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Defining the allometry of stem and crown diameter of urban trees

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ABSTRACT

There is a strong allometric relationship between stem diameter at breast height (DBH) and crown diameter in healthy trees in the young to mature stages of their growth. How do geographical position, site conditions and management treatments influence this relationship?

This study included only free-standing urban trees, thus providing data on the growth potential of the species included in the survey in typical urban conditions by linking this with estimated tree age.

Fieldwork involved recording the dimensions and growing conditions of 400 urban trees in two UK cities; Norwich and Peterborough. Species selected for this study were pedunculate oak (*Quercus robur* L.), sycamore (*Acer pseudoplatanus* L.), silver birch (*Betula pendula* Roth.) and Norway maple (*Acer platanoides* L.).

The mean relationship between DBH and crown diameter exhibited a restricted range (a ratio of 24 to 27) in this large sample. The results indicated that the factor of species did not have a strong impact on the allometric relationship in the case of the four species measured. It is therefore possible to produce good predictions of crown size by combining data from all the species used in this survey.

A key finding of this study is that previous tree pruning and external site factors, such as hard surfacing over the rooting area and soil type, had no significant influence on the relationship between DBH and crown diameter.

1. Introduction

This study focuses on the allometric relationship between DBH and crown diameter. The ability to predict crown diameter from DBH and *vice versa* has a wide range of applications in arboriculture and urban forestry, especially the ability to manage trees to enhance their crown diameter and hence overall canopy cover in urban areas.

Urban trees provide many beneficial ecosystem services and if measurements of DBH can be confidently used to calculate crown diameter, better estimates of ecosystem services provided by urban trees could be made from more easily collected data. It is important to recognise that most of the ecosystem services provided by urban trees are directly related to their crown dimensions. The following examples demonstrate the relevance of canopy size to the magnitude of the benefits gained from urban trees. The larger crowns of open grown urban trees sequester more carbon than typical woodland trees (Nowak and Crane, 2002). Trees also provide important shading and cooling, for example, research by Shashua-Bar et al. (2010) in Tel Aviv, Israel found a strong link between canopy size and mitigation of the urban heat island effect. Additionally, surface water runoff from hard surfaces, which leads to flooding in urban areas, can be mitigated by trees and the amount of mitigation is directly related to the extent of canopy cover provided (Armson et al., 2013). As a final example, trees can contribute towards improving air quality, with increased canopy cover providing greater mitigation from air pollution (Nowak et al., 2006).

A better understanding of crown spread over time would also aid the management of trees in relation to urban development. For example, development of crown spread and branch extension can cause legal nuisances in the urban environment (Lyytimäki et al., 2008; Lyytimäki and Sipilä, 2009), e.g. where branches come into contact with adjacent property (Mynors, 2011). A better knowledge and application of tree growth patterns could help reduce instances of this form of nuisance and thus reduce the need for tree pruning. Furthermore, where trees are found within a proposed development site, the ability to predict crown diameter has applications both at the pre-development survey stage, by allowing quick estimates of crown spread from DBH measurements, and also at the design stage if reliable predictive equations for ultimate crown diameters can be formulated to allow better placement and retention of trees within developments.

Knowledge of tree crown development has the potential to reduce tree numbers used in some urban planting schemes. Smaller numbers of successful tree plantings in positions that will not necessitate frequent pruning or thinning could provide substantial economic benefits in terms of reducing the costs of tree planting, maintenance and

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intervention. Avoiding wounding trees via pruning processes because they are well-placed would also promote greater longevity in urban trees. Focusing resources onto smaller numbers of young trees should help ensure that funds are available for ongoing and careful maintenance through to establishment in the landscape.

There has been increasing interest in this relationship between DBH and crown spread in urban trees from arboriculturists and urban foresters in the last twenty years, particularly with the increased availability of tree population data (Nowak et al., 2018). The interest in calculating the ecosystem services provided by urban tree stocks has also been a driver in this respect (Troxel et al., 2013). Researchers have approached the study of the allometric relationship in different ways, undertaking small detailed studies and wider studies based on mass tree population data. Peper et al. (2001a,b) carried out a small-scale study sampling fifteen species of street trees and 480 individual trees in California, to produce equations for predicting tree dimensions including DBH and crown diameter. Three recent large-scale studies have also been published. First, Pretzsch et al. (2015) conducted a large, worldwide study which attempted to match results against allometric theory. Second, McPherson et al. (2016) produced an extensive urban tree database in the USA, providing predictive allometric equations covering a range of climate zones. Third, Vaz Monteiro et al. (2016) analysed the i-Tree data for eight British cities to compare this allometric relationship in seven tree species. The resultant analysis found significant variation between these regional centres, but the cause(s) of this variation was not determined.

The small-scale study presented here is designed to improve predictions by exploring the extent of variation of the allometric relationship between DBH and crown diameter between sites and assess the impact of urban site factors, which is one of the key areas of divergence in the literature. Dawkins (1963) noted that the relationship was little affected by site, tree age and silvicultural treatments. This finding has been corroborated by other researchers (Krajicek et al., 1957; Hummel, 2000; Stoffberg et al., 2008; Blanchard et al. 2016). Furthermore, Hasenauer (1997) found site factors little affected regression analyses in a study of open grown trees. However, this contrasts with findings from more recent studies that reported significant regional variations (Urban et al., 2010; Lines et al., 2012; Vaz Monteiro et al., 2016).

This study also attempts to examine the trees' age in relation to crown diameter. Recent studies of growth rates of urban trees include the work of Monteiro et al. (2017) which examined trees in five UK cities, including Peterborough; however, the conditions of this study were not directly comparable, with the data collected for our study.

The three primary aims of our research were as follows. First, to define the allometric relationship between DBH and crown diameter in free-standing urban trees of four common species. Second, to explore the impact of geographic and site factors on this allometric relationship. Third, to provide a guide to ultimate growth potential for two of the species included in the study where current growth rates were measured to estimate tree age for a given DBH.

2. Materials and methods

2.1. Data collection

This study surveyed only free-standing urban trees, which included street trees and trees in city parks or other urban green space. All data were collected within the boundaries of two selected cities: Norwich and Peterborough, UK (Fig. 1), with Peterborough being situated 124 kilometres west of Norwich. A wide range of age classes were sampled from recently established young trees to large mature specimens.

An initial pilot study in 2013 measured 100 trees in Norwich. The trees measured in the pilot study in Norwich included 50 oak and 50 sycamore. Further to this, 400 free-standing urban trees were surveyed in 2016-17, including re-surveying all 100 trees used in the pilot study. The four tree species measured for the main study were pedunculate oak (*Quercus robur* L.), silver birch (*Betula pendula* Roth.), sycamore (*Acer pseudoplatanus* L.) and Norway maple (*Acer platanoides* L.). The main study was completed in the winter 2016/2017, surveying 200 trees in Peterborough and 200 trees in Norwich.

The two cities selected for the study have very similar climates as reported in Table 1, which shows ten-year averages for maximum and minimum temperatures, hours of sunshine, amount of rainfall and daily rainfall in both areas (Met Office, 2017).

Both cities are at a low elevation; Norwich is 19 m and Peterborough only 12 m above sea level (Ordnance Survey, 2017). The main difference between the two cities is that soils in Peterborough are largely composed of clay, as opposed to the predominately sandy soils found in Norwich (Williamson, 2006).

Table 2 shows the distribution of the samples between the two cities and the site conditions including street trees, city parks and other urban green spaces. Other green spaces included areas such as traffic islands, wide verges and small recreation grounds. The inclusion of trees growing in green space and street trees with varying amounts of hard surfacing was fundamental to the exploration of the impact these factors had on the allometric relationship being assessed. Only free-standing trees were sampled. Pre-selected areas of the two cities were systematically searched for free standing trees of the target species. Where suitable trees were located, all were measured to avoid selection bias. The Ordnance Survey (OS) grid reference of each tree was recorded. Only trees where accurate crown dimensions could be collected were included, for example, street trees where part of the crowns overhung private property were excluded.

The measurement of DBH and crown diameter were based on the method used by Hemrey et al. (2005). The DBH was measured with a centimetre diameter tape at 1.3 m above ground level. The crown diameter was calculated by measuring the radial branch spread at the four cardinal compass points. These radial measurements were then added together and divided by two to calculate an average crown diameter (Fig. 2).

Work by Ayhan (1974) has established that taking four radial measurements provides the same level of accuracy as more complicated systems involving multiple measurements of crown diameter. The radial crown diameters were measured with a steel tape. The end of the tape was secured directly onto the stem at each compass bearing at 1.3 m and the distance to the edge of the crown was then measured. An allowance of half the stem's diameter was added to each radial measurement to give a true representation of the radial spread from the centre of the tree's stem. The extent of the crown was measured using a Suunto clinometer following the methodology of Hemery et al. (2005). This instrument has a scale up to 90° and allows the edge of the branches to be sighted accurately looking through the eye piece of the instrument directly upwards to fix the maximum extent of the crown. This method was tested and proved to be repeatable with only a 100 mm variation.

The height and crown depth of the trees were established using a laser hypsometer. Height was measured from ground level to the tip of the tree and crown depth was calculated by deducting clearance height from the total crown height.

An estimate of the life stage of each tree surveyed was made based on the following criteria: i) young - newly established trees, ii) semi mature – well established trees in the first quarter of their life expectancy, iii) early mature – trees approaching maturity and in the second quarter of their life expectancy, iv) mature - trees in the third quarter of their life expectancy.

Dead or senescent trees, along with trees showing extensive crown die back were excluded from the survey. Cultivated varieties often have an untypical crown form: while pedunculate oak and sycamore are normally planted as type trees, there are many cultivars of both silver birch and Norway maple in common use in the UK. For this reason, as far as was practicable, cultivated varieties were also excluded from the

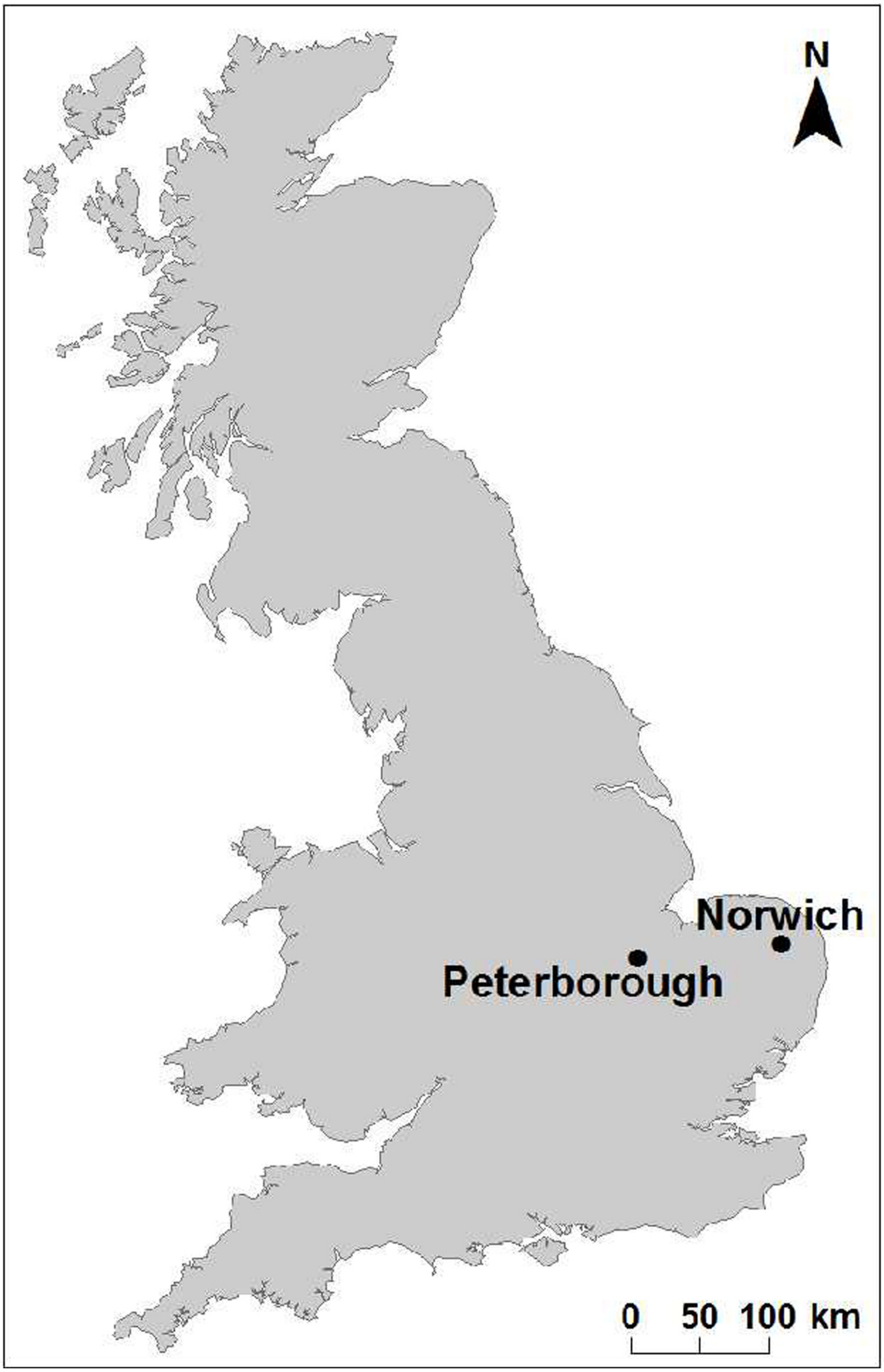

Fig. 1. The locations of Norwich and Peterborough in the UK (Ordnance Survey, 2017).

Table 1
Comparison of 10-year average annual climate data for Norwich and Peterborough.

Location	Max temp (°C)	Min temp (°C)	Sunshine (hrs)	Rainfall (mm)	Days rainfall > 1mm
Norwich	13.9	6.1	1592.6	661.8	124.0
Peterborough	13.7	6.1	1596.0	608.9	112.6

survey. A visual assessment of the crown form was made, for example excluding the common cultivar of silver birch *Betula pendula* 'Tristis' with its exaggerated weeping form, common in both cities. Google Street View was used to confirm the colour of the summer foliage of street trees surveyed to exclude purple foliaged varieties, particularly of Norway maple. Double stemmed or multi-stemmed trees, newly pollarded or topped trees were also excluded.

Previous pruning activity was recorded in two ways. First, a visual estimate of the time since the last pruning as evidenced by the condition

Table 2
The sampling pattern for Norwich and Peterborough.

Species	Total Sample	Young	Semi-Mature	Early Mature	Mature	Over Mature	Street Trees	City Parks	Other Urban Green spaces
Norwich									
Oak	50	9	3	10	28	0	30	20	0
Sycamore	50	0	4	10	36	0	38	9	3
S Birch	50	7	12	19	12	0	33	13	4
Norway Maple	50	0	6	25	19	0	36	14	0
Peterborough									
Oak	50	4	15	19	11	1	33	11	6
Sycamore	50	0	21	25	4	0	24	22	4
S Birch	50	0	10	31	9	0	49	1	0
Norway Maple	50	1	8	34	7	0	49	1	0
	400	**21**	**79**	**173**	**126**	**1**	**292**	**91**	**17**
		5%	20%	43%	32%	0%	73%	23%	4%

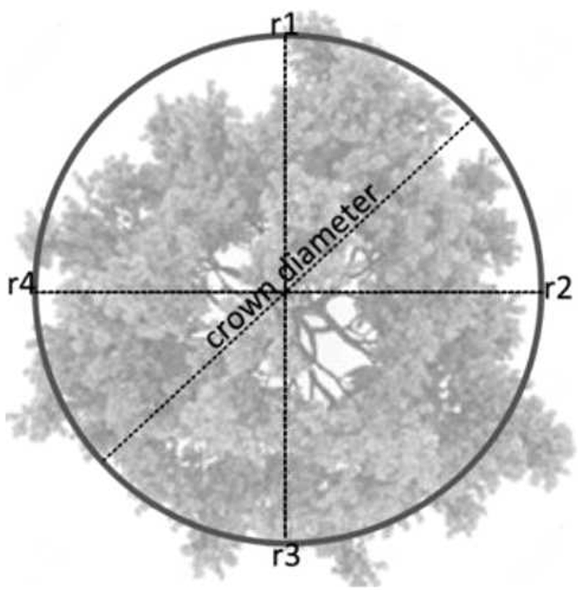

Fig. 2. Average crown diameter was obtained for each of the 400 trees measured by the formula: (r1 + r2 + r3 + r4) / 2.

of pruning cuts and the extent of wound occlusion was recorded (Clark and Matheny, 2010). The three categories recorded were: i) no pruning evident, ii) pruning carried out within the last five years, and iii) pruning carried out between five and ten years ago. Second, the type of pruning was also noted using four categories: i) no pruning, ii) crown lifted, iii) other pruning (e.g. crown reduction or crown thinning), and iv) combinational pruning (e.g. a crown lift combined with either crown reduction or crown thinning).

The percentage of hard standing that covered the ground within the crown area of the trees was estimated. These estimates ranged from 0% (no hard surfaces present) to 100% (all of the area under the tree's canopy was completely covered with a hard surface).

Soils in urban areas are often adulterated and potentially restrictive of root growth. It was not practicable, however, to carry out individual soil assessments for the four hundred trees surveyed, which is a limitation of this study. The generic soil type was added to the data as a desk study recording the superficial deposits for each tree position located on the 'Geology of Britain Viewer' website (British Geological Survey, 2017). Recorded deposits were allocated to one of three categories as follows: i) sand and sandy loam, ii) clay and clay loam, and iii) mixed (sand, clay and silt).

2.2. Tree age calculation

Verifiable tree planting dates were unavailable, and it was not possible to take core samples or use a micro drill to produce estimates for tree age. Therefore, the 50 pedunculate oak and 50 sycamore that were sampled in 2013 in Norwich were re-measured to assess the annual growth increment and these data were used to produce an estimated age of all the oak and sycamore in the survey. With regard to annual growth increment for silver birch and Norway maple, as these species were not included in the pilot study it was not possible to predict their crown diameter for a given age. However, the data collected on these two species were used for all the other aspects of the study.

2.3. Data analysis

The first step in the analysis was to produce scatter plots of DBH versus crown diameter with a best fit line to gauge which regression method might be appropriate. Linear and quadratic regressions were produced to provide equations for data collected in each of the two cities and for each of the four species surveyed. Only the quadratic regressions are presented in this paper as, overall, the quadratic regression produced the higher adjusted R^2 value.

A model was fitted using interaction terms to test for between-species differences in the allometric relationship between DBH and crown diameter. This showed generally small differences and therefore the data for the four species were combined to provide a better powered analysis, and to enable investigation of site factors and to work towards a general formula for predicting the allometric relationship. As part of combining the data, a regression of crown diameter versus DBH was produced showing each city's data separately to check for geographical differences. The importance of species to the allometric relationship was investigated using interval plots.

The accuracy of the regression equations produced using the combined data was tested by allocating random numbers to the data to split the data in half, and then using the first two hundred trees (Dataset A) to predict the crown diameters of the second two hundred trees (Dataset B).

While the focus of this study was on the allometric relationship between DBH and crown diameter, regressions were also produced to examine the relationship between crown diameter versus tree height and crown diameter versus crown depth.

A quadratic regression based on the ratio of crown diameter/DBH versus DBH was also produced. To establish if this method produced similar predictions to the equations derived from the analysis of the crown diameter, the data was randomised splitting it into datasets A1 and B1 and using the equation derived from A1 to predict B1. The predictions for this method and the method used for Datasets A & B were then compared.

Multiple regression was used to investigate the impact of physiological and site factors. All analyses were conducted in Minitab v.17. The multiple regression produced included the Variation Inflation Factor (VIF) as a measure of collinearity. The ratio of crown diameter/DBH versus DBH for the combined data was used instead of crown diameter versus DBH as an additional analytical technique to help assess the impact of site factors.

An assessment of growth increment was made based on the re-measurement of the 100 trees in Norwich measured in 2013 (50 oak and 50 sycamore). The estimated increment value was divided by the value for DBH to produce an estimate of tree age for the two species surveyed. For oak and sycamore, a regression of estimated age versus crown diameter was produced and this provided an equation for predicting crown diameter for trees of a given age. This prediction was applied to all the data for these two species and used to produce a table of predicted crown diameters for trees of a given age and DBH.

3. Results

3.1. Allometric modelling

Regression equations for crown diameter based on DBH for all four species are shown in Table 3. the individual quadratic regressions produced for all four species examined are shown in the Supplementary Material. The similarity of the equations and regressions from two separate tree stocks in terms of their DBH and crown diameter ratios is evident, particularly in the case of oak and sycamore. A model was fitted using interaction terms to test for between-species differences in the allometric relationship between DBH and crown diameter. This showed generally small differences and therefore data for the four species were combined.

The combined quadratic regression showing crown diameter versus DBH for all four species (Fig. 3) was statistically significant and had an adjusted R^2 value of 0.82. Data from the four species combined conformed well to the regression line ($p < 0.001$).

The data were combined in a regression of the ratio of crown diameter/DBH versus DBH as shown in Fig. 4. This produced a significant range of higher ratios in smaller trees from 0.05 to 0.5 m DBH. The regression shows gradual stabilisation of the ratio with increased stem growth towards a ratio of around 1:25. This result suggests this ratio may be typical for open-grown urban broadleaf trees of these four species where their crowns have been unfettered throughout their early development.

The interval plot produced for species versus the ratio of crown diameter/DBH is shown in Fig. 5. This shows that the mean ratio for all four species lay between 1:24 and 1:27.

The results of testing the predictive ability of the regression equations using the randomised combined data, for DBH versus crown diameter and the randomised ratio of crown diameter/DBH versus DBH produced statistically significant results with a p-value of < 0.001. The root mean squared errors represented 1.5 m and 2.5 m respectively.

3.2. Multiple regression

The regressions produced for tree height and crown depth versus crown diameter highlighted that both had a relationship with crown diameter. This was confirmed in an initial multiple regression where these two elements had a Variation Inflation Factor (VIF) of 13.8 and 9.8 respectively. High VIF figures signal multicollinearity, height and crown depth were therefore excluded from the multiple regression presented in Table 4 to allow the effect of the site factors to be examined.

The multiple regression shown in Table 4 demonstrates that species and age class were statistically significant predictors of crown diameter from DBH. While the hard-standing around a tree was shown as statistically significant, the p-value is much closer to 0.05, implying a weaker relationship. Other site factors were not statistically significant when included in the model.

Comparing the predicted canopy size for a tree with a DBH of 0.50 m produced using the quadratic regression equation presented in Fig. 3 versus the predicted value produced using the multiple regression equation in Table 4 gave a difference of only 0.12 m in canopy size, suggesting that the site factors included in the multiple regression model had only a weak effect on the predicted crown diameter.

3.3. Relationship between canopy diameter and tree age

The re-measurement of oak and sycamore in Norwich found average annual diameter increments of 7 mm and 9.5 mm respectively. One of the aims of this study was to provide a measure of ultimate growth potential at a given age for these two species. Table 5 presents the equations for calculating crown diameter for trees of a given age for oak and sycamore. The equations provided here represent what must be regarded as estimations and there will be a degree of variation from the calculated figure when any one tree is assessed.

Table 6 provides predictions of DBH and crown diameter for a given age for free-standing urban trees for two of the four species surveyed, based upon the sample means from our study.

4. Discussion

The choice of statistical techniques to provide predictions of crown diameter from DBH and vice versa differs widely in the literature. In this study, overall quadratic regressions produced a higher adjusted R^2 value than linear regressions. However, the non-linear nature of quadratic regression lines means their use for making predictions outside the range of the data presented here is cautioned against.

As first noted by Hemery et al. (2005), in a study of forest trees, the

Table 3
Linear and quadratic regression results.

Species	Norwich Sample size	Formula	Adjusted R^2	Peterborough Sample size	Formula	AdjustedR^2
Linear Regressions						
Oak	50	$y = 4.42 + 14.68x$	80.97	50	$y = 4.66 + 14.22x$	78.01
Sycamore	50	$y = 4.42 + 14.16x$	72.16	50	$y = 2.42 + 19.47x$	78.01
Silver birch	50	$y = 1.92 + 18.30x$	85.67	50	$y = 2.50 + 16.31x$	63.67
Norway maple	50	$y = 5.94 + 12.54x$	55.46	50	$y = 2.09 + 20.26x$	58.89
Quadratic Regressions						
Oak	50	$y = 1.42 + 28.17x-11.26x^2$	83.46	50	$y = 1.68 + 27.51x -11.48x^2$	84.46
Sycamore	50	$y = 3.18 + 19.07x- 4.40x^2$	72.04	50	$y = 0.95 + 29.69x -13.10x^2$	79.74
Silver birch	50	$y = 1.38 + 22.62x-7.10x^2$	85.39	50	$y = 2.33 + 17.37x -1.58x^2$	67.07
Norway maple	50	$y = 3.47 + 56.70x-48.21x^2$	60.37	50	$y = 11.81 + 98.39x-104.1x^2$	61.73

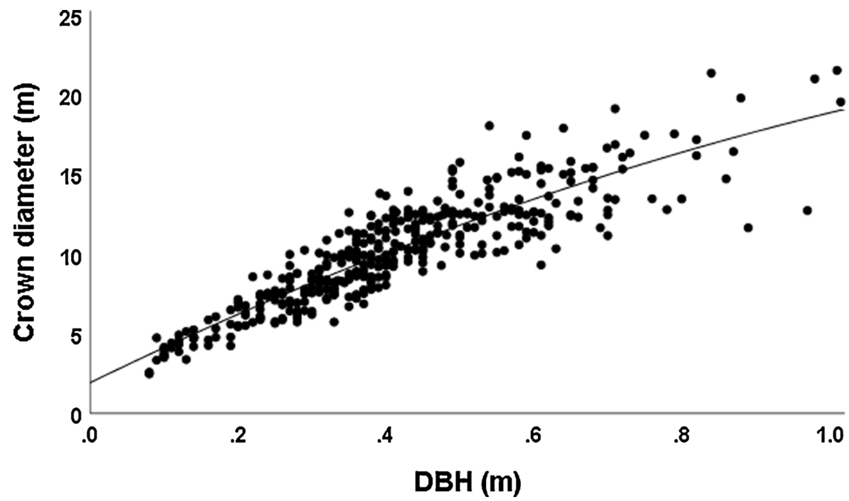

Fig. 3. Crown diameter versus DBH for the combined data. (Crown diameter = 0.8304 + 27.82 DBH - 10.68 DBH^2).

relationship between the DBH and crown diameter is close to linear up to 0.5 m stem diameter. The results of our study indicate that this also applies to urban trees with unfettered crowns.

The research trend in this subject is to use ever more sophisticated statistical models to produce results that explain the coefficient of variation in terms of R^2 (McPherson et al., 2016). The predictive strength is often little better than what was achieved in earlier work, for example Duchaufour (1903) working with forest grown beech produced a linear regression for DBH versus crown diameter with an R^2 of 0.92. The body of work that has been undertaken in this field demonstrates that there is a very strong relationship between these two dimensions for most tree species and in a wide range of site conditions worldwide. The findings of this study suggest that general, non-species specific regression equations could provide acceptable accuracy for many purposes (Krajicek et al., 1957; Gering and May, 1995; O'Brien et al., 1995; Hemrey 2005).

The key finding of this study and one that has not featured widely in the literature is that, in this sample at least, site factors had a very limited impact on the allometric relationship between DBH and crown diameter. For example, pruning was found not to have a statistically significant impact on the relationship; however, it should be noted that pollarded and topped trees were excluded from the study. Other researchers have found pruning a problem in the formulation of regression equations e.g. Peper et al. (2001a,b), but in an earlier paper Peper (1998) also concluded that light pruning had no impact on this allometric relationship. Given that just over half the trees in this survey had been crown lifted the limited impact is perhaps surprising. Crown lifting, by definition, removes lower branches which are potentially suppressed and subject to the apical dominance of the upper crown (Rahman et al., 2014), which could also explain this result.

Hard standing and impermeable surfaces within the crown spread of the trees was also found to have a very limited effect on the allometric relationship. In an urban tree growth study, Quigley (2004) found the growth of early successional species such as oak and silver birch were little affected by hard surfacing which, to an extent, supports our finding.

While detailed soil analysis was not possible, there appeared to be no statistically significant difference in the allometry of the trees sampled due to local soil types, including the sandy soils of Norwich and heavy clays of Peterborough.

Our study shows minimal variation in the relationship between crown diameter and DBH in the two locations surveyed. However, in other situations, researchers have reported geographical variation (Urban et al., 2010; Lines et al., 2012; Montallebi and Kangor 2016; Vaz Monteiro et al., 2016). It is accepted that these studies are not directly comparable. Some studies where regional variation in the DBH to crown diameter relationship has been reported, have examined more extreme changes in altitude and climatic zones (Korhonen and Heikkinen, 2009; Lines et al., 2012; McPherson et al., 2016). For example, the extensive study completed by McPherson et al. (2016)

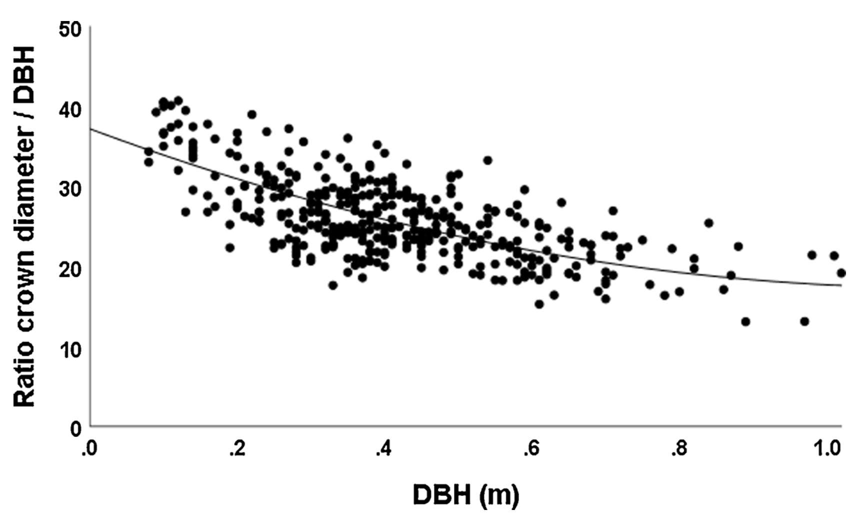

Fig. 4. Ratio of crown diameter/DBH versus DBH for the combined data. (Ratio = 35.9 - 31.19 DBH + 14.19 DBH^2).

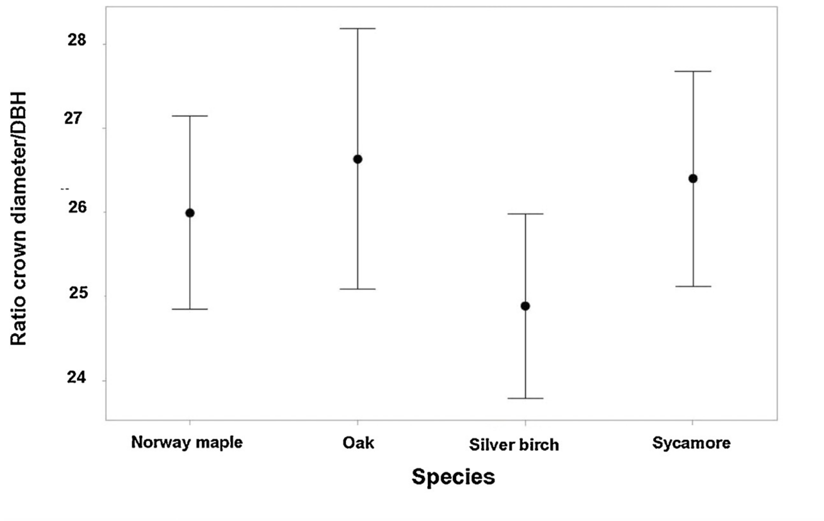

Fig. 5. Interval plot showing the ratio of crown diameter/DBH by species. Mean ratio for the species are as follows: Norway maple 1:25.98, oak 1:26.62, silver birch 1:24.88 and sycamore 1: 26.39. All four species fell within the range 1:24 to 1.27. The bars show standard deviation.

Table 4
Combined data - Multiple regression of the ratio of crown diameter to stem diameter (y) versus dbh (x).

Term	Coef	SE Coef	p-value	VIF
Constant	38.366	0.929	0.000	–
dbh (m)	−16.51	1.36	**0.000**	2.62
Hard standing %	−0.0195	0.0088	**0.028**	1.33
Dataset				
Peterborough (reference category)	–	–	–	–
Norwich	0.673	0.510	0.188	2.33
Species				
Oak (reference category)	–	–	–	–
Sycamore	−1.427	0.502	**0.005**	1.68
Silver birch	−4.516	0.587	**0.000**	2.22
Norway maple	−2.106	0.530	**0.000**	1.97
Age Class				
Young (reference category)	–	–	–	–
Semi mature	−3.118	0.914	**0.001**	4.76
Early mature	−3.755	0.943	**0.000**	7.80
Mature	−4.60	1.07	**0.000**	8.92
Pruning History				
No pruning (reference category)	–	–	–	–
Pruned within last 5 years	1.06	1.40	0.449	14.46
Pruned within last 5-10 years	0.64	1.36	0.637	16.39
Type of Pruning				
No pruning (reference category)	–	–	–	–
Crown raise	−1.00	1.31	0.447	14.82
Other types (crown thin or reduction)	−1.70	1.36	0.214	6.16
Crown raise and other	−1.19	1.42	0.403	7.99
Recovered pollard	−0.95	2.65	0.720	1.32
Soil Type				
Sand and gravel (reference category)	–	–	–	–
Clay	0.758	0.536	0.158	2.39
Mixed (clay, sand and gravel)	1.266	0.637	0.048	1.28

Table 5
Crown diameter against age equations based on species combined data.

Species	Sample size	Formula	R^2
Oak	100	$y = 4.630 + 0.12x - 0.088x^2$	67.99
Sycamore	100	$y = 1.750 + 0.168x$	72.91

covered sixteen climatic zones. In contrast, there were only minor differences between the climate and altitude in the two locations included in our project, which may explain the similarity of the results. However, Vaz Monteiro et al. (2016) found variations in DBH versus crown diameter relationships between Luton and London (54 km apart) and Glasgow and Edinburgh (74 km apart). These are closer than the distance from Norwich and Peterborough.

Table 6
Individual allometry predictions for a given tree age of oak and sycamore.

Age(Yrs.)	Oak		Sycamore	
	DBH (m)	Crown Diameter (m)	DBH(m)	Crown Diameter (m)
15	0.25	7.3	0.11	4.3
20	0.29	8.1	0.15	5.1
30	0.37	9.7	0.24	6.8
40	0.44	11.1	0.32	8.5
50	0.50	12.4	0.41	10.2
60	0.56	13.5	0.49	11.8
70	0.61	14.5	0.58	13.5
80	0.65	15.4	0.66	15.2
90	0.69	16.1	0.75	16.9
100	0.72	16.7	0.83	18.6
110	0.74	17.1	0.92	20.2

All the figures presented in this study relate to free-standing urban trees. From the literature it is sometimes difficult to distinguish between studies of general tree populations and open grown specimens. The concentration on free standing trees in this study is important in that it allowed a measure of ultimate crown spread.

Arboriculturists need to work with and have a good understanding of tree development over time. The attempt in this study to link DBH to crown diameter predictions and to the age of the trees is unusual in this field. The growth rate estimates used compare well with other published figures. For example, White (1998) suggests that, mature oak continue steady growth to around 100 years with an annual DBH increment of 6 mm and sycamore to 60 years with an annual increment of 12 mm. Both figures are roughly comparable with the growth increments reported here (7 mm for average growth for mature oak and 9.5 mm for sycamore). The key finding of Monteiro et al. (2017) was that tree growth rates varied significantly across the regions sampled; however, this study was confined to trees growing in green space and therefore is not directly comparable. In the urban forest, local site characteristics are often a more important factor (Sanders 2013). Our results showed significant localised variation in growth rates in the samples re-measured. It is important to distinguish growth rates from the allometric relationship between DBH and crown diameter which, based on our sample, remained stable regardless of the growth rates

(Berlyn, 1962). The corroboration of the estimate of annual growth by the literature provides a firm base for the calculation of age in relation to DBH, by dividing DBH by the appropriate annual increment.

Providing predictive data in tables has not been widely used other than when associated with studies of free-standing trees (Jobling and Pearce 1997; Frelich, 1992; Lukaszkiewicz and Kosmala, 2008). This approach provides a useful way of disseminating the results of predictive equations to a wider audience. However, any expanded working model would need to present not just tables but also the supporting equations, as the equations are needed to facilitate computer modelling for tree management purposes.

4.1. Limitations of the study and avenues for further research

The results presented apply specifically to free-standing urban trees and no attempt has been made to extend the study to explore the effects of crown competition. However, the focus on open grown trees does provide a measure of the growth potential of the species included. It also provides comparative data on which to base further studies of the DBH versus crown diameter relationships of trees with competing crowns (Pretzsch et al., 2015).

A further limitation is that no definitive planting dates were available for the population of trees surveyed. While the estimates of growth increment and age compare well with other published data, basing the calculations on known planting dates would have provided a firmer basis for the predictions of crown diameter for a tree of a given age. In addition, a detailed comparison of soil qualities for the individual tree positions may have given insight into differences in tree growth rate and tree form.

5. Conclusions

The relationship between DBH and crown diameter for both cities was very similar, which suggests that geographical location alone may not be significant in the UK context, although further studies may find differences when surveying in locations with greater environmental differences. In the context of our survey the results demonstrate that the allometric relationship between DBH and crown diameter was not strongly linked to species (for the four species studied). The exploration of other allometric relationships found that tree height and crown depth also have a significant relationship with crown diameter, but with significantly lower coefficients of determination than for DBH.

The influence of site factors including the extent of pruning, hard standing around the tree, and soil type did not significantly affect the allometric relationship for the 400 trees surveyed in this study.

There is a strong underlying allometric relationship between DBH and crown diameter and, based on the findings of this study, this appears to transcend common external influences that may disrupt tree growth. There is also a degree of variation that cannot be explained by geographical location, site factors or past management. If more accurate predictions are sought, it may be necessary to research other factors, especially variation in tree form that may relate to plant genetics. There are also many other urban site factors not included in this study, for example the effects of air pollution, restricted rooting environments, relative exposure to wind, soil drainage and soil compaction.

Predictive equations have been produced by many authors over an extended period. They have received limited attention outside academia, other than their use in software calculating ecosystem services provided by trees such as i-Tree. The body of research on this topic needs to be collated and rationalized producing generalized equations for urban tree populations that will be of immediate use to practitioners. The use of the ratio of DBH to crown dimeter in this paper illustrates the value of a simple multiplier that would be useful for practitioners in the field. Results presented in Table 6, and the corresponding models may be useful to a wider audience, particularly those concerned with urban tree management.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ufug.2019.126421.

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