Urban Forestry & Urban Greening 47 (2020) 126481

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

How should we measure the DBH of multi-stemmed urban trees?

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ARTICLE INFO

Handling Editor: Justin Morgenroth

Keywords:
Diameter at breast height
Crown diameter
Ecological monitoring
Street tree
Tree allometry
Urban forest

ABSTRACT

Foresters use diameter at breast height (DBH) to estimate timber volumes, quantify ecosystem services, and predict other biometrics that would be difficult to directly measure. But DBH has numerous problems, including a range of "breast heights" and challenges with applying this standard to divergent tree forms. Our study focuses on street trees that fork between 30 and 137 cm of height (hereafter "multi-stemmed trees"), which researchers have identified as particularly challenging in the ongoing development of urban allometric models, as well as consistency in measurements across space and time. Using a mixed methods approach, we surveyed 25 urban forestry practitioners in twelve cities in the northeastern United States (US) about the measurement and management of multi-stemmed street trees, and intensively measured 569 trees of three frequently planted and commonly multi-stemmed genera (*Malus, Prunus,* and *Zelkova*) in Philadelphia, PA, US. Specifically, we measured stem diameter at several distances above the ground: at the root collar, at 30 cm, just below the fork (which occurred between 30 and 137 cm), and at 137 cm (up to six stems following established protocols). Survey responses indicated that current mensuration practices are burdensome, that practitioners employ alternatives to the current protocols for measuring at 137 cm, and that small-statured, frequently multi-stemmed trees are an increasing proportion of street tree populations. Analysis of field data did not find substantial differences between methods of measurement with regard to predictive power for total height and average crown width. Alternatives to the current protocols for measuring at 137 cm have other advantages, including time required, ease of measurement, simplicity, and capacity to compare measurements between trees and over time. For trees that fork between 30 and 137 cm, we recommend taking a single diameter measurement at a lower height—either just below the fork or at 30 cm. Diameter measurements at 30 cm better serve researchers seeking to consistently measure radial growth over time, whereas diameter below the fork may suit practitioners who do not need fine resolution in trunk measurements.

1. Introduction

Practical forest mensuration applies the principle that we cannot properly manage that which we cannot accurately measure. Accordingly, since the 19th century, foresters have measured trees' diameters at breast height (DBH) to estimate standing volumes of timber (Schlich, 1895; Oderwald and Johnson, 2009), analyze and classify sites (Graves, 1906; Hammer, 1981), define trees (Beech et al., 2017), measure radial stem growth (Pinchot, 1899; Evans et al., 2015), estimate biomass and carbon (Emmanuel et al., 1997; Brown, 2002; Chave et al., 2005), manage silvicultural treatments (Clough et al., 1997), and quantify ecosystem services (Jenkins et al., 2004; McHale et al., 2009). A single, convenient, and relatively standardized measurement enables efficient surveying, and DBH is often employed, via allometric models, as a proxy variable for various biometrics that would be far more difficult, time-intensive, costly, or destructive to directly measure (Hemery et al., 2005; Stewart and Salazar, 1992). DBH is thus a core element in forest inventories and monitoring.

However, DBH—and, specifically, breast height above the ground (BH)—has notable shortcomings. Standard heights presently used range from 137 cm in the United States (US; corresponding to 4.5 ft in the US Customary System) to 130 cm in Europe and tropical forests (Chave et al., 2015), although researchers employ many other BH values and sometimes do not report the BH used (Brokaw and Thompson, 2000). Brokaw and Thompson (2000) suggested the alternative term D_x, with x = intended height of measurement in cm (adopted, for instance, by Dahdouh-Guebas and Koedam, 2006). The wording "intended height" is deliberate; because of divergent tree forms, foresters have deliberately

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https://doi.org/10.1016/j.ufug.2019.126481
Received 6 September 2018; Received in revised form 27 June 2019; Accepted 9 October 2019
Available online 01 November 2019

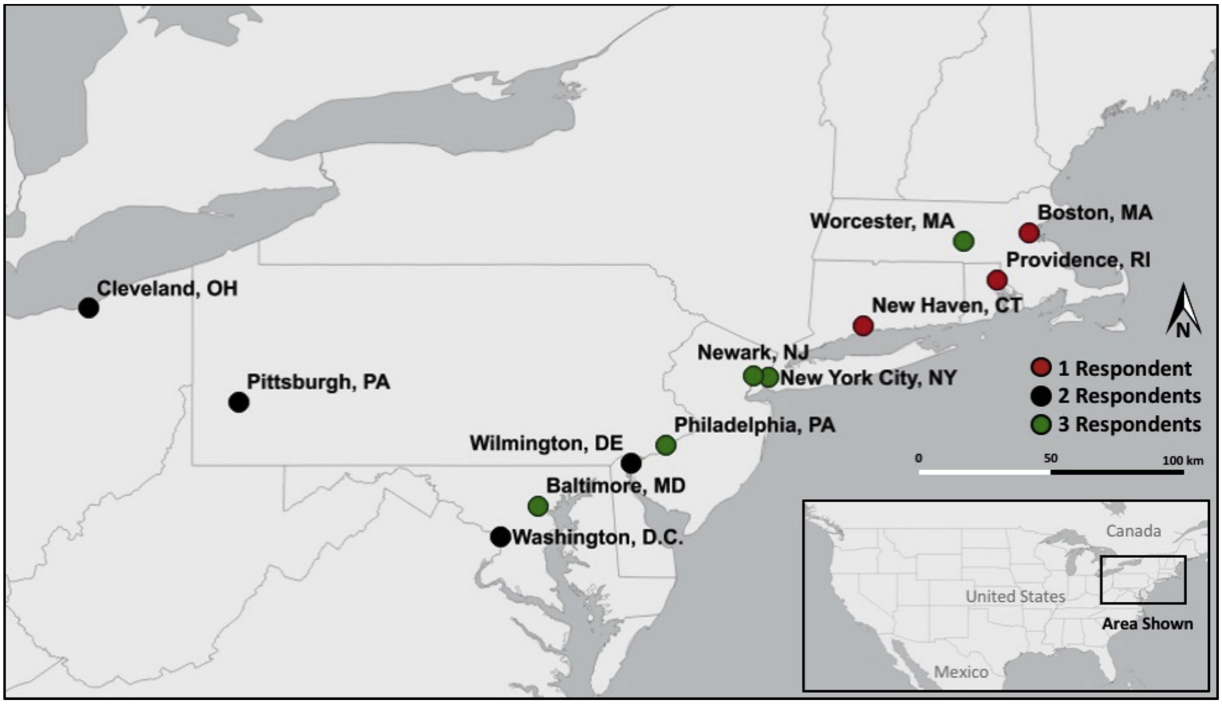

Fig. 1. The 12 cities listed online as members of the Urban Ecology Collaborative (UEC) (2019), whose urban forestry practitioners were invited to participate in our survey on the measurement and management of multi-stemmed street trees. Cities are color-coded depending on how many respondents from each responded to our survey: one, two, or three.

used different heights for as long as DBH has been standard (Brandis, 1876; Carter, 1890; Coleman et al., 2011; Tietema, 1993).

Divergent tree forms that are not condusive to classic BH at 130 or 137 cm include species that have multiple stems and/or are of small stature: mangroves (Bukoski et al., 2017; Clough et al., 1997; Dahdouh-Guebas and Koedam, 2006; Friess et al., 2016), small trees in temperate and tropical forests (Paradzayi et al., 2008; Weiskittel et al., 2011), multi-stemmed trees in African savannahs such as *Acacia* spp. (Mabowe, 2006; Tietema, 1993), multi-purpose trees in agroforestry systems (Stewart and Dunsdon, 1994; Stewart and Salazar, 1992; Emmanuel et al., 1997), and multi-stemmed urban street and park trees such as *Crataegus* spp., *Laegerstromia* spp., *Malus* spp. and *Prunus* spp. (McPherson et al., 2016b; Peper et al., 2001; Roman et al., 2017; Troxel et al., 2013). For instance, urban forestry researchers have previously found relatively low correlations between DBH and height for small-stature ornamental species (Blood et al., 2016; Troxel et al., 2013). This last case—situated within the urban forest—is the focus of our research.

The proper valuation of the social, economic, and ecological benefits of urban forests depends on accurate quantification of each tree's biometrics. However, until recently, urban forest researchers relied on allometric models developed for trees in rural forests and plantations (McHale et al., 2009; Monteiro et al., 2016; Timilsina et al., 2017; Pretzsch et al., 2015), despite markedly different growing conditions for urban trees. For street trees in particular, these differences include lower density, more regular pruning, more regular (and open) spacing, different nutrient and water availability, and an array of stressful conditions (McHale et al., 2009). To account for these discrepancies, researchers have derived allometric models specific to urban trees using non-destructive sampling (McPherson et al., 2016b; Monteiro et al., 2016; Peper et al., 2001, 2014; Pretzsch et al., 2015; Timilsina et al., 2017; Troxel et al., 2013). Yet multi-stemmed trees—defined for the purposes of this study as trees that fork between 30 cm and 137 cm of height—continue to challenge the accuracy, precision, and usefulness of such measurements (Troxel et al., 2013; Roman et al., 2017). Furthermore, this problem may grow as cities replace tall trees under utility lines with short-statured, frequently multi-stemmed ones, and as they aim to meet resident preferences for flowering and fruiting trees (Flowers and Gerhold, 2000; McPherson et al., 2016a; Nguyen et al., 2017).

To address these challenges, we assessed various methods for measuring the stem diameter of multi-stemmed street trees. We posed the following three research questions:

1) How prevalent within street tree populations in the northeastern US are genera that commonly fork below 137 cm of height, and how do practitioners currently measure multi-stemmed street trees?
2) For multi-stemmed street trees, how well correlated are the DBH-equivalents derived via different stem diameter collection techniques with the key biometrics of total height and average crown width?
3) How should we measure multi-stemmed street tree diameters when considering practical efficiency and repeatability, as well as correlation with key biometrics?

2. Methods

To determine how we should measure the stem diameter of multi-stemmed street trees, we employed a mixed methods approach, consisting of both a social survey of urban forestry professionals and a field inventory of street trees.

2.1. Practitioner survey

We wanted to ascertain what protocols urban forestry practitioners use to measure multi-stemmed trees, assess what burdens these protocols may impose, understand the specific uses of DBH in the street tree management context, and estimate the prevalence of these trees in a subset of US cities. We therefore surveyed a set of urban forest practitioners about the measurement and management of multi-stemmed and small-statured street trees.

We chose potential respondents from the 12 cities listed online as members of the Urban Ecology Collaborative (UEC), a network of northeastern US cities with a stated interest in and dedication to urban forestry research and practice (UEC 2018). The cities thus invited were: Baltimore, MD; Boston, MA; Cleveland, OH; New Haven, CT; New York City, NY; Newark, NJ; Philadelphia, PA; Pittsburgh, PA; Providence, RI; Washington, DC; Wilmington, DE; and Worcester, MA (Fig. 1). The UEC has a history of research-practice collaborations (Galvin, 2012; Leff, 2013; Nguyen et al., 2017). For each city, we identified one municipal urban forestry professional, one non-governmental organization (NGO)-affiliated urban forestry professional, and one city-contracted arborist and invited them to complete the survey (Appendix A). For one city that handles all street tree management through the municipality, and therefore lacks urban forestry NGOs/city-contracted arborists, we invited only the municipal practitioner.

The survey was administered online via Google Forms between October 24 and December 15, 2017. Thirty-five practitioners were asked to participate; initial and up to three reminder emails were sent based on best practices in survey methods (Dillman et al., 2008). In total, 25 practitioners from all 12 cities completed the survey (71% response rate). The survey was a mix of categorical and open-ended questions (Appendix A). Following Babbie (2004), open-ended responses were open-coded into categories of common themes (Appendix B, Table A3, described in Results) by a single analyst; these themes were not pre-determined.

Seven respondents (from Newark, New Haven, New York City, Philadelphia, Pittsburgh, Washington, DC, and Wilmington) provided us with street tree inventories and/or recent planting lists, which we analyzed (considering only trees with species identification) for trends in the planting of small-statured, commonly multi-stemmed trees. Based on species descriptions in Dirr (1998) and our prior field experience, we considered the following street tree genera in this region to be commonly multi-stemmed: *Amelanchier*, *Carpinus*, *Cercis*, *Cornus*, *Corylus*, *Crataegus*, *Lagerstroemia*, *Malus*, *Prunus*, *Pyrus*, *Syringa*, and *Zelkova*. Most of these genera are also commonly short-statured; Zelkova is medium height at maturity (Dirr, 1998). We considered short-statured trees as those with maximum mature heights of less than 9.1 m, and medium-statured as those with maximum height of 9.1–13.7 m (Miller et al., 2015).

2.2. Field study

2.2.1. Study site

We conducted the field sampling in Philadelphia, PA (39°57′ N, 75°10′ W), because of the availability of a cultivar-level planting list spanning many years. The climate is at the northern edge of humid subtropical (Köppen Classification System subtype "Cfa"): summers are hot, with high humidity, while winters are cold with variable snowfall (Kottek et al., 2006). The growing season lasts from April until November, with a mean annual temperature of 14.2 °C, a mean July temperature of 25.8 °C, and a mean January temperature of 2.1 °C (National Oceanic and Atmospheric Administration (NOAA, 2018). Monthly precipitation is steady throughout the year with an annual average of 1053 mm (National Oceanic and Atmospheric Administration (NOAA, 2018). Philadelphia has a human population of approximately 1.58 million (US Census Bureau, 2017) and a street tree population of approximately 112,000 (Maldonado, 2016). There is no current inventory of Philadelphia's street trees with reliable species information.

2.2.2. Sampling design

Our sampling method used both relatively young, recently planted trees (based on planting records) as well as older, established trees. We used 2003–2015 planting records from Tree Tenders, a street tree planting and stewardship program of the Pennsylvania Horticultural Society (PHS), a local non-profit organization. We selected commonly short- and medium-stature multi-stemmed genera that were well-represented in the PHS dataset: *Malus*, *Prunus*, and *Zelkova*. Together, these three genera account for 21.8% of the planting records' 15,321 trees.

We included the two most common *Malus* cultivars and four most common *Prunus* cultivars, and excluded trees either marked as "yard" or with insufficient address information within the PHS dataset. We randomly selected 80 trees from each of the chosen *Malus* and *Prunus* cultivars, and selected all 190 *Zelkova serrata* within the PHS dataset, with the expectation that some of these (hereafter "target" trees) could not be measured due to mortality or difficulty finding the tree in the field.

To supplement the sample of target trees and ensure that sufficient larger specimens were measured for meaningful regression analysis, we also used an opportunistic sampling protocol. For each target tree in the dataset described above, up to one opportunistic tree was sampled—-whether or not the target tree was actually located. The opportunistic tree had to be greater than 15 cm D_{30} (notation following Brokaw and Thompson, 2000), clearly identifiable as one of the three target genera, and within 30 m (an arbitrary, convenient distance) of the target tree.

In total, we measured 569 trees (109 *Malus*, 301 *Prunus*, and 159 *Zelkova*). Of these, 345 were multi-stemmed (i.e., forked between 30 cm and 137 cm of height), with the remainder single-stemmed (i.e., forked above 137 cm). We used measurements of single-stemmed trees to assess time demands of measuring multiple stems, calculate the proportion of trees in each genera that were multi-stemmed, and compare coefficient of determination values for models that use only single-stemmed trees to models that used multi-stemmed trees.

2.2.3. Data collection

Using mm-accuracy diameter tape, we measured stem diameters in the following four ways:

1) Diameter at root collar (DRC), comparable to diameter at ankle height (often 5–10 cm above ground) measured on multi-stemmed specimens in Botswana woodlands (Tietema, 1993; Mabowe, 2006) and by some urban forestry researchers (Sithole et al., 2018), as well as D_{10} as measured in Australia's National Carbon Accounting System (Snowdon et al., 2002).

2) At 30 cm of height (D_{30}), following i-Tree Eco's alternative height of measurement for trees with more than six stems at breast height (US Forest Service, 2017b), as well as researchers' recommendations for multi-stemmed mensuration (Stewart and Salazar, 1992; Stewart and Dunsdon, 1994; Stewart et al., 1992; Emmanuel et al., 1997; MacDicken et al., 1991; Snowdon et al., 2002), and the measurement height for all nursery stock greater than 10.2 cm (4 in. in diameter (American Nursery and Landscape Association, 2004).

3) Below the fork (D Below Fork)—the highest possible point to take a single trunk measurement below any swelling/irregularities in stem taper due to forking/branching—following recommendations from a pilot test of the Urban Tree Monitoring Field Guide (Roman et al., 2017), from the United States (US) Forest Service's Forest Inventory and Analysis (FIA) Program for trees which fork "at or immediately above 4.5 feet [137 cm]" (US Forest Service, 2017a), and from recently revised field protocols for the Urban Forest Inventory and Analysis (UFIA) program (US Forest Service, 2018).

4) Following the method prescribed by i-Tree Eco: Measure, at 137 cm, up to the six largest stems that are each > 2.54 cm diameter and < 45° from the vertical; if there are more than six such stems, instead measure a single diameter at 30.5 cm of height (US Forest Service, 2017b). We set BH to 137 cm because of the direct conversion to the US customary system; we chose a 2.5 cm minimum for stems and a 30 cm value for D_{30} based on our metric measuring devices' resolution. When multiple stems were measured, we combined them into one value via the quadratic sum, following MacDicken et al. (1991), Stewart and Salazar (1992), Snowden et al. (2002), McPherson et al. (2016b), and US Forest Service (2017b). For DBH values of stems 1 through 6, the quadratic sum representing the DBH of that multi-stemmed tree, DBH_{MS}, is:

$$DBH_{MS} = \sqrt{\sum_{i=1}^{6} DBH_i^2} \quad (1)$$

(after Monteiro et al., 2016, eqn. 1, and Awang et al., 1994)

For every diameter, we measured the height of *actual* measurement; we also measured the heights to the top of the first fork (hereafter "forking height"), to the base of live crown, the total tree height, the crown widths parallel and perpendicular to the street (following McPherson et al., 2016b), and the start and end times of measurement. All heights were measured with a cm-accuracy height pole for specimens smaller than 8.3 m; for specimens taller than 8.3 m, a cm-accuracy digital hypsometer was used. All widths were measured using a cm-accuracy tape measure. In addition to the variables used in our analysis, we also measured a comprehensive set of parameters related to site condition and cultivation that were not included in our results. We include those parameters in the open access data for any other researchers who may find these useful.

All field data was collected betweenJune 7 and August 16, 2017. The Stanley® Level app (Stanley Black and Decker, Inc. 2017) was used to gauge stem angles. For consistency, all heights were measured from the sidewalk on the building side of the tree, and not from within the planting pit itself, due to variation in mulch and trash within the pit. We only included trees in pits/strips measuring less than 2 m in at least one direction, representing typically constrained growing spaces for street trees in this city (i.e., not wide planting lawns). Further details on measurement protocols can be found in Appendix B, Table A1.

2.2.4. Data analysis

Field data were analyzed in R 3.4.1 (R Core Team, 2017). To answer our second research question, we fit a linear regression (using the nlme package) for each combination of: diameter methods (D_{30}, D Below Fork, i-Tree's aforementioned hybrid method), multi-stemmed genera (*Malus*, *Prunus*, and *Zelkova*), and predicted biometrics (total height and average crown width). We used cultivars as indicator variables (following Gregoire, 2015) when those cultivars proved statistically significant in the model (i.e., $p < 0.05$). We discarded DRC early in the analysis process because field surveying indicated that its actual measurement was too variable and challenging, given basal flare, graft unions, tree pit guards, weeds, and stump sprouts.

Because the graphs for *Prunus* exhibited both heteroscedasticity and non-linearity when we included opportunistic trees, we added a separate group of models solely for target *Prunus*. For the model groups of *Prunus* that included opportunistic trees (and thus exhibited non-linearity), we first logarithmically transformed each relevant diameter measurement, but fit all models within the linear framework.

Thus, all regression models were fit to the form:

$$Y = \beta_0 + \beta_1 X + \beta_2 I + \varepsilon \quad (2)$$

where Y is the biometric (total height or average crown width), X is the given method's DBH-equivalent (or logarithmithically transformed DBH-equivalent), and I is the cultivar indicator variable that was included, β_0, β_1, and β_2 are the coefficients, and ε is the error term.

Models are grouped and named by genus and response variable, for all diameter measurement methods. We thus fit 24 regression models comprising eight model groups with data from the multi-stemmed trees: twelve with *Prunus* (four model groups: PaH, PaW, PtH, and PtW), six with *Malus* (two model groups: MH and MW), and six with *Zelkova* (two model groups: ZH and ZW). The H and W represent models for total height and average crown width, respectively, while Pa refers to all *Prunus* and Pt refers to only target *Prunus*. For comparison, we also fit for each model group the relevant model type with the dataset of that taxon's single-stemmed specimens.

We wanted to evaluate the magnitude and uncertainty of difference in R^2 values within each model group. We therefore bootstrapped by sampling, with replacement, n trees from each genus where n is the number of n multi-stemmed trees measured (e.g., sampling, with replacement, 77 trees, from *Malus*)—and repeating 10,000 times. At each iteration, we fit the relevant regression model (using the nlme package), obtained the R^2 values, and calculated the differences between diameter measurement techniques (i.e., $R^2_{DBF} - R^2_{D30}$, $R^2_{i\text{-}Tree} - R^2_{D30}$, and $R^2_{i\text{-}Tree} - R^2_{DBF}$). For the distribution of each difference for each genus, we generated 95% confidence intervals, following Carpenter and Bithell, 2000. All means and confidence intervals are summarized in Appendix B, Table A2.

To answer our third research question, we analyzed measurement times of trees with different numbers of stems via two-sample unpaired t-tests (two-tailed, assuming unequal variances) between single-stemmed and each set of trees with different numbers of stems (i.e., two-stemmed trees, three-stemmed trees). We used a significance level of $p < 0.05$. We also used a coarse approximation of additional measurement time for each additional stem: subtracting the single-stemmed trees' median measurement time from each of the sets of trees with different numbers of stems. Finally, we graphed the distributions of heights at which each measurement was actually taken.

Because we wanted to assess not merely the predictive power, but also the practicality, of each method, we evaluated the methods according to a number of other criteria. We calculated summary statistics based on the 345 multi-stemmed trees we measured and rated each method by various criteria, including time requirement for field work, proportion of multi-stemmed trees on which this method is possible at default (intended) height, mean height of actual measurement, bodily strain, complexity, and capacity for re-measurement. Our assessment of these criteria used field observations, results from the practitioner survey, and our literature review. The characteristics associated with single-stemmed trees' DBH are provided for comparison.

3. Results

3.1. Research question 1: current practice

Multi-stemmed and small-statured trees represent a significant and, in some cases, increasing, proportion of urban forests in the

Table 1
The proportions of the genera *Amelanchier*, *Carpinus*, *Cercis*, *Cornus*, *Corylus*, *Crataegus*, *Lagerstroemia*, *Malus*, *Prunus*, *Pyrus*, *Syringa*, and *Zelkova* of existing street tree inventories and recent street tree planting lists obtained from survey respondents. Only trees with known genus were included in this analysis.

	Multi-stemmed and Small-statured Species' Proportion of:		
City	Existing Street Tree Inventory	Recent Street Tree Plantings	Street Tree Planting Organization (Number of trees; Date range)
New Haven, CT	18.2%	41.7%	Urban Resources Initiative (3,354 trees; 2010-2017)
Newark, NJ	n/a	50.5%	Renaissance Trees Program (2,485 trees; 2006-2017)
New York City, NY	23.9%	34.7%	NYC Parks Forestry Division (10,636 trees; fall 2016-spring 2017)
Philadelphia, PA	n/a	51.5%	Pennsylvania Horticultural Society Tree Tenders (15,321 trees; 2003-2015)
Pittsburgh, PA	15.3%	n/a	n/a
Washington, DC	19.9%	n/a	n/a
Wilmington, DE	27.3%	n/a	n/a

northeastern US (Table 1). Fifty-two percent of our 25 survey respondents reported that the proportions of small-statured street trees in their cities are increasing.

All but one respondent (who prefers DRC) use DBH in their work, but there is variety in the protocols used by respondents for multi-stemmed trees. D Below Fork is a common protocol for practitioners (48% of respondents). Seventy-two percent of respondents indicated that multi-stemmed tree measurement imposes additional burdens for them or their organizations—particularly increased measurement error and the difficulty of complex protocols.

The survey also yielded valuable insights into the context behind the planting of these small-statured trees. Based on survey responses, the major reason that practitioners plant these small-statured trees, instead of large shade trees, is conflict with overhead utility lines (cited by 92% of respondents); a secondary reason is resident preference (48% of respondents). However, 84% of respondents indicated that they see drawbacks to planting small-statured trees. The major themes from open-ended responses were: lower canopy cover, traffic conflicts (both vehicular and pedestrian), visibility inhibition, and shorter lifespans. Survey responses are summarized in greater detail in Appendix B, Table A3.

3.2. Research question 2: biometric predictive power

Taxa differed markedly in their crown architecture and multi-stemmed form (Table 2). Of the 159 *Zelkova* we measured, only 34% were multi-stemmed, and *Zelkova* often forked at or just above breast height—requiring alternative measurement methods because of swelling rather than multiple branches. In contrast, of 109 *Malus* and 301 *Prunus*, just over 70% of each genus were multi-stemmed. Cultivars also exhibited varying proportions of multi-stemmed form, the most notable outlier being *Prunus virginiana* 'Canada Red Select'. Only 25% of 'Canada Red Select' were multi-stemmed; the cultivar exhibits much stronger apical control (strong central leader) than the other three *Prunus* cultivars.

The diameter measurement approaches we applied were all highly correlated with total height and average crown width. For five of the eight model groups that regressed total height or crown width against stem diameter (Table 3), i-Tree's hybrid protocol showed slightly higher R^2 values than either D_{30} or D Below Fork—but in most cases this difference was less than 0.05. In two cases (ZH and MW), i-Tree's current protocol exhibited larger differences—but no model that used i-Tree diameter measurements explained more than 8% more of the variability in predicted biometrics than the alternatives. In 3 model groups (PtW, PaW, and ZW), D Below Fork actually exhibited higher R^2 values than i-Tree. Average crown width showed generally higher correlations with stem diameter measurements of multi-stemmed trees than did total height. The diameter measurements themselves are highly correlated with each other, with R^2 values generally above 0.90 (Table 2, left-most two columns). For example, with model group MH, the close similarities in the regression lines of stem diameter measurements and total height are illustrated in Fig. 2 (similar graphs for other model groups are provided in Appendix B, Figs. A2–A6).

For all but one of the eight model groups, 95% confidence intervals of the difference between R^2 values obtained via bootstrapping included 0, indicating that there was no evidence of systematic difference between R^2 values (Appendix B, Table A2). For these seven model groups with no evidence of difference, the bootstrapped mean difference in R^2 was never > 0.063, and most mean differences were substantially lower. The one model group for which the confidence interval did not include 0 was MW—for which i-Tree's method yielded R^2 values that were, on average, 0.069 > D_{30}'s and 0.099 > D Below Fork's. For MW, D_{30} yielded a R^2 value that was, on average, 0.031 greater than D Below Fork's.

We also tested whether including heights to actual measurement could improve our regression models. However, because all D_{30} heights were 30 cm, and the heights to measurement associated with i-Tree's quadratic sum method do not have a straightforward manner for combination, we only employed heights to measurement with one method: D Below Fork. Including the heights to measurement did marginally improve most models' fit for D Below Fork, but only in the case of *Malus* (MH and MW) was the difference in R^2 values greater than 0.015.

Interestingly, for models using the i-Tree measurements, the predictive power of the quadratic sum of DBHs does not markedly improve as each next largest DBH is added to the quadratic sum—and in some cases, it even decreases (Fig. 3). For 4- to 6-trunked trees, the predictive power of the quadratic sum of DBHs with regard to Average Crown Width does seem to improve with the first three stems, but these are the very trees for which measurement time also increases so dramatically.

Table 2
Summary statistics for the three multi-stemmed genera (*Malus*, *Prunus*, *Zelkova*) measured in Philadelphia, PA. Methods for four diameter methods are described in the text: diameter at root collar (DRC), diameter at 30 cm (D_{30}), diameter below fork (D Below Fork). After providing the sample size for each taxa, including the proportion multi-stemmed (i.e., those forking between 30 and 137 cm height), the remainder of the table pertains to only multi-stemmed trees. We report the means and standard deviations for each diameter method, as well as the means and standard deviations of the forking height [i.e., the height (cm) to the lowest forking branch]. The last two columns provide R^2 values for i-Tree diameter values correlated with D_{30} and D below fork, within each taxa.

	Sample Size		Mean ± Standard Deviation (cm)					R^2 with i-Tree	
	Total	Multi-Stemmed	DRC	D_{30}	D Below Fork	i-Tree	Forking Height	D_{30}	D Below Fork
Malus	**109**	**77**	**15.2 ± 5.6**	**13.5 ± 5.1**	**12.7 ± 4.9**	**12.8 ± 4.9**	**99 ± 19**	**0.93**	**0.92**
'Prairifire'	**41**	**24**	**11.7 ± 3.1**	**10.4 ± 2.9**	**9.5 ± 2.7**	**10.2 ± 3.4**	**121 ± 13**	**0.96**	**0.96**
'Spring Snow'	**50**	**40**	**15.0 ± 5.0**	**13.4 ± 4.5**	**12.8 ± 4.4**	**12.5 ± 4.2**	**95 ± 17**	**0.91**	**0.90**
Unknown	**18**	**13**	**22.2 ± 5.0**	**19.8 ± 4.5**	**18.4 ± 4.8**	**18.7 ± 5.0**	**92 ± 24**	**0.87**	**0.84**
Prunus	**301**	**214**	**19.0 ± 9.8**	**17.3 ± 9.3**	**16.9 ± 9.2**	**17.1 ± 8.6**	**95 ± 19**	**0.93**	**0.93**
***sargentii* x *subhirtella* 'Accolade'**	**58**	**53**	**14.4 ± 4.1**	**12.8 ± 3.8**	**12.4 ± 4.0**	**13.1 ± 4.0**	**95 ± 15**	**0.90**	**0.91**
***subhirtella* 'Autumnalis'**	**36**	**35**	**15.1 ± 3.7**	**13.7 ± 3.5**	**13.9 ± 3.7**	**14.2 ± 3.9**	**88 ± 17**	**0.87**	**0.86**
***virginiana* 'Canada Red Select'**	**51**	**13**	**13.2 ± 3.5**	**11.6 ± 3.5**	**10.6 ± 3.3**	**11.2 ± 3.7**	**107 ± 16**	**0.96**	**0.95**
***sargentii* 'Pink Flair'**	**32**	**27**	**10.8 ± 2.7**	**9.7 ± 2.3**	**9.3 ± 2.3**	**9.2 ± 2.8**	**94 ± 14**	**0.91**	**0.92**
Unknown	**124**	**86**	**26.7 ± 10.7**	**24.7 ± 10.2**	**24.2 ± 10.0**	**24.0 ± 8.7**	**96 ± 23**	**0.88**	**0.87**
Zelkova	**159**	**54**	**16.9 ± 5.7**	**15.3 ± 5.5**	**13.3 ± 5.2**	**14.8 ± 5.9**	**116 ± 11**	**0.94**	**0.96**
***serrata* 'Green Vase'**	**55**	**21**	**14.2 ± 5.0**	**12.8 ± 4.8**	**10.9 ± 4.4**	**12.1 ± 5.1**	**118 ± 12**	**0.92**	**0.95**
***serrata* 'Musashino'**	**4**	**4**	**17.8 ± 1.4**	**16.1 ± 1**	**14.5 ± 1.0**	**15.8 ± 0.6**	**99 ± 12**	**0.83**	**0.61**
***serrata* 'Village Green'**	**11**	**9**	**15.4 ± 4.4**	**13.6 ± 4.2**	**11.7 ± 4.0**	**13.3 ± 5.0**	**120 ± 6**	**0.99**	**0.99**
Unknown (Target & Opportunistic)	**89**	**20**	**20.3 ± 5.9**	**18.4 ± 5.8**	**16.3 ± 5.6**	**18.2 ± 6.1**	**116 ± 11**	**0.91**	**0.95**
Total	**569**	**345**	**17.8 ± 8.6**	**16.1 ± 8.1**	**15.4 ± 8.1**	**15.8 ± 7.7**	**99 ± 20**	**0.93**	**0.93**

Table 3
Summary of all 32 fitted regression models. For reference, models are grouped by multi-stemmed dataset (M, Pt, Pa, or Z), then Y response variable (Total Height or Average Crown Width). Hence, for instance, PtW is the group of regressions fit with *Prunus* (target) and Average Crown Width as the response variable (Y).

Model Group	Multi-Stemmed Dataset	Response Variable (Y)	Independent Variable (X)	Cultivar Indicator Variable (I)	R^2 Values			
					D_{30}	D Below Fork	i-Tree	Single-Stemmed DBH (for Comparison)
MH	*Malus*	Height	Method	Cultivar Unknown	0.768	0.780	0.800	0.800
PtH	*Prunus* (Target)	Height	Method	Cultivar 'Canada Red Select'	0.655	0.676	0.679	0.901
PaH	*Prunus* (All)	Height	log(Method)	Cultivar 'Canada Red Select'	0.607	0.610	0.624	0.596
ZH	*Zelkova*	Height	Method	Cultivar 'Green Vase'*	0.600	0.600	0.680	0.670
MW	*Malus*	Average Crown Width	Method	None	0.718	0.686	0.789	0.640
PtW	*Prunus* (Target)	Average Crown Width	Method	Cultivar 'Pink Flair'	0.787	0.796	0.782	0.874
PaW	*Prunus* (All)	Average Crown Width	log(Method)	Cultivar 'Pink Flair'*	0.747	0.756	0.752	0.801
ZW	*Zelkova*	Average Crown Width	Method	Cultivar 'Village Green'*	0.802	0.835	0.819	0.814

* For the sake of comparison with the three alternative stem measurement methods, for $ZH_{Single\text{-}Stemmed\ DBH}$, 'Green Vase', and for $PaW_{Single\text{-}Stemmed\ DBH}$, 'Pink Flair', were included as indicator variables although they did not prove statistically significant (i.e., p > .05). For $ZW_{Single\text{-}Stemmed\ DBH}$, 'Village Green' was not included as an indicator variable because there were only two single-stemmed 'Village Green' specimens.

3.3. Research question 3: field surveying and data utility considerations

As expected, it takes significantly longer to measure multiple stems (Appendix B, Fig. A1). Two-sample unpaired t-tests indicate that single-stemmed trees' total measurement times (mean = 390 s) are significantly lower than those of two-stemmed trees (p = 0.005), three-stemmed trees (p = 0.001), four-stemmed trees (p = 3.17e-7), five-stemmed trees (p = 2.74e-8), and six-stemmed trees (p = 3.22e-6). By subtracting the median measurement time for single-stemmed trees from the median measurement time for each set of n-stemmed trees, we estimate that measuring multiple stems requires 59 s additional for two-stemmed trees, and as much as 207 s more for six-stemmed trees.

With the exception of D_{30}, there was wide variation in the heights at which we could actually take each measurement (Fig. 4). For DRC, this variation (which caused us to discard DRC early in our analysis) is due to the combination of swollen bases and surficial roots with the presence of weeds, tree fences, animal feces, trash, stump sprouts, vines, and elevated tree pits. For D Below Fork, variation of heights is inherent to the protocol. For the multiple measurements at D_{137} in i-Tree's protocol, forking, swelling, and other irregularities at 137 cm account for variation in recorded heights. Only D_{30}'s standard height exhibited resilience to stem irregularities and complex site conditions (Fig. 4, Table 4).

4. Discussion

The issue of how to measure multi-stemmed urban trees has gained heightened interest in light of the new UFIA program of the US Forest Service—an expansion of the traditional FIA program into urban areas (US Forest Service, 2018)—and researchers' interest in urban tree allometry (Troxel et al., 2013; Monteiro et al., 2016; McPherson et al., 2016b). UFIA, facing the challenge of divergent tree forms, has already simplified their protocol for multi-stemmed trees, to use D Below Fork (US Forest Service, 2018). But this issue is also clearly important for urban forest managers, based on responses to our practitioner survey.

Although classical DBH helps us apply existing dendrometry practices to urban landscapes, there is simply no "true" DBH for a multi-stemmed tree. As much as possible, we tried to follow i-Tree Eco guidelines (US Forest Service, 2017b) for assessing and measuring multiple stems at BH. However, rules concerning minimum diameter and maximum branching angle, while perhaps intended to reduce total number of recorded measurements, ultimately require additional time and measurement to ascertain on trees with extremely complex branching structures. The distinctions between "stems," "trunks," and "branches" varies between researchers (Dunphy et al., 2000; Condit, 1998), and in some cases, researchers even reject the distinction as "largely a question of semantics" (Clough et al., 1997; echoed by Stewart and Salazar, 1992). Meanwhile, our practitioner survey indicated that multi-stemmed mensuration does burden practitioners, as had been found for researchers and citizen scientists, who recorded widely varying numbers of stems for multi-stemmed street trees in Roman et al. (2017). Because of current street tree planting trends, challenges with multi-stemmed street tree measurement will likely continue to be a concern. Even after measuring hundreds of trees with the same i-Tree Eco protocols, we found the assessment and decision-making process at each tree arduous, and the need for simplification became apparent.

Although i-Tree Eco measurement protocols show in some cases a slightly higher R^2 compared to D Below Fork and D_{30}, the results from the second part of the analysis do not show a decisive advantage for any of the individual options. The inability to differentiate measurement techniques based on biometric predictive power makes intuitive sense, given that researchers have known for years that standard geometric shapes like frustums are fair approximations of tapering tree stems (Larsen, 2016), but also arises from the fact that i-Tree Eco's diameter protocol is a hybrid approach that actually includes D_{30} when more

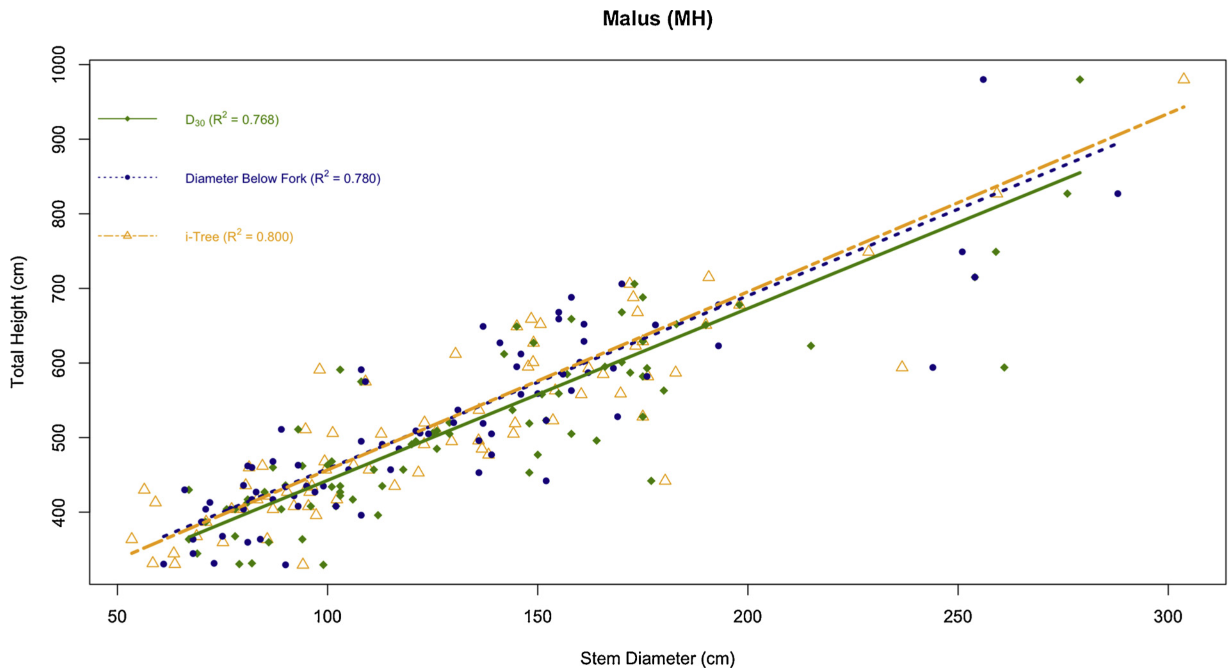

Fig. 2. Data for *Malus* for each diameter measurement method, showing regression lines for each model predicting Total Height. Each multi-stemmed *Malus* appears on this graph three times—once in each different diameter method.

than six eligible stems are present (US Forest Service, 2017b).

Results from the third part of our analysis are more conclusive. The measurement of multiple stems at 137 cm poses significant challenges due to additional time required and task complexity, as well as high deviation in BH actually used and potential challenges with consistency and remeasurement. The minor gains in R^2 values using the i-Tree measurement method do not appear to be worth the costs in terms of field crew time and capacity for consistent re-measurements. Given the locality and genera we considered, D_{30} and D Below Fork are the most promising alternatives for measuring multi-stemmed trees.

These two alternative techniques may have different applications—depending on goals. D Below Fork involves less bodily strain but more discretion on the part of field crews—which may increase survey time or confusion. It is currently employed by and may be better suited for practitioners who are not interested in longitudinal monitoring or cross-tree comparisons to fine measurement resolutions. For urban

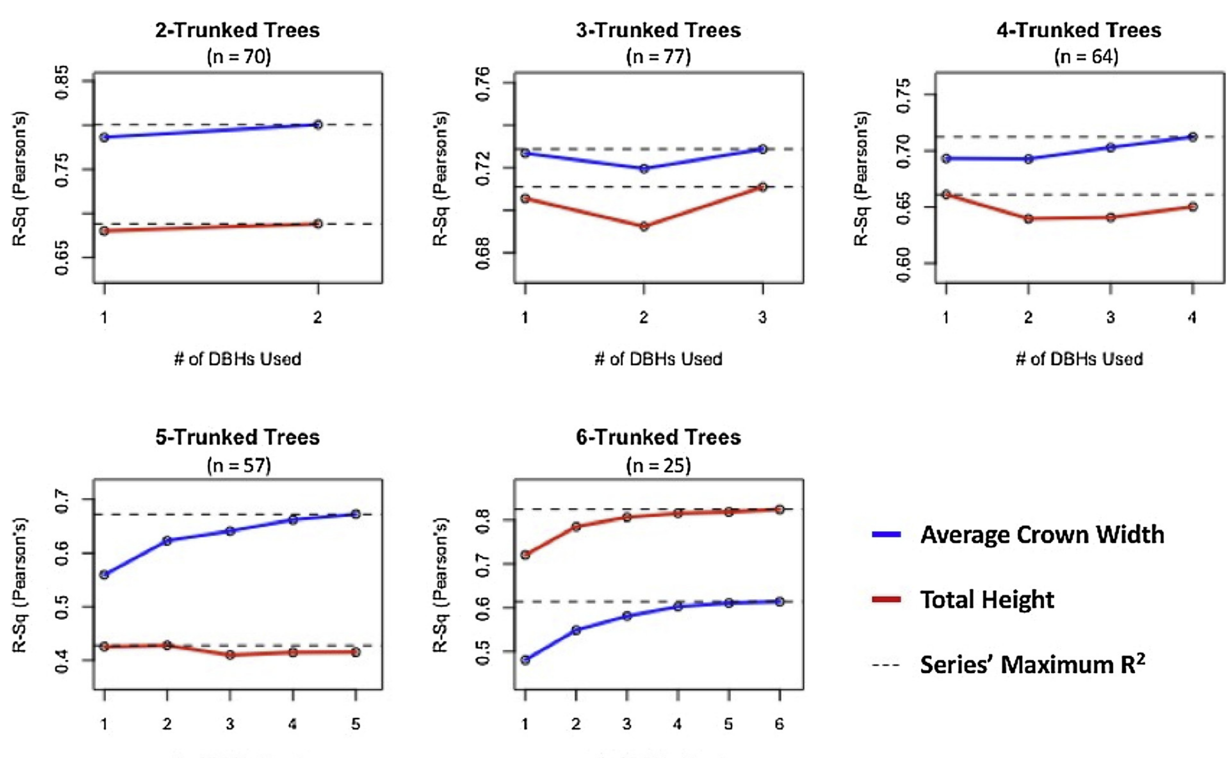

Fig. 3. Correlations of stem diameter measured with the i-Tree method with Total Height and Average Crown Width for a given dataset (e.g., 2-trunked trees), as each next largest DBH is added to the quadratic sum.

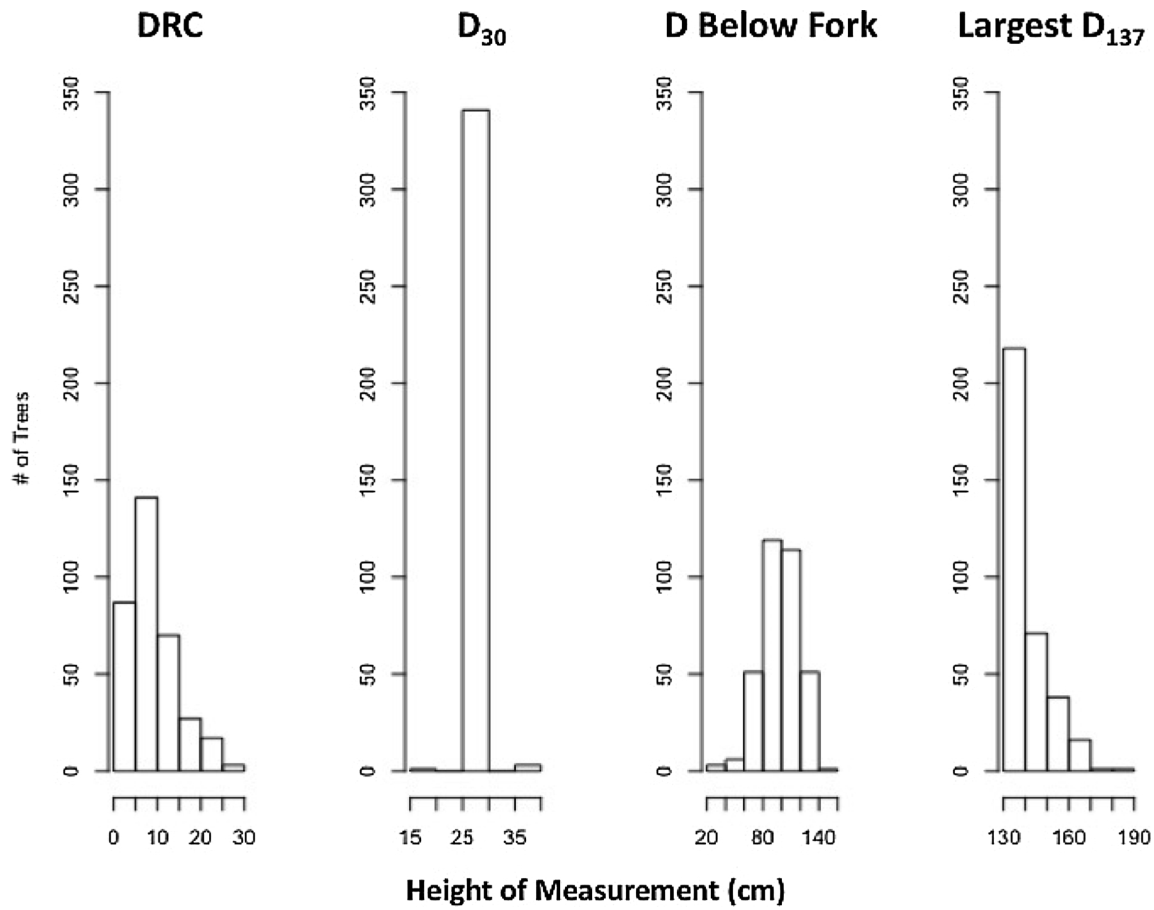

Fig. 4. The distribution of heights at which each method could be employed for the 345 multi-stemmed trees we measured (i.e., the measurement height actually used, as opposed to the intended default height). The largest D_{137} is the largest diameter at breast height (which would then be employed, for 2-6-stemmed trees, via a quadratic sum, to compute the tree's DBH-equivalent, using the i-Tree protocol).

forest management applications, such as describing the overall size class distribution of street trees in a city, trunk measurements to the nearest 2.5 cm are acceptable (Roman et al., 2017), and height to actual measurement is rarely recorded, so D Below Fork can be suitable. The bodily strain issue is a relevant consideration for citizen science urban forestry programs that use retired or elderly volunteers (Roman et al., 2017; Johnson et al., 2018). By virtue of being at varying heights, though, D Below Fork does not meet researchers' needs for re-measurement and comparison between trees, and would complicate the development of accurate allometric models for these trees.

On the other hand, D_{30} may be better suited for researchers, as it enables consistency in longitudinal monitoring for re-measurement of radial growth, comparisons between trees, and ultimately, the development of allometric models for multi-stemmed street trees of each genus. D_{30} requires simple explanations and equipment, and was measureable at its default height on all but one of the 345 multi-stemmed trees in our study. Its shortcomings are higher bodily strain (from bending down) and the fact that, at least from our survey results, it is not currently used by urban practitioners as an alternative height of diameter measurement. Notably, however, agroforestry trials in the 1990s recommend D_{30} as the superior option, based on time required, predictive power, objectivity, and ease of sampling (Stewart, 1990;

Table 4
Qualitative rubric for evaluating each method according to criteria related to measurement ease, complexity, replicability, and other considerations associated with surveying and data usefulness.

Criterion	D_{30}	D Below Fork	i-Tree	Single-Stemmed DBH
Time requirement	Low	Medium	High	Low
Proportion of multi-stemmed trees on which this measurement is possible at default height	100%	100%	56%	0%
Mean height of actual measurement (cm)	30	99	142 & 30	137
Standard deviation of heights of actual measurement (cm)	0	20	9 & 0	2
Pieces of equipment required	1	2	2	2
Bodily strain	High	Medium	Medium	Low
Maximum number of measurements (including height of measurement)	2	2	12	2
Complexity	Low	Medium	High	Low
Comparability between trees	High	Low	Medium	High
Capacity for re-measurement	High	Medium	Low	High
Sensitive to "negative" growth given pruning	No	No	Yes	No
Practitioners currently use	No	Yes	Yes	Yes
Researchers currently use	Yes	Yes	Yes	Yes

MacDicken et al., 1991). Additionally, the authors of the Australian National Carbon Accounting System have adopted D_{30} for multi-stemmed trees (Snowdon et al., 2002). These previous studies, combined with our results in Philadelphia, suggest that urban forestry researchers should use D_{30} for multi-stemmed trees.

4.1. Further research

There are numerous avenues for further research regarding multi-stemmed urban trees. First, a biomass estimation study, using non-destructive LiDAR techniques (Lefsky and McHale, 2008; McHale et al., 2009; van Leeuwen and Nieuwenhuis, 2010) could confirm (or complicate) our findings about the comparable predictive power of D_{30} and D Below Fork. Researchers might also consider a related study on whether similar protocol simplifications could be made for multi-stemmed trees in rural forests. Our recommendations to use D_{30} and D Below Fork also need to be evaluated for other genera and regions, as street tree species—and thus frequency and type of commonly multi-stemmed trees—differ by region and country (McPherson et al., 2016a; Ramage et al., 2012; Thomsen et al., 2016).

Second, our field sampling yielded a dataset that could be used to further explore some of the questions about crown architecture raised by previous researchers. Such questions include urban street tree crown eccentricities (McPherson et al., 2016b), environmental characteristics associated with multi-stemmed form (Bellingham and Sparrow, 2009; Dunphy et al., 2000; Stokes et al., 2011), crown width/DBH relationships (Hemery et al., 2005), and basal area relationships above and below forking (Matérn, 1990; Minamino and Tateno, 2014; Murray, 1927). Because we also gathered data for each tree pertaining to crown health and site characteristics (data not included in our models, but provided in Appendix 3), other researchers could use our dataset to examine the roles that such characteristics play in tree sizing and crown architecture. One key question for researchers is which characteristics of allometry transfer from rural to urban forests—and which need amendment or replacement for urban application (McHale et al., 2009).

Researchers may also want to tease apart differences in crown architecture due to genetics as opposed to site conditions. For instance, a possible reason for the more erect form of 'Canada Red Select' is that it is a sport of *Prunus virginiana* 'Schubert'—and thus descends from native North American chokecherries, rather than the Japanese flowering cherries from which the others are bred (Barborinas, 2017; Breen, 2017; Bailey Nurseries, 2017; Leopold, 2005; Petrides, 1972). Such genetic variability impacts the relationship between stem diameter(s) and crown architecture, complicating the search for a universal protocol. Yet cultivar identification was only possible for this study because of access to reliable planting records. For many urban tree inventories—as with several of those that we analyzed for planting trends—ornamental *Prunus* are lumped together, so this genetic variability may not figure into urban allometric models anyway. Indeed, the largest set of urban allometric models currently available were developed at the species level, and make no mention of cultivar (McPherson et al., 2016b).

Third, although we tried to record pruning to potentially incorporate the extent of pruning into our allometric models—because pruning obviously impacts the allometry of urban trees—we found our own methods inadequate, and echo previous researchers' call to develop a quantitative "pruning index to adequately and consistently describe reductions to crown dimensions and density" (Peper et al., 2001).

4.2. Conclusion

The ideal measurement technique should be selected in consideration of the study goals, and our research uncovered some unique findings to help inform this decision with regard to multi-stemmed urban trees, which have challenged urban forest researchers for years. When efficiency of measurement is paramount, such as for managers where population counts and species are more important than precise tree size, D Below Fork is adequate and faster than measuring multiple stems, while also imposing lower bodily strain than D_{30}. For research and monitoring, D_{30} is preferable for its repeatability and consistency. However, research that will benefit from comparisons to historical work or application of existing allometric models methods will need to reflect established protocols. The increasing adoption of urban forest inventories lends urgency to the resolution of this and similar questions of mensuration.

Funding sources

This work was supported by the Hixon Center for Urban Ecology at the Yale School of Forestry and Environmental Studies and the TREE Fund.

CRediT authorship contribution statement

Yasha A.S. Magarik: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Lara A. Roman:** Conceptualization, Methodology, Supervision, Writing - review & editing, Project administration. **Jason G. Henning:** Methodology, Writing - review & editing.

Acknowledgement

We are deeply grateful to E. Bannar and M. Sutter for their assistance in field sampling. We thank M. Ashton, C. Murphy-Dunning, T. Gregoire, J. Reuning-Scherer, D. Doroski, D. Locke, J. Westfall, M. Majewski, A. Doolittle, S. Low, and J. Bukoski for advising various aspects of the project, the Ashton Lab Group for providing valuable feedback on data analysis, interpretation and presentation, and the Pennsylvania Horticultural Society and USDA Forest Service for providing us with tree planting records, staff time, equipment, and office space. We also appreciate comments from two anonymous reviewers. Finally, we thank all of the urban forestry practitioners who took the time to share their perspectives with us, and the residents of Philadelphia—whose trees we were able to measure.

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.2019.126481.

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