best for larger trees. The possibility to identify the allometric type for trees with stem diameters <20 cm is a helpful feature because these are typical tree sizes at which trees are planted in urban greening.

Additional allometric relationships

The allometric type specific crown projection area (cpa)–diameter (d) curves (Eq. (3)) are shown in Fig. 6. Their parameters can be taken from Table 3. As they are mere transformations of the crown radius–diameter allometry, they show just the same differentiation. At a stem diameter of 25 cm, the medium-sized allometric types (2, 3, 4) have crown projection areas of about 30 m^2, while allometric type 1 reaches more than the double value. Necessarily, the special case, *A. cunninghamii*, shows a very low cpa_{25} of 10 m^2 only.

A different view is obtained for the 5% quantile (which represents open-grown trees) fits of the tree height–stem diameter allometry (Eq. (4)). The distribution of the species specific estimates for the allometric exponent α (Table 4, Fig. 7, middle) – in most cases significant at $p < 1/10{,}000$ – shows a notable concentration in the range between 0.6 and 1.0 well in line with theory, which assumes values of either 2/3 or 1 (Pretzsch et al., 2012). Remarkably, the spread of heights expected at stem diameter $d = 25$ cm is high, covering a span between about five (*Platanus* × *hispanica*) and more than 20 m (*A. alba*) (Table 4, Fig. 7, right). *F. excelsior* and *U. glabra* were left out of this analysis due to an insufficient number of height measurements.

We aggregated the species specific height diameter allometries in the same way as described above for the previously defined allometric types (see Table 3 for the parameters and Fig. 8 for a visualisation). The order of the curves, as evident in Fig. 8, reveals a somewhat opposing pattern compared with crown radius–diameter allometry (Fig. 5). Allometric type 1 which shows broadest crowns at a given diameter has lowest heights while allometric type 4 – medium wide crowns, flat allometric slope – is highest at a given diameter, followed downwards by types 2 (medium crown width–medium slope) and 3 (medium crown width–steep slope). Only the special case *A. cunninghamii* (slender crown–flat slope) is not in line with this contrasting trend; its curve is very similar to allometric type 1. As can be seen best in the left diagram of Fig. 8 all aggregated allometric type lines have similar

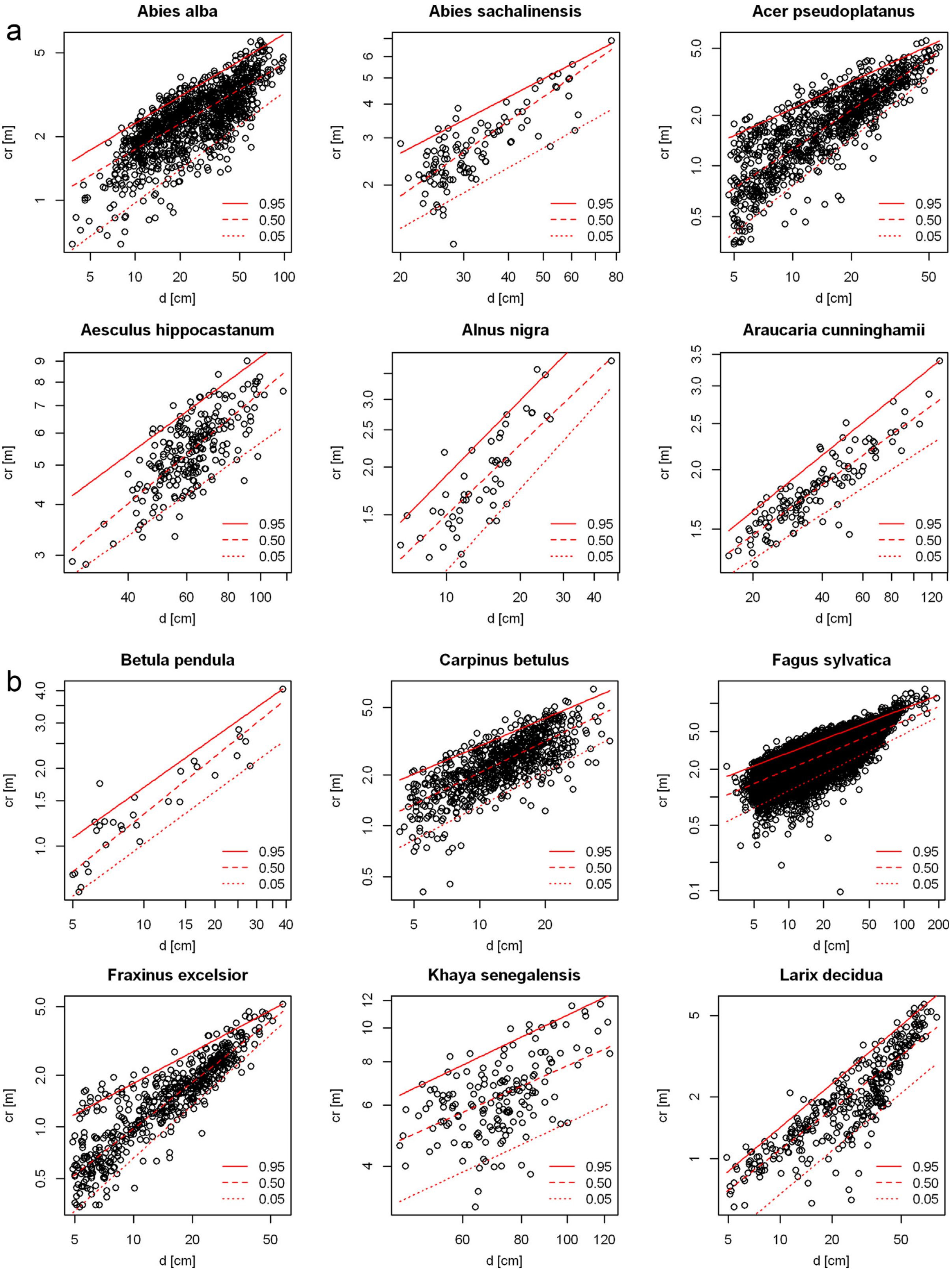

Fig. 2. (a) Quantile regression results (95%, 50%, and 5% quantiles) for the allometric relationship $\ln(cr) = a + \alpha \times \ln(d)$ for Species 1–6 (in alphabetical order). (b) The same for Species 7–12 (in alphabetical order). (c): The same for Species 13–18 (in alphabetical order). (d): The same for Species 19–22 (in alphabetical order).

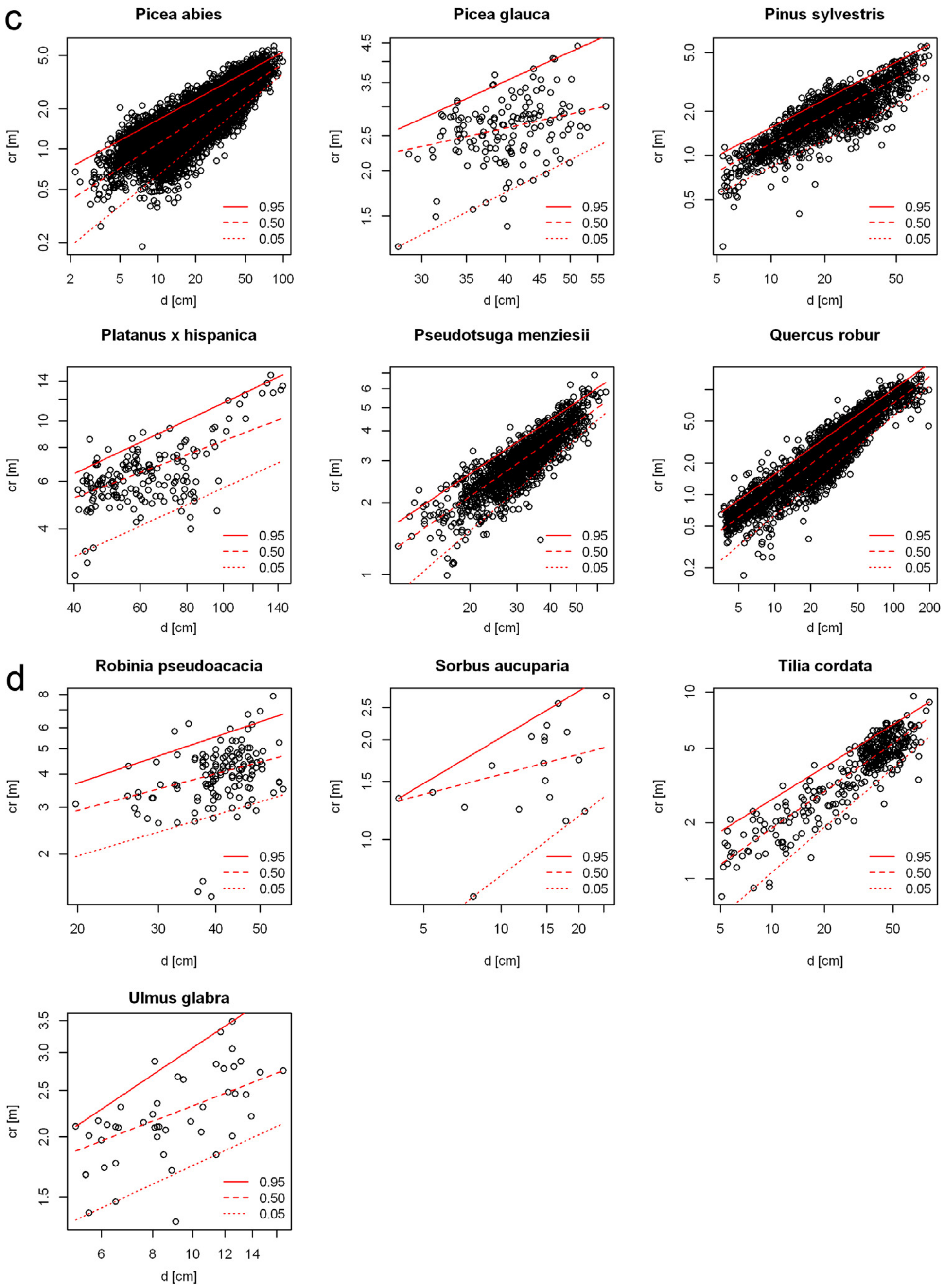

Fig. 2. (*Continued*)

slopes; thus, the differentiation mostly originates from the scaling factor *a*.

The species specific fitted allometric curves for crown volume cv relating to stem diameter *d* (Eq. (5)) show an even more distinct concentration of the α estimates (Table 5, Fig. 9, middle). Most of them are inside a range of 1.5 to 2.5, while 2.0 is the value following from theory for an allometrically ideal plant (West et al., 2009). Comparing the parameter estimates given in Tables 2–5 for the cr–*d*, *h*–*d*, and the cv–*d* relationship we see that in most cases roughly $\alpha_{\mathrm{cv},d} = 2 \times \alpha_{\mathrm{cr},d} + \alpha_{h,d}$ which is to be theoretically expected according to Pretzsch and Dieler (2011). When plotting the aggregated curves for the previously defined allometric types, the resulting picture does not show any differentiation at all (Fig. 10, parameter values in Table 3). This as well confirms a finding by Pretzsch and Dieler (2011) that, seemingly, tree allometry may be considerably different related to one-dimensional variables like tree height and crown radius; however, when a resulting variable with a three-dimensional meaning, like crown volume, is taken into account, the bandwidth is much narrower. Even *A. cunninghamii* does, unexpectedly, not deviate from the common field of curves which results from this species' extraordinary crown lengths.

Discussion

From describing to modelling tree crown. Evidence of species specific morphology

Quantitative knowledge of urban tree species' morphological shape and scaling is relevant for appropriate species selection, fixing the planting location, assessment of further growing space

Table 2

Quantile regression results for the crown radius–stem diameter allometry (Eq. (2), 95%-quantile). Sample size (n), parameter estimates (a, α) with standard errors (std. err.), and significances (p). cr_{25} is the species specific estimate for the crown radius at stem diameter = 25 cm.

Species	n	a	std.err. (a)	p (a)	α	std.err. (α)	p (α)	cr_{25}
Abies alba	1079	−0.1366	0.0508	0.0073	0.4239	0.0155	< 0.0001	3.4
Abies sachalinensis	110	−1.0972	0.4040	0.0077	0.6894	0.1163	<0.0001	3.1
Acer pseudoplatanus	942	−0.4446	0.0447	<0.0001	0.5339	0.0162	<0.0001	3.6
Aesculus hippocastanum	230	−0.5481	0.4700	0.2447	0.6011	0.1137	<0.0001	4.0
Alnus nigra	51	−0.8563	0.2258	0.0004	0.6507	0.0845	<0.0001	3.4
Araucaria cunninghamii	126	−0.6754	0.1232	<0.0001	0.3899	0.0340	<0.0001	1.8
Betula pendula	31	−0.9688	0.0766	<0.0001	0.6483	0.0316	<0.0001	3.1
Carpinus betulus	778	−0.1744	0.0711	0.0144	0.5470	0.0276	<0.0001	4.9
Fagus sylvatica	14,963	0.0111	0.0135	0.4118	0.4710	0.0045	<0.0001	4.6
Fraxinus excelsior	541	−0.8089	0.1288	<0.0001	0.6052	0.0470	<0.0001	3.1
Khaya senegalensis	163	−0.5889	0.3132	0.0619	0.6461	0.0732	<0.0001	4.4
Larix decidua	340	−1.2919	0.0576	<0.0001	0.7131	0.0176	<0.0001	2.7
Picea abies	10,775	−0.6713	0.0202	<0.0001	0.5083	0.0063	<0.0001	2.6
Picea glauca	143	−1.7910	0.2517	<0.0001	0.8276	0.0681	<0.0001	2.4
Pinus sylvestris	1609	−1.0345	0.0527	<0.0001	0.6381	0.0172	<0.0001	2.8
Platanus × *hispanica*	171	−0.5540	0.1873	0.0035	0.6532	0.0453	<0.0001	4.7
Pseudotsuga menziesii	1613	−1.2808	0.1006	<0.0001	0.7522	0.0291	<0.0001	3.1
Quercus robur	4839	−1.4370	0.0353	<0.0001	0.8157	0.0103	<0.0001	3.3
Robinia pseudoacacia	135	−0.4345	1.1200	0.6987	0.5822	0.3016	0.0557	4.2
Sorbus aucuparia	19	−0.3534	0.0750	0.0002	0.4621	0.0289	<0.0001	3.1
Tilia cordata	353	−0.3375	0.0728	<0.0001	0.5728	0.0208	<0.0001	4.5
Ulmus glabra	46	−0.2066	0.2005	0.3084	0.5763	0.0910	<0.0001	5.2

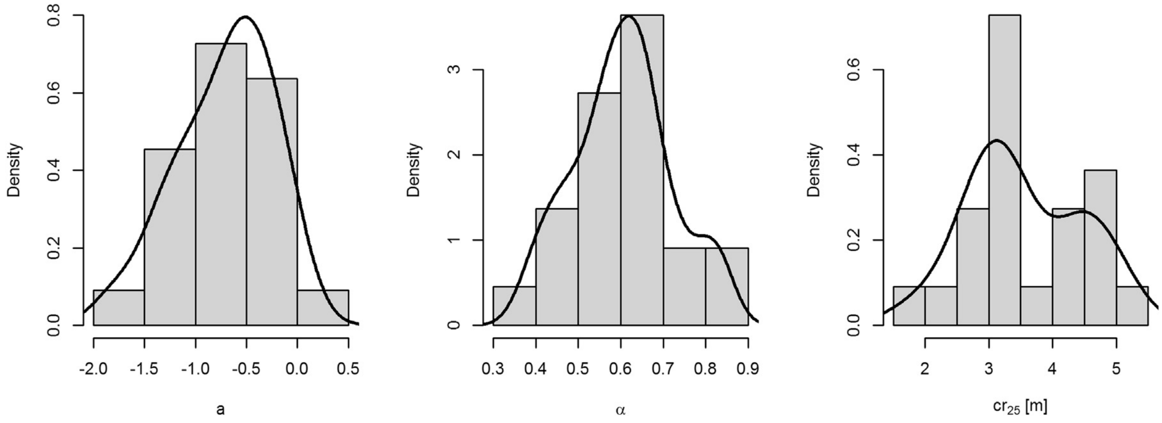

Fig. 3. Histograms and empirical density functions of the species specific parameter estimates (95% quantile regression) a (left) and α (middle) in the allometric relationship $\ln(cr) = a + \alpha \times \ln(d)$ (Eq. (2)). The rightmost histogram shows the distribution of the estimated crown radii cr_{25} which result for $d = 25$ cm.

requirement, and model-based prediction of functions and services. Knowledge on crown shape is available for a few often selected species in some ecoregions (Hasenauer and Monserud, 1996; Hasenauer, 1997; Pretzsch, 2009), but hardly summarized and available in standardized form. Our study includes 22 worldwide urban tree species and covers some typical for roads and boulevards (*Tilia, Robinina*), places (*Aesculus, Platanus*), and parks (e.g., *Larix, Pinus, Acer, Quercus*).

To our knowledge an overarching information base about the possible crown size of the 22 included urban tree species at a given diameter was so far not available. The presented figures and tables can also be used for other species if their type of crown allometry

Table 3

Parameters for the four investigated allometric relationships per allometric type. d: stem diameter in breast height (cm), cr: crown radius (m), cpa: crown projection area (m^2), h: tree height (m), cv: crown volume (m^3). The slope α was obtained by averaging the species specific slopes per allometric type, tree size cr_{25}, h_{25}, cv_{25} at $d = 25$ cm was also obtained by averaging the species specific estimates per allometry type. With α and tree size at $d = 25$ known, a could by simply obtained by rearranging the respective equation. As cpa is a mere transformation of cr $\left(cpa = cr^2 \times x\right)$, the parameters of the latter could be calculated from the former.

Allometric type	$\ln(cr) = a + \alpha \times \ln(d)$ (Eq. (2))			$\ln(cpa) = a' + \alpha' \times \ln(d)$ (Eq. (3))			$\ln(h) = a + \alpha \times \ln(d)$ (Eq. (4))			$\ln(cv) = a + \alpha \times \ln(d)$ (Eq. (5))		
	a	α	cr_{25}	a'	α'	cpa_{25}	a	α	h_{25}	a	α	cv_{25}
1 Large Size – Moderate Slope	−0.3512	0.5812	4.6	0.4424	1.1624	65.6	0.2520	0.6291	9.7	1.2816	1.6195	661.5
2 Medium Size – Medium Slope	−1.0065	0.6575	3.0	−0.8683	1.3149	28.9	0.5303	0.6736	14.9	1.6584	1.5527	777.7
3 Medium Size – Steep Slope	−1.4936	0.7985	2.9	−1.8424	1.5970	27.1	0.2832	0.6961	12.5	−0.8845	2.0549	307.9
4 Medium Size – Flat Slope	−0.3947	0.4821	3.2	0.3554	0.9641	31.8	0.5080	0.7338	17.6	0.2008	1.8791	517.6
Special Case: Small Size – Flat Slope	−0.6754	0.3899	1.8	−0.2061	0.7797	10.0	0.1012	0.6586	9.2	−0.9404	2.1499	395.3

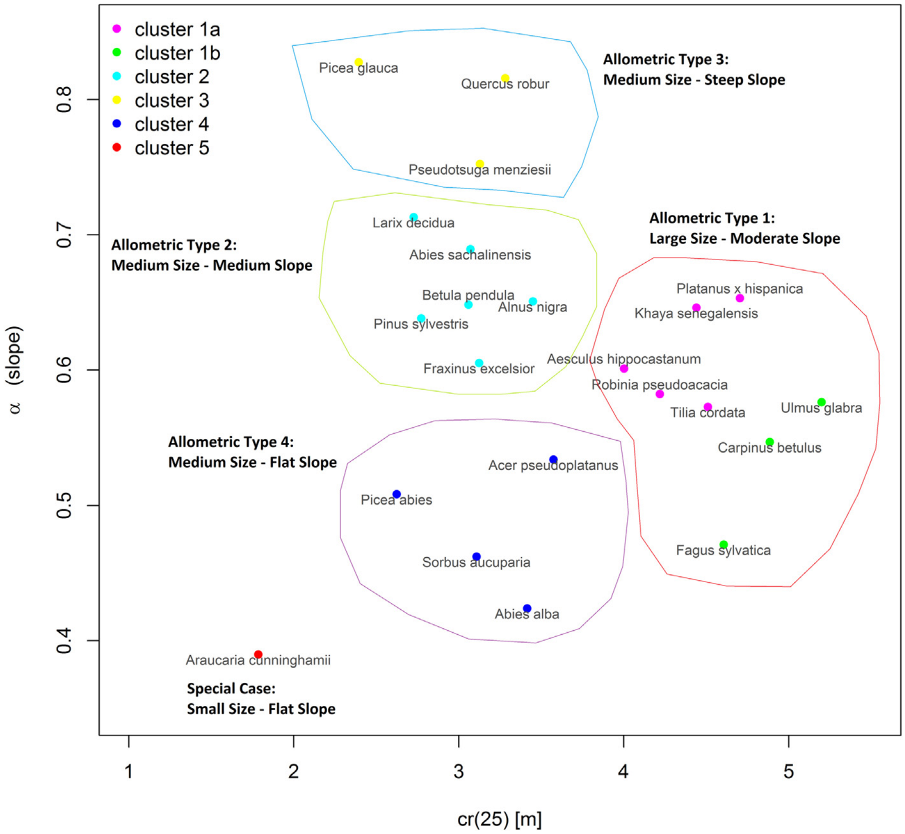

Fig. 4. Species clusters (equally coloured points) based on the parameter estimate for α (Eq. (2)) obtained by 95%-quantile regression and cr(25), the 95%-quantile crown radius estimated for a stem diameter of 25 cm. The six clusters obtained by k-means clustering were aggregated into four allometric types (marked with coloured outlines) for practical purposes. *Araucaria cunnignhamii* was considered a special case as it was clearly separated from all other clusters.

is analogous to one of the tree species covered by this study. The data base for fitting the regression functions is well-grounded for most of the species. Even when the sample size is below $n = 100$ the measured trees cover a broad spectrum of tree sizes and tree ages fairly well. The scatter diagrams of crown size over diameter and tree diameter over age represent the species specific behaviour in terms of crown plasticity and growth rate variability enabling stable model fitting quite well.

The sample size is high for most of the investigated species. In case of species less frequent in forests and rarely grown in cities (e.g.

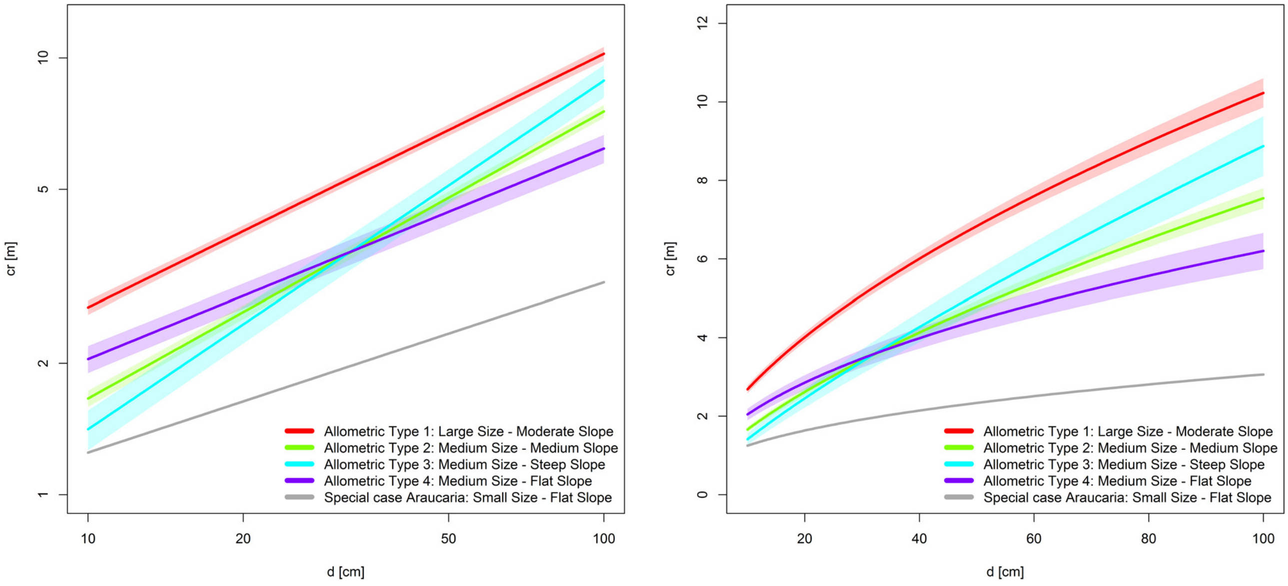

Fig. 5. Crown radius (cr)–diameter (d) allometry for the identified allometric types in logarithmic scale (left) and normal scale (right). Bold lines: Species-overarching mean curves per allometric type. Coloured areas: Standard error of the species specific predicted crown radii per allometric type. Colours correspond to the allometric type outlines in Fig. 4.

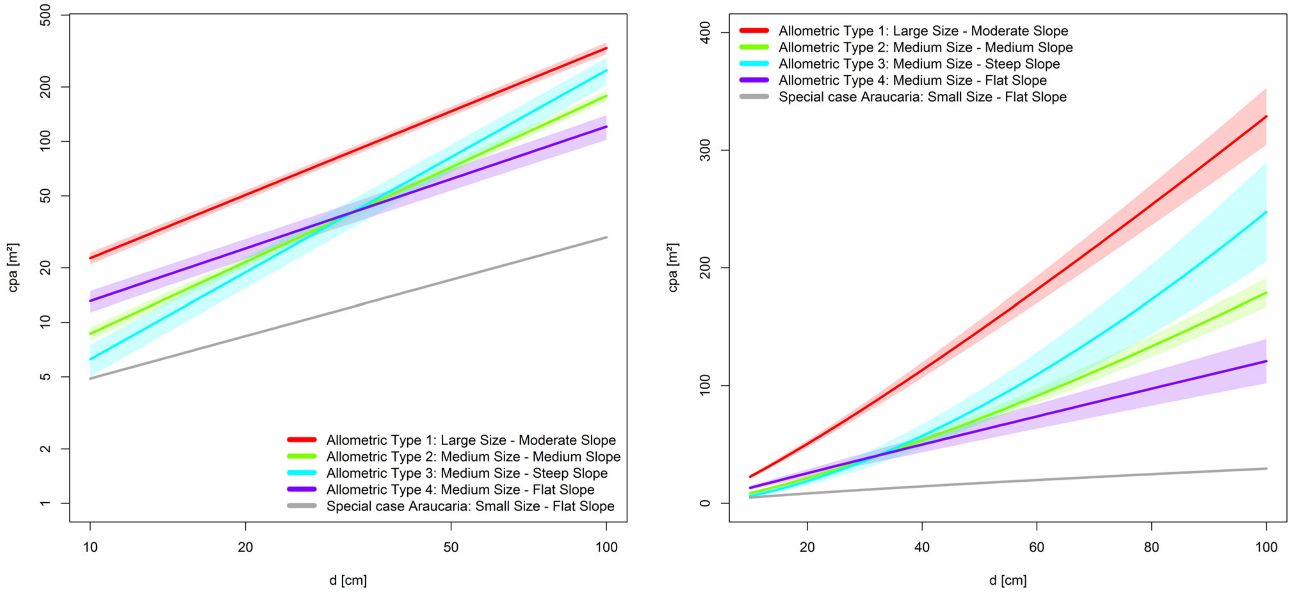

Fig. 6. Crown projection area (cpa)–diameter (d) allometry for the identified allometrictypes in logarithmic scale (left) and normal scale (right). Bold lines: Species-overarching mean curves per allometric type. Coloured areas: Standard error of the species specific predicted crown radii per allometric type. Colours correspond to the allometric type outlines in Fig. 4.

Table 4

Quantile regression results for the tree height–stem diameter allometry (Eq. (4), 5%-quantile). Sample size (n), parameter estimates (a, α) with standard errors (std. err.), and significances (p). h_{25} is the species specific estimate for the height at stem diameter = 25 cm.

Species	n	a	std.err. (a)	p (a)	α	std.err. (α)	p (α)	h_{25}
Abies alba	534	0.8278	0.0549	<0.0001	0.6948	0.0201	<0.0001	21.4
Abies sachalinensis	110	1.2821	0.4121	0.0024	0.3843	0.1186	<0.0001	12.4
Acer pseudoplatanus	3248	0.9669	0.0376	<0.0001	0.5858	0.0112	<0.0001	17.3
Aesculus hippocastanum	231	−0.1019	0.3367	0.7624	0.6281	0.0816	<0.0001	6.8
Alnus nigra	687	0.0800	0.1119	0.4749	0.8645	0.0436	<0.0001	17.5
Araucaria cunninghamii	126	0.1012	0.2568	0.6942	0.6586	0.0708	<0.0001	9.2
Betula pendula	26	0.6952	0.1773	0.0006	0.5490	0.0768	<0.0001	11.7
Carpinus betulus	9011	0.5009	0.0251	<0.0001	0.7246	0.0082	<0.0001	17.0
Fagus sylvatica	640	−0.2154	0.0764	0.0049	0.8607	0.0235	<0.0001	12.9
Khaya senegalensis	144	−0.4335	0.5412	0.4244	0.7724	0.1268	<0.0001	7.8
Larix decidua	833	0.8585	0.0860	<0.0001	0.6378	0.0317	<0.0001	18.4
Picea abies	6713	−0.1753	0.0347	<0.0001	0.9113	0.0108	<0.0001	15.8
Picea glauca	143	0.9573	1.0950	0.3835	0.5714	0.2962	0.0557	16.4
Pinus silvestris	331	−0.3449	0.1807	0.0572	0.9326	0.0552	<0.0001	14.3
Platanus × hispanica	170	−0.9138	1.0252	0.3740	0.8221	0.2479	0.0011	5.7
Pseudotsuga menziesii	2677	0.1377	0.0433	0.0015	0.8005	0.0133	<0.0001	15.1
Quercus robur	69	−0.5239	0.2355	0.0295	0.7163	0.0551	<0.0001	5.9
Robinia pseudoacacia	136	0.7198	1.3752	0.6016	0.3930	0.3705	0.2907	7.3
Sorbus aucuparia	45	0.3818	0.1747	0.0344	0.7431	0.0790	<0.0001	16.0
Tilia cordata	264	1.7286	0.4030	<0.0001	0.2029	0.1069	0.0589	10.8

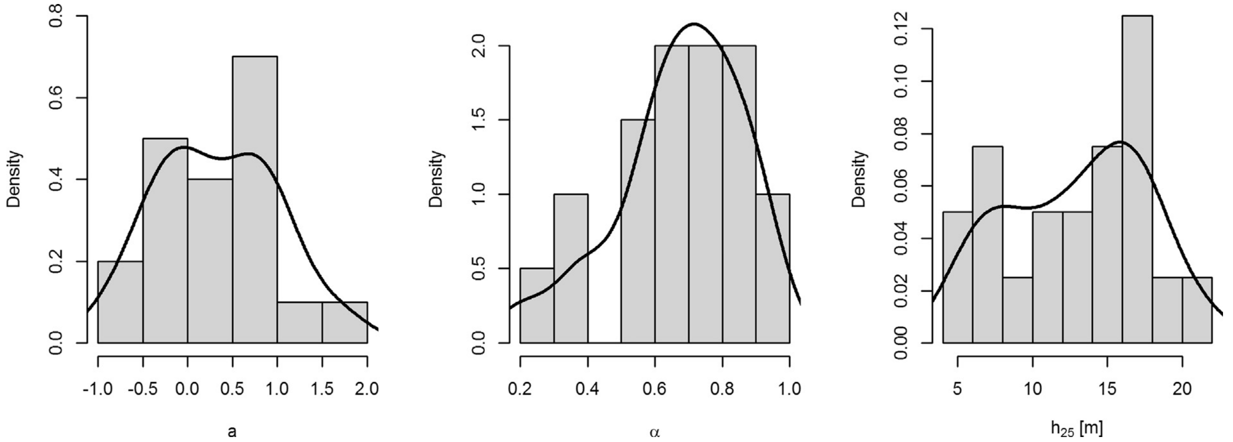

Fig. 7. Histograms and empirical density functions of the species specific parameter estimates (95% quantile regression) a (left) and α (middle) in the allometric relationship $\ln(h) = a + \alpha \times \ln(d)$ (Eq. (4)). The rightmost histogram shows the distribution of the estimated tree heights h_{25} which result for $d = 25$ cm.

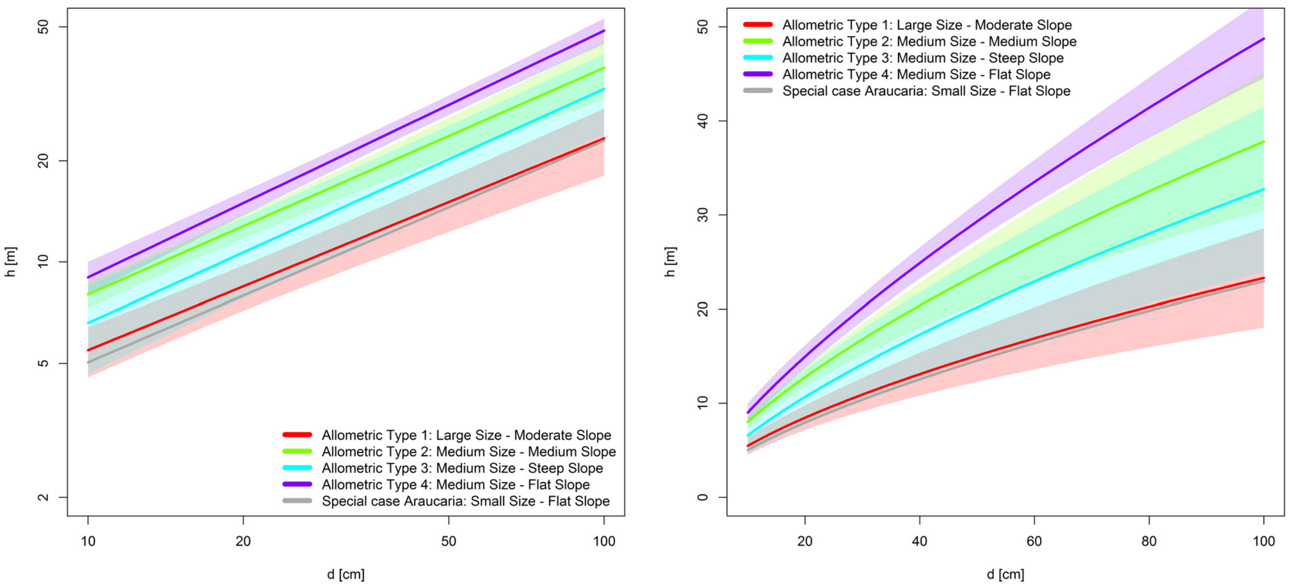

Fig. 8. Tree height (h)–diameter (d) allometry for the identified allometric types in logarithmic scale (left) and normal scale (right). Bold lines: Species-overarching mean curves per allometric type. Coloured areas: Standard error of the species specific predicted crown radii per allometric type. Colours correspond to the allometric type outlines in Fig. 4.

Table 5
Quantile regression results for the crown volume–stem diameter allometry (Eq. (5), 95%-quantile). Sample size (n), parameter estimates (a, α) with standard errors (std. err.), and significances (p). cv$_{25}$ is the species specific estimate for the height at stem diameter = 25 cm.

Species	n	a	std.err. (a)	p (a)	α	std.err. (α)	p (α)	cv$_{25}$
Abies alba	534	0.2255	0.2002	0.2605	1.8276	0.0731	<0.0001	449.5
Abies sachalinensis	110	5.6954	0.5228	<0.0001	0.5162	0.1505	0.0009	1567.2
Acer pseudoplatanus	3248	−1.1370	0.0689	<0.0001	2.1341	0.0206	<0.0001	308.7
Aesculus hippocastanum	231	0.9504	1.2272	0.4395	1.6274	0.2973	<0.0001	487.2
Alnus nigra	687	0.5676	0.2762	0.0402	2.0317	0.1075	<0.0001	1220.8
Araucaria cunninghamii	126	−0.9404	1.0687	0.3806	2.1499	0.2946	<0.0001	395.3
Betula pendula	26	0.5019	0.1943	0.0163	1.6244	0.0841	<0.0001	308.2
Carpinus betulus	9011	2.1880	0.0444	<0.0001	1.4570	0.0145	<0.0001	970.5
Fagus sylvatica	640	0.8528	0.1601	<0.0001	1.6104	0.0492	<0.0001	418.5
Khaya senegalensis	144	0.0830	1.3956	0.9527	1.9032	0.3269	<0.0001	497.3
Larix decidua	833	0.7781	0.1653	<0.0001	1.7334	0.0610	<0.0001	576.9
Picea abies	6712	−0.1639	0.0728	0.0243	1.7394	0.0226	<0.0001	229.3
Picea glauca	143	−2.2211	0.7142	0.0023	2.4136	0.1932	<0.0001	256.7
Pinus silvestris	331	−0.6073	0.2320	0.0093	1.8579	0.0708	<0.0001	215.5
Platanus × hispanica	170	1.5408	0.3606	<0.0001	1.5931	0.0872	<0.0001	787.4
Pseudotsuga menziesii	2677	−0.2241	0.0967	0.0205	1.9781	0.0298	<0.0001	465.5
Quercus robur	940	−0.4008	0.1443	0.0056	1.7729	0.0446	<0.0001	201.5
Robinia pseudoacacia	136	1.5883	2.5233	0.5301	1.5542	0.6798	0.0238	728.6
Sorbus aucuparia	45	1.1448	0.2721	0.0001	1.8151	0.1230	<0.0001	1083.0
Tilia cordata	339	1.4866	0.2121	<0.0001	1.5911	0.0598	<0.0001	741.2

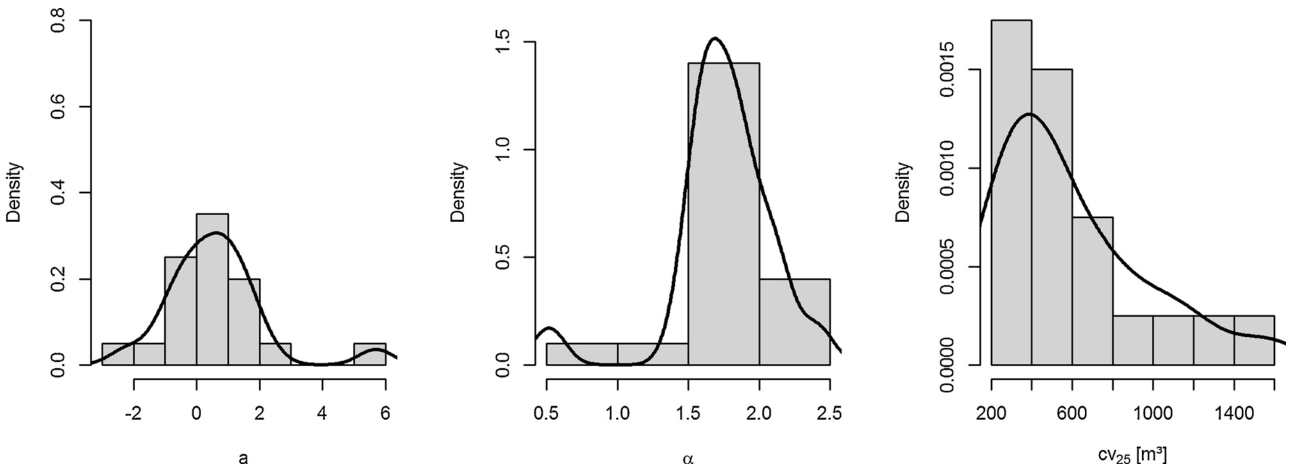

Fig. 9. Histograms and empirical density functions of the species specific parameter estimates (95% quantile regression) a (left) and α (middle) in the allometric relationship $\ln(cv) = a + \alpha \times \ln(d)$ (Eq. (5)). The rightmost histogram shows the distribution of the estimated crown volumes cv$_{25}$ which result for $d = 25$ cm.

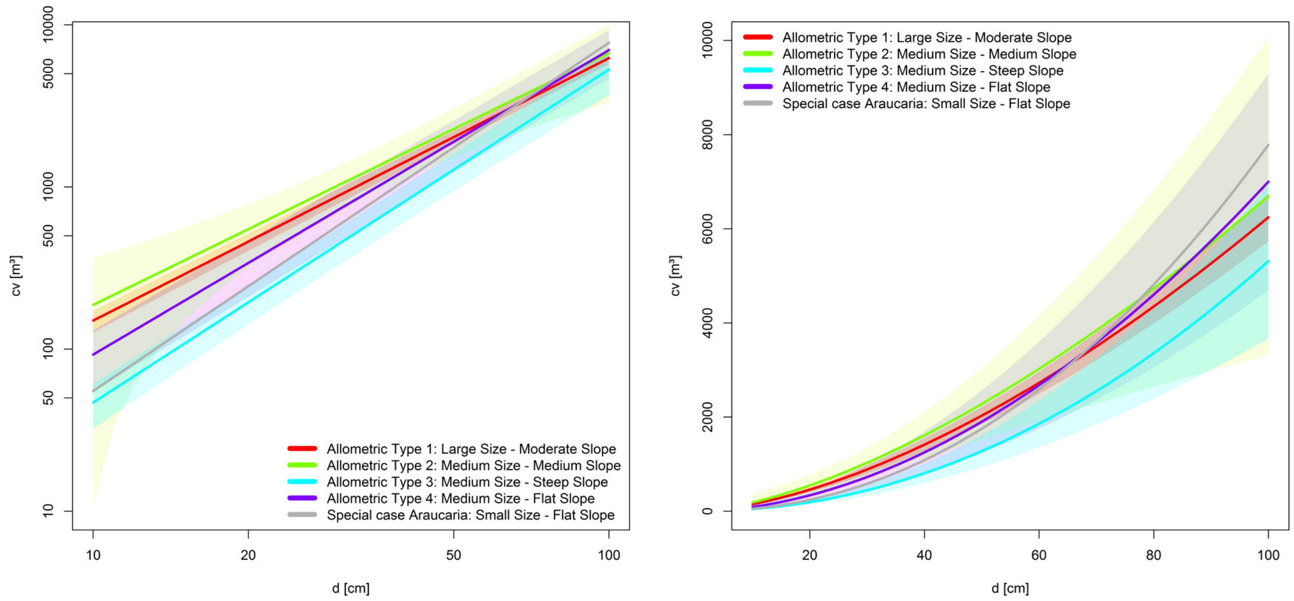

Fig. 10. Crown volume (cv)–diameter (*d*) allometry for the identified allometric types in logarithmic scale (left) and normal scale (right). Bold lines: Species-overarching mean curves per allometric type. Coloured areas: Standard error of the species specific predicted crown radii per allometric type. Colours correspond to the allometric type outlines in Fig. 4.

S. aucuparia, *B. pendula*, *U. glabra* and *A. nigra*) as well as in case of species from tropical and subtropical zones sample size is relative small. However, even for species with small sample sizes the range of covered tree sizes is rather wide and provides a sound basis for fitting the regressions for the allometric relationships considered in this study.

The included species cover a broad range of crown morphology and crown expansion types. The range can be demonstrated by calculation of the expected crown radius for trees with stem diameter of 25 cm. These radii range between 1.8 m (*A. cunninghamii*) and 5.2 m (*U. glabra*). However, it is remarkable that most of the included species concentrate around 3–4 m radius for a tree with $d = 25$ cm. These radii refer to the maximum crown expansion (95%-quantile) which is most relevant for any planning and prognosis, as it indicates the growing space requirement for a tree growing without lateral restrictions.

As our data base covers open-grown trees as well as trees which developed under medium or strong lateral restrictions, we can also provide species-specific mean and minimum crown radii which might be of interest for predicting the space requirement of trees in denser planting schemes (places, parks, municipal forests).

In contrast to stem diameter, tree height, or tree mass, measurements of crown dimensions (height to crown base, crown length, width, and crown projection area) are much more complicated and rare. To our knowledge, the authors' dataset is rather unique comprising standardised crown measurements since the 1950s. Compared with other more specific or fragmentary crown studies (Alves and Santos, 2002; Monserud and Marshall, 1999; Osunkoya et al., 2007) the reported species-specific allometric relationships and underlying dataset have the advantage of (i) a wide range of boreal, temperate, mediterranean, and subtropical tree species with different ecological and morphological traits, (ii) a wide range of neighbourhood conditions including trees growing in maximum density and solitarily, (iii) availability of combined measurements of several crown measures at the same tree, so that the convex hull can be derived, (iv) combination of trees in urban and rural areas, (v) standardized crown measurements according to Röhle (1986), Röhle and Huber (1985) and Pretzsch (2009, pp. 115–118).

Allometric models

Allometric theory predicts species specific intercepts a, but species overarching exponents $\alpha = 2/3$ for the relationship $\mathrm{cr} = e^{a} \times d^{\alpha}$ $(\ln(\mathrm{cr}) = a + \alpha \times \ln(d))$ for the allometric ideal plant (Enquist et al., 2009; West et al., 2009). In contrast, our analysis reveales a broad variation for the allometric factor a, but also for exponent α. Factor a represents a multiplicative effect of species on the crown expansion. Species specific differences of exponent α result in an exponential difference in the dynamic of the crown expansion with increasing size. The same is true in principle for the tree height–stem diameter allometry, where, however, the allometric factor a varies more than the exponent. Remarkably, though, there is much less differentiation in the crown-volume–stem diameter allometry, which is largely in line with findings and considerations by Pretzsch and Dieler (2011). Clustering the species specific results leads to five distinct allometric types that show no clear conformance with phylogenetic relatedness. Only Allometric Type 1 which consistently exhibits broadest crowns at given stem diameters exclusively comprises broadleaved species and no conifers. Thus, for applying the allometric types to species which are not covered by this study in practice, it seems not feasible to simply assume that species of the same genus will belong to the same allometric type. Instead, we suggest measuring crown radii and stem diameters of a sample of the species in question and compare the values with Fig. 5 in order to identify the allometric type that fits best.

Temporal dynamics

Note that the allometric relationships presented in this study provide information about the crown dimensions that can be expected at given stem diameters, however, they do not inform us about the time dimension, i.e. whether a certain tree size will be achieved earlier or later. The rate of stem diameter growth is highly variable which forbids constructing general age–diameter relationships. However, if the age of a given tree is known, or if diameter growth in the last decades is available from increment coring samples or occasionally felled trees, time-specific extrapolations become feasible.

Application of the derived models for crown size and shape

Based on vertical and lateral crown expansion (height, height to crown base, crown diameter) many tree characteristics, functions, and services can be derived. Crown volume can be calculated and used as a proxy for leaf area, transpiration, and filtering fine particulates. Crown cross section area may be used for estimating the shading function, and tree height, diameter, and crown width may be used for estimating tree growth and carbon sequestration. Peper et al. (2001) or Troxel et al. (2013) for example calculated volume and crown dimensions of different urban tree species for the US cities New Haven, CT and Modesto, CA based on allometric equations using the tree diameter as explanatory variable. However, local site conditions such as soil characteristics and climate clearly influence allometric models (Urban et al., 2010). Consequently, information about the aboveground and belowground structure of urban trees, particularly for different age classes, might support urban green space planning.

Worldwide, urban areas increase at the expense of forests. Therefore, through land cover changes also biomass and carbon fixation rates change (e.g. Hutyra et al., 2011). The differences in the carbon storage of urban trees were shown by McHale et al. (2009) estimating the biomass based on tree size.

If crown dimensions and growing space of urban tree species (maximum values but also dynamics) are known, the cooling effect of single trees can be determined. In urbanized areas clear relationships between the surface temperatures and the vegetation fraction can be found (e.g. Heldens et al., 2013). This vegetation effect of reducing temperature is caused by both shading and transpiration withdrawing energy from the atmosphere. It depends on “abiotic” variables like solar radiation, wind velocity, or vapour pressure (Lin and Lin, 2010) as well as on “biotic” variables like size of trees or the green space and species composition (Souch and Souch, 1993; Berry et al., 2013; Leuzinger et al., 2010; Oliveira et al., 2011) or species specific parameters such as foliage density, leaf colour or leaf thickness (Lin and Lin, 2010). Souch and Souch (1993) for example found a reduction in temperature and an increase in relative humidity underneath the trees’ crown for three different species under different site conditions (parks, gardens and streets). This way, along with climate and soil conditions, transpiration can vary in a wide range depending on species specific crown dimensions and the LAI of a tree. Enlarging a tree’s crown area (e.g. by growth) will cause stronger cooling effects not only by increasing the shading area but also by increasing the leaf area for transpiration.

Cooling effects reduce surface temperature underneath and around the vegetation clearly (e.g. Armson et al., 2012; Declet-Barreto et al., 2013; Lin and Lin, 2010; Oliveira et al., 2011). Increasing the vegetation fraction – either by establishing new green areas or by plant growth (i.e. by enlarging the crown area) – will reduce surface and air temperature (e.g. Sailor, 1998; Heldens et al., 2013). Based on crown dimensions of urban trees (e.g. cross section area, volume) cooling effects by shading and transpiration can be quantified.

Nowak et al. (2013, 2014) and Dobbs et al. (2014) report about the effects of trees on air quality through air pollution removal. The filtering of fine particulates by trees is depending on the total leaf area of a tree and on the physical properties (e.g. specific leaf area, hair density, roughness) of the leaf surfaces (Beckett et al., 1998; Sæbø et al., 2012). This way, the capturing of particulate matter is strongly related to the tree species. Yin et al. (2011) could show that crown size (crown volume coverage) can be used as a key predictor to estimate the pollutants removal rate. On the other hand, feedback reactions have to be taken into account as air pollution can change tree properties such as LAI (Gratani and Varone, 2007).

Additional urban green spaces also fulfil an important function for landscape enhancement and noise reduction (e.g. Carinanos et al., 2014). On the other hand, the role of trees in providing emission of ozone precursors of urban areas, i.e. biogenic volatile organic compounds BVOC, has to be considered (Calfapietra et al., 2013). The contribution to the photochemical reactivity of BVOC in the urban environment is species specific and this way closely related to plant quantity and diversity in urban areas (Calfapietra et al., 2013). Further on, pollen emission by plants affects human health by causing allergies (Carinanos et al., 2014). And Bosch-Cano et al. (2011) report that pollen exposures are closely related with the urbanization gradient, while allergenic pollen exposure was found to be higher in rural areas than in urban areas.

Conclusion

Large crown sizes, tree heights and exponential crown expansion may have desired effects as shading or filtering of fine particulars. It may also have negative effects as interference with neighbouring road traffic or electric circuit lines. Because of its exponential effect accurate prediction of the species-specific allometric exponent appears most important. Our results support the estimation of species specific space requirements and evaluation of connected benefits and risks of trees in urban planning processes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ufug.2015.04.006

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