Urban tree database and allometric equations

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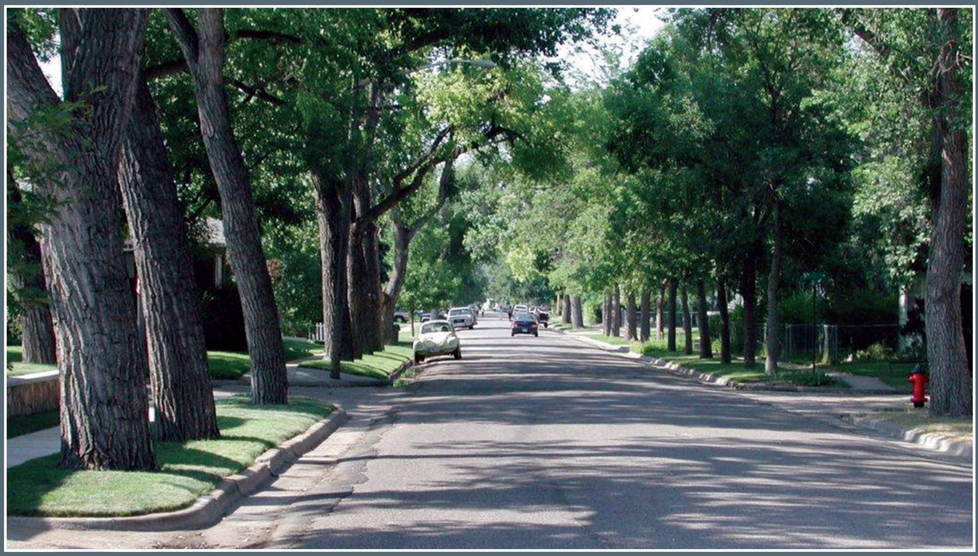

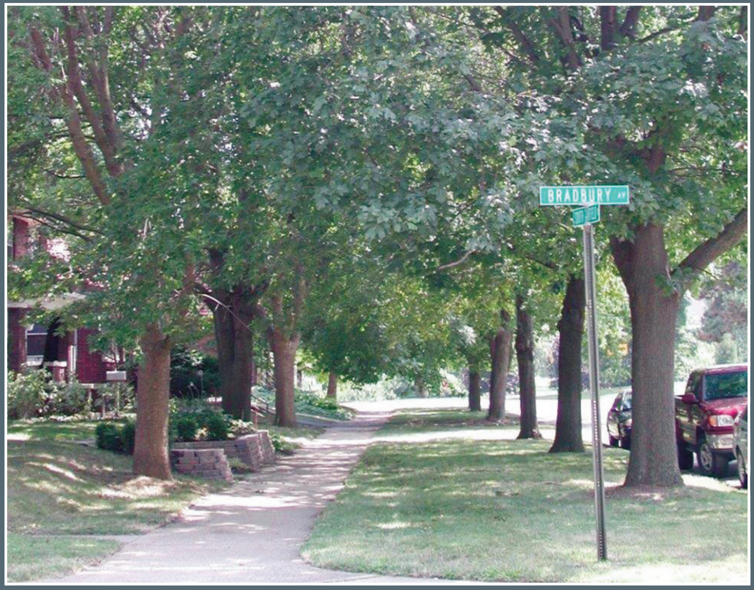

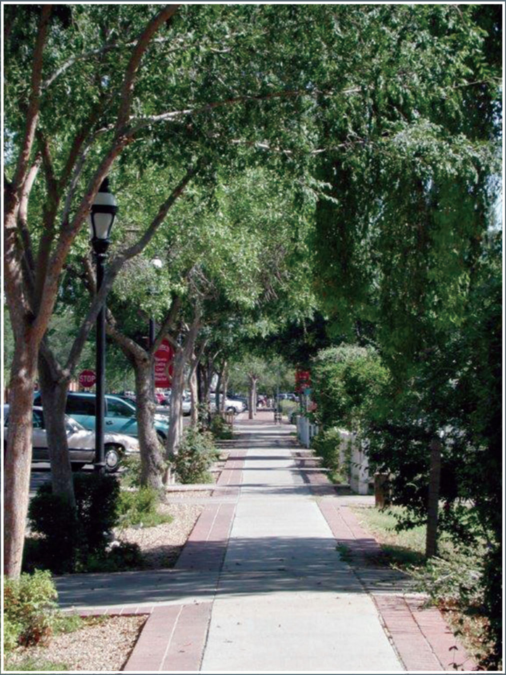

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Cover photos: top—Mature street trees frame a view down a residential street in Bismarck, North Dakota. Bottom right—Young street trees shade a sidewalk and parked cars in Glendale, Arizona. Bottom left—Street and front yard trees join to provide continuous shade in this Indianapolis, Indiana, neighborhood. (Photos courtesy of Pacific Southwest Research Station.)

Abstract

McPherson, E. Gregory; van Doorn, Natalie S.; Peper, Paula J. 2016. Urban Tree Database and Allometric Equations. Gen. Tech. Rep. PSW-GTR-253. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 86 p.

Information on urban tree growth underpins models used to calculate the effects of trees on the environment and human well-being. Maximum tree size and other growth data are used by urban forest managers, landscape architects, and planners to select trees most suitable to the amount of growing space, thereby reducing costly future conflicts between trees and infrastructure. Growth data are used to examine relationships between growth and influencing factors such as site conditions and stewardship practices. Despite the importance of tree growth data to the science and practice of urban forestry, our knowledge in this area is scant. Over a period of 14 years, scientists with the U.S. Forest Service Pacific Southwest Research Station recorded data from a consistent set of measurements on over 14,000 trees in 17 U.S. cities. Key information collected for each tree species includes bole and crown size, location, and age. From this Urban Tree Database, 365 sets of tree growth equations were developed for the 171 distinct species. Appendices contain field data collection protocols, foliar biomass data that are fundamental to calculating leaf area, tree biomass equations for carbon storage estimates, and a user guide that illustrates application of the equations to calculate carbon stored over many years for tree species that were measured in multiple cities. An online database at http://dx.doi.org/10.2737/RDS-2016-0005 includes the raw data, growth equations, coefficients, and application information for each species' volume and dry-weight-biomass equations for urban and rural forest trees; and an expanded list of biomass density factors for common urban tree species.

Keywords: Allometry, growth models, predictive equations, tree growth, urban trees.

Contents

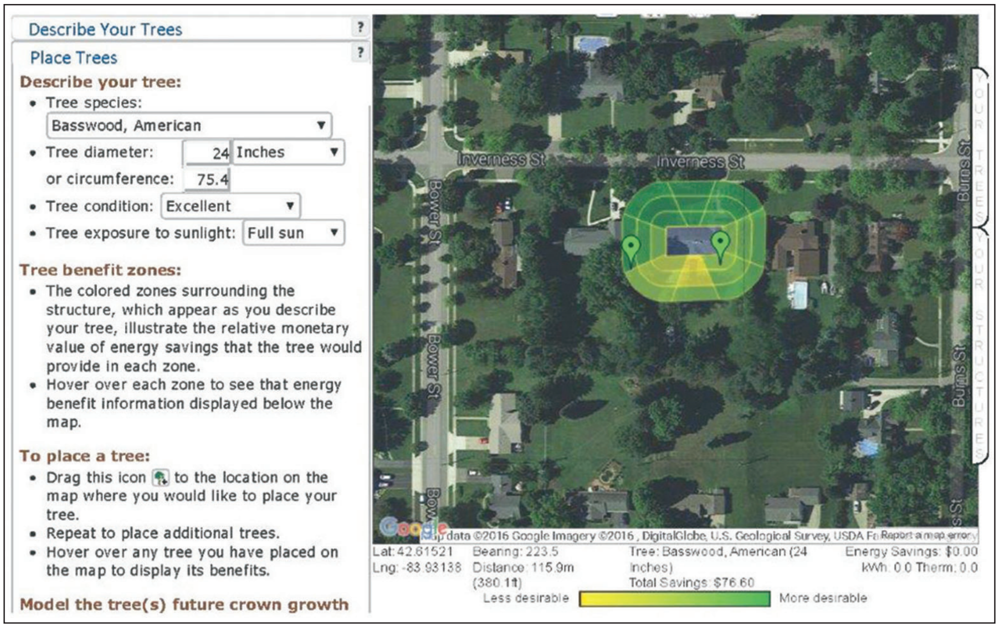
Chapter 1: Introduction

Tree size and age influence management costs and ecosystem services derived from urban trees. Urban forest researchers have developed allometric equations for trees in urban environments, but their range of application and predictive power are limited owing to small sample sizes, few species, young trees only, excellent-condition trees only, and narrow geographic region. This research overcomes many of these limitations. Based on measurements of 14,487 urban street and park trees, an Urban Tree Database (UTD) was constructed. From the UTD, 365 sets of allometric equations were developed for tree species from around the United States. Each "set" consists of eight equations for each of the approximately 20 most abundant species in each of 16 climate regions. Tree age is used to predict species diameter at breast height (d.b.h.), and d.b.h. is used to predict tree height, crown diameter, crown height, and leaf area. Diameter at breast height is also used to predict age. For applications with remote sensing, average crown diameter is used to predict d.b.h. There are 171 distinct species represented within this database. Some species grow in more than one region and tend to grow differently from one region to another owing to environmental and management differences. Thus, there are multiple equations for the same species that reflect those differences, and it is important to select the equation for the appropriate region. The UTD contains foliar biomass data that are fundamental to calculating leaf area, as well as tree biomass equations for carbon storage estimates. Also, a user guide illustrates application of the equations to calculate carbon stored over many years for tree species that were measured in multiple cities. The raw data and equations may be accessed and downloaded at http://dx.doi.org/10.2737/RDS-2016-0005.

Uses of Urban Tree Growth Equations

Information on urban tree growth is indispensable to modeling urban forest function and value. The economic, social, and ecological benefits of trees are directly related to their size, as indicated by leaf area, crown volume, and biomass (Scott et al. 1998, Stoffberg et al. 2010, Xiao et al. 2000a). Growth equations underpin the calculations produced by many computer models used in urban forestry, such as i-Tree, National Tree Benefit Calculator, OpenTreeMap, and ecoSmart Landscapes (fig. 1).

Urban tree growth and size data can assist municipal foresters because the costs for pruning and removing trees tends to increase with tree size (O'Brien et al. 1992). For example, accurate projections of size-related costs for pruning species that require frequent care can improve budgeting. Sanders et al. (2013) noted that managers are hindered in developing tree removal and replacement plans and obtaining public acceptance when they lack empirical data on each species' useful



i-Tree.org

Figure 1—Computer programs such as i-Tree use tree growth equations when calculating annual carbon dioxide sequestration by trees.

service life. Without maximum size end points that are linked to constraints posed by the designed space, it is difficult to plan for phased removal and replacement that minimizes liability and maintains continuous tree canopy cover.

Knowledge of maximum tree size can inform tree selection to avoid conflicts between tree roots and nearby sidewalks or between crowns and utility lines (Randrup et al. 2001). Conversely, field-based predictions of crown projection area at 10, 15, and 20 years after planting can help designers select species to achieve targeted tree canopy cover in parking lots (McPherson 2001). Other examples of design and management issues influenced by tree growth and size include spacing between trees and in relation to building infrastructure, soil volumes required, irrigation demands, and pest-control and fertilization dosages (fig. 2). A better understanding of tree allometry by landscape architects and arborists can potentially reduce management costs, improve functional performance, and increase the benefits derived from healthy and sustainable urban forests (Clark et al. 1997).

Allometric equations that describe the bole and crown growth of different urban tree species can be used to create more realistic animations that compress years of growth into seconds (Peper et al. 2007). Landscape architects and planners are increasingly using three-dimensional models to visualize alternative landscapes (fig. 3). Incorporating empirically derived allometric equations to simulate development of the tree canopy can allow designers to anticipate spatial impacts and potential conflicts between maturing trees and other design elements (Larsen and Kristoffersen 2002).

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Figure 2—Urban tree growth equations can be used to estimate the maximum trunk diameter of different aged trees to help managers reduce infrastructure repair costs.

Figure 3—Tree growth equations underpin three-dimensional models that are used to visualize the spatial and economic impacts of alternative landscapes. (Linsen et al. 2005)

Analyses of allometric and site data can find correlations between variables that will inform management (Grabosky and Gilman 2004). Moreover, tree size and age data can be used to form local baselines for cities. Repeated measurements of the same trees can identify trends in growth, survival, and replacement. By building upon these baseline data, long-term tree growth and demographic studies could fill important knowledge gaps in urban forestry.

Development of Urban Tree Growth Equations

Although tree growth is the result of very complex processes, growth equations capture changes in tree size with age in a surprisingly simple and accurate way. Growth equations contain two components that reflect the interaction of two opposing biological forces. The expansion component is responsible for the increase in the increment with age, and growth expansion is proportional to the current size of the tree (Zeide 1993). The growth-decline component is responsible for the decrease in the increment with age from constraints imposed by internal (aging) and external (stress) factors. Hence, growth equations bring together these two biological forces over the entire lifespan of a species. Because tree growth reflects the unique genetic traits of trees, as well as their responses to environmental trends and management, no one growth equation suits all species, sites, or growth processes. Growth equations are best applied when the scope of analysis includes many individual trees over long time periods.

Growth equations are traditionally associated with rural forests, where they provide quantitative guidelines for planting, thinning, and harvesting. Growth equations for forest trees may not be directly transferable to open-grown urban trees because they grow and partition bole, branch, twig, and leaf biomass differently (Anderegg et al. 2015, Nowak 1994a, Peper and McPherson 1998) (fig. 4). For example, in forests, tree crowns compete for limited space and may not reach their maximum expansion potential (Martin et al. 2012).

The development of allometric equations for urban open-grown trees has been sporadic. Fleming (1988) measured trees in New Jersey having full healthy crowns to develop linear relationships between d.b.h., height, crown spread, and age. Frelich (1992) measured only healthy trees (12 species, 221 trees total) growing in Minneapolis and St. Paul, Minnesota, to predict linear size relationships. Nowak (1994b) developed an allometric equation for leaf area based on data from park trees in Chicago. Tree dimensions and leaf area were predicted

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Figure 4—The form of red maple trees (*Acer rubrum*) can vary from relatively upright in forest stands (left) (Zimmerman 2011) to spreading when growing in the open (right).

for the most abundant street tree species in Modesto and Santa Monica, California (Peper et al. 2001a, 2001b). In New Haven, Connecticut, Troxel et al. (2013) developed allometric equations for predicting d.b.h. from age and height, crown diameter, and crown volume from d.b.h. for early growth (15 years) of 10 street tree species.

Outside of North America, growth equations have been developed for street-side *Tilia* species in Copenhagen, Denmark (Larsen and Kristoffersen 2002), and *T. cordata* Mill., *Fraxinus excelsior* L. and *Aesculus hippocastanum* L. in Warsaw, Poland (Lukaszkiewicz and Kosmala 2008, Lukaszkiewicz et al. 2005). Predictive models were developed from allometric data for five street tree species in northeastern Italy by Semenzato et al. (2011). Stoffberg et al. (2008) used allometric relationships between age and d.b.h., height, and crown diameter to estimate dimensions at 10, 15, and 30 years after planting for three street tree species in Tshwane, South Africa. The allometric equations from all these studies reflect the effects of local site conditions, management practices, and growing season on growth, limiting application outside their region of origin (fig. 5).

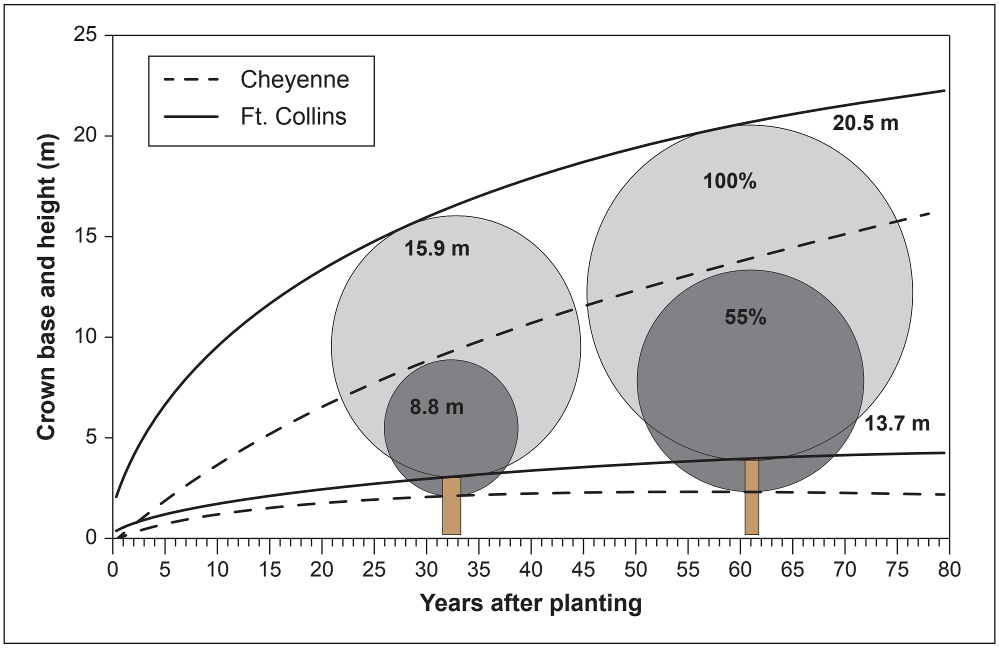

Figure 5—Urban tree growth modeling has shown how crown dimensions for trees of the same age and species can vary due to differences in climate and management practices (McPherson and Peper 2012). Upper and lower lines represent height and height to first branch, respectively. Cheyenne green ash (*Fraxinus pennsylvanica*) have 55 percent of the Fort Collins' ash leaf area after 60 years.

Origin of These Urban Tree Growth Equations

For this report, the need to develop urban tree growth equations was first prompted by a grant that required calculating the 40-year annual stream of carbon stored by urban trees across the United States (McPherson and Simpson 1999). Measured data were lacking for most regions. Following Frelich (1992), d.b.h. was predicted using a power function with age and two constants (fig. 6). Coefficients were adjusted for different regions based on the number of frost-free days, and calibrated with the few data points that were available. This absence of reliable data led the U.S. Forest Service to undertake a 14-year campaign that measured more than 14,000 trees in cities across the United States. Crews began systematically sampling street and park trees in 1998. The initial tree growth equations were used with numerical models to calculate the annual stream of benefits associated with energy effects, air pollutant uptake and emissions, carbon storage, rainfall interception, and effects on property values (Maco and McPherson 2003, McPherson et al. 2005).

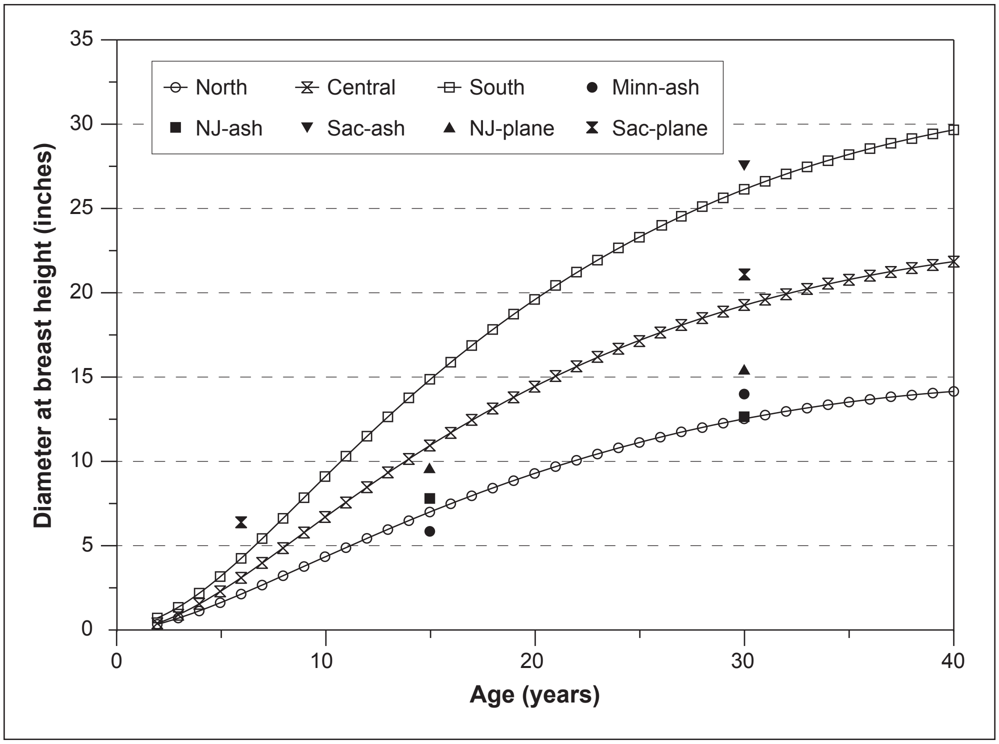

Figure 6—Initial efforts to model tree growth to calculate carbon storage were limited by a scarcity of measured data (McPherson and Simpson 1999).

This work evolved into the i-Tree Streets (formerly STRATUM) software program and a series of related products that are highlighted below.

- **Sixteen regional tree guides** quantified the long-term benefits and costs for trees and provided information on program design and implementation, optimal configurations of trees, tree species for different situations, techniques for successful establishment of new trees, and sources of funding and technical assistance. These technical reports provide regionally specific science-based information for elected officials, planners, landscape architects and contractors, urban foresters, arborists, and nonprofit tree organizations (McPherson et al. 2000, 2010; Peper et al. 2009; Vargas et al. 2007) (http://www.fs.fed.us/psw/topics/urban_forestry/products/tree_guides.shtml).
- **Seventeen municipal forest resource assessments** combined results of citywide street/park tree inventories with benefit-cost modeling to describe structure, function, and value, along with resource management needs (McPherson and Simpson 2002, McPherson et al. 1999) (http://www.fs.fed.us/psw/topics/urban_forestry/products/mfra.shtml).

- **Trees in Our City PowerPoint presentations** (http://www.fs.fed.us/psw/topics/urban_forestry/TreesInOurCity/index.shtml) **and Trees Pay Us Back brochures** (http://www.fs.fed.us/psw/topics/urban_forestry/products/treebrochures.shtml) translated regional results into customized images and figures for audiences such as city councils and homeowners (McPherson et al. 2011).

In 2008, the U.S. Forest Service Pacific Southwest Research Station received funding from CAL FIRE to develop a tree carbon calculator to predict carbon stored by tree planting, following guidance in the Urban Forest Greenhouse Gas Reporting Protocol (Climate Action Reserve 2008). The Center for Urban Forestry Research (CUFR) Tree Carbon Calculator was released in 2010 and incorporated revised tree growth equations for the most abundant tree species in each of 16 U.S. climate zones (http://www.fire.ca.gov/resource_mgt/resource_mgt_urbanforestry).

This report presents the third, most recent and most complete sets of growth equations. The equations presented in this report were developed using more sophisticated statistical methods than before. For example, in the first studies, logarithmic regression and exponential models predominantly provided the best fits to measured data (Peper et al. 2001a, 2001b). In these equations, the best model fits ranged from polynomials (from simple linear to quartic) to logarithmic and exponential models (Peper et al. 2014). The newest equations have been integrated with numerical models of tree benefits in the ecoSmart Landscapes software (McPherson et al. 2014).

Limitations of Urban Tree Growth Equations

The biophysical, social, and economic forces that influence tree growth are highly variable within and among cities. Consequently, large sample sizes are required to fully capture overall growth trends within a species. In rural forests, relatively uniform growing conditions allow foresters to create site indices and generate site-specific growth equations for each species in the stand. This has not been done for trees in the urban forest because of their heterogeneity and limited resources for measurements.

Management practices can differ widely among the arborists and amateurs who plant and maintain trees. For example, pruning practices such as topping trees to reduce their height can affect tree growth and size (fig. 7). Crown damage from storms, pests, drought, and other stressors can result in highly variable height and diameter dimensions among trees of the same species and age. The presence of trees with dimensions that deviate from the norm can result in growth equations that produce less reliable size predictions.

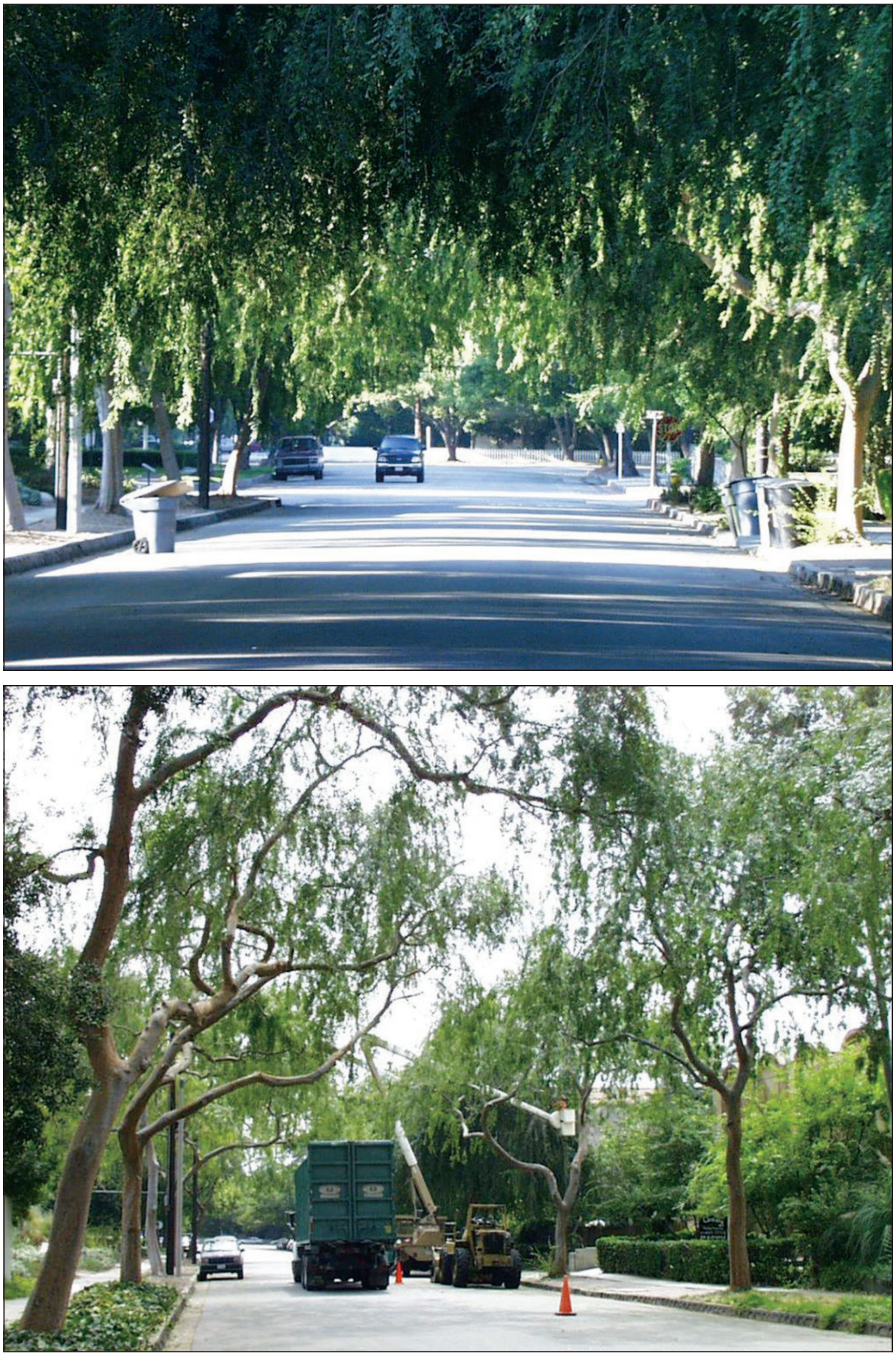

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Figure 7—Tree management practices, especially pruning, can affect crown size. The two Chinese elms (*Ulmus parvifolia*) before (above) and after (below) pruning in Claremont, California.

Another limitation to the development of robust growth equations for urban trees is the difficulty of obtaining accurate age data for older trees. In the context of this research, tree age refers to years after planting, not after germination or propagation. Records of planting dates seldom extend beyond 30 to 40 years. Similarly, detecting the presence and size of individual trees using high-resolution aerial imagery becomes difficult prior to 1990. As a result, predictions of urban tree dimensions reflect the increasing uncertainty about true tree age compounded by naturally increasing variability associated with aging (fig. 8).

Allometric equations for urban tree species have many valuable uses. Although researchers have developed such equations, their range of application and predictive power are limited by small sample sizes, few species, young and excellent-condition trees only, and narrow geographic range. This research overcomes some of these limitations by presenting 365 sets of allometric equations for the most abundant tree

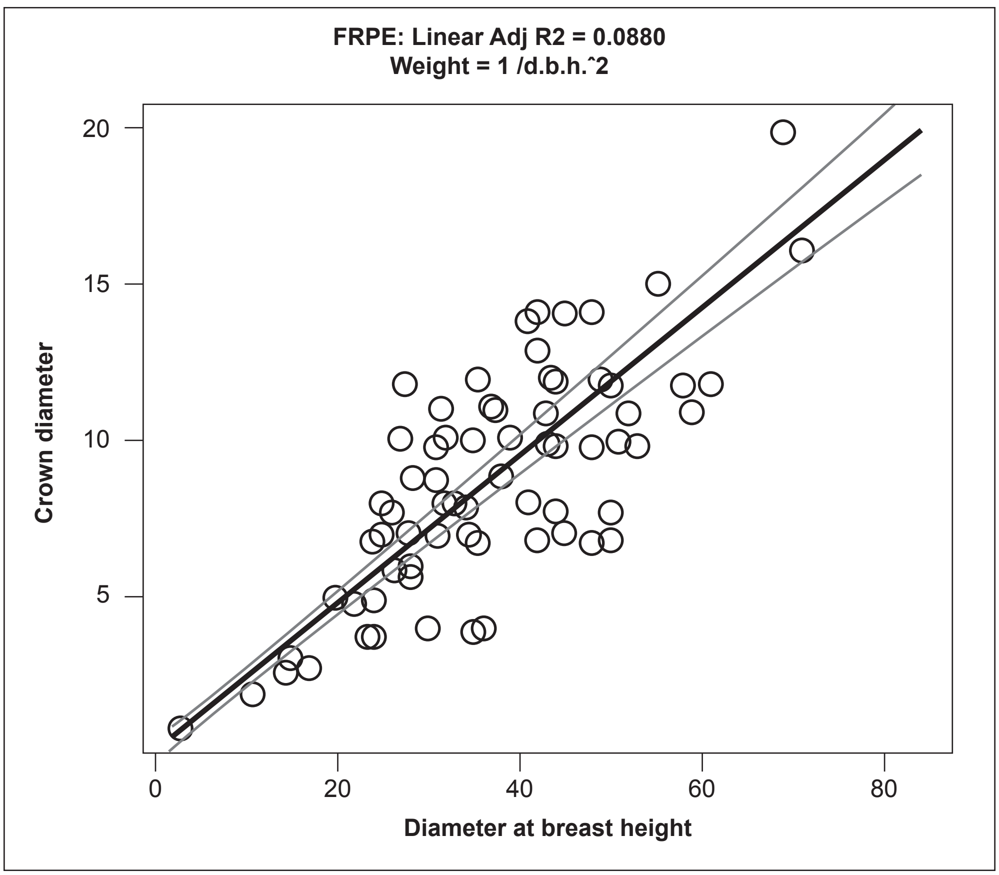

Figure 8—Tree crown measurements typically reflect increased variability with age. In this scatter plot of green ash diameter at breast height (d.b.h.) (in centimeters) and crown-diameter data (in meters) the variability is greatest for trees with d.b.h. in the 20-to 60-cm range. Accordingly, the prediction interval increases with d.b.h. size (Peper et al. 2014).

species in cities from around the United States. Also, this report illustrates application of these growth equations by calculating the predicted amounts of carbon dioxide stored over 50 years by the same species of trees growing in cities with different climates, soils, and management practices.

Foliar Biomass

Accurate estimates of leaf area are fundamental to modeling physiological and functional processes of urban forests. For example, the volume of rainfall intercepted by a tree crown is related to the amount of leaf area as well as the foliage surface saturation storage capacity, both of which are species dependent (Xiao et al. 2000b). Leaf area is used to calculate dry deposition rates of air pollutants and emissions of biogenic volatile organic compounds (BVOC) for different tree species (Benjamin and Winer 1998). Hirabayashi et al. (2012) used a regression equation to estimate leaf area that uses crown dimensions and a species-specific shade factor (Nowak 1996). Bottom-up modeling approaches such as this calculate interception, uptake, and emissions of individual trees and scale-up these estimates to the region. This approach allows for modeling future effects of different management strategies.

The accuracy, precision, efficiency, and other practical considerations associated with four methods of estimating leaf area of open-grown urban trees were evaluated with a completely destructive sample of 50 trees (Peper and McPherson 2003). The color digital image processing method was the only method to produce estimates within 25 percent of mean true leaf area and meet additional requirements for precision and efficient use in urban settings. The regression equation that is currently applied in the i-Tree Eco dry deposition model (Cabaraban et al. 2013, Nowak et al. 2014) had the lowest correlation of the four approaches.

Isoprene and other BVOC emission factors are important components of air quality models because tree emissions can occur at levels that influence atmospheric composition (Geron et al. 2001). Isoprene emission rates of different plant species range from <0.1 to >100 $\mu g \cdot m^{-2} \cdot h^{-1}$. Species-specific emission factor data have been summarized and measurement techniques detailed (Ortega et al. 2008). Allometric relationships between leaf area, fresh and dry leaf weight make it possible to estimate values of these important model parameters from measurements on a related parameter. For example, emission factors are expressed in units for dry foliar weight ($g\text{-}C \cdot kg^{-1} \cdot$ dry leaf day^{-1}). To scale-up the emission calculation to an entire tree, one can estimate its total dry foliar weight if the kilogram of dry leaf to square meter leaf area is known, as well as total tree leaf area. Similarly, if total tree foliar dry weight is unknown but the foliar dry weight to fresh weight ratio is known, total tree foliar dry weight can be estimated by sampling and weighing leaves in quadrats within the crown volume.

The UTD described in this report contains allometric equations that can be used to calculate tree leaf area by d.b.h. for selected species. Also, it contains species-specific ratios for foliar dry weight to fresh weight and dry weight to leaf area. The UTD is the most extensive compilation of these ratios for urban trees published to date.

Woody Biomass

Tree species, wood density, moisture content, and size data (d.b.h. and height) are used with biomass equations and other information (e.g., condition) to calculate tree wood volume and stored carbon. Because wood densities and moisture contents can vary within and among species, there is error associated with the use of average values in allometric equations (Yoon et al. 2013). Volumetric equations calculate the aboveground green wood volume of a tree using species d.b.h. and height. Total biomass and carbon stored are estimated by converting green volume to dry weight using density conversion factors, adding the biomass stored belowground, and converting total biomass to carbon.

Direct equations, a second type of equation, yield the aboveground dry weight of a tree, eliminating the need for density conversion factors. Direct equations are very site specific, and they assume that wood density value does not change. This is a limitation if the equations are to be applied across a variety of trees, sites, and climate zones because wood density varies within a tree and by site. Our focus has been on using volume equations and species-specific wood density factors obtained from the Global Wood Density Database (Zanne et al. 2009). This allows the user to select a volume equation from a species whose structure most resembles the structure of the subject tree, then apply the density factor for the subject tree's species.

Destructive sampling methods used to develop biomass equations in forests are occasionally used in urban forests, such as for *Quercus virginiana* Mill. and *Q. laurifolia* Michx. in Florida (Timilsina et al. 2014). Pillsbury et al. (1998) took nondestructive manual measurements of 15 species of street and park trees in California. Terrestrial LiDAR was used to develop biomass equations for 11 species in Fort Collins, Colorado (Lefsky and McHale 2008). A laser dendrometer was used for measurements on the five most abundant street tree species in Daegu, Korea (Yoon et al. 2013).

Application of forest-based biomass equations for tree species is less desirable than applying urban-based equations because of differences in tree architecture (McHale et al. 2009, Yoon et al. 2013). Nowak (1994c) recommended multiplying forest-based equation results by a correction factor of 0.80 because they overestimated actual biomass. However, McHale et al. (2007) found that standard application of the correction factor may lead to underestimates of biomass at the city scale. Yoon et al. (2013) found that the urban-based biomass equation for *Zelkova serrata* (Thunb.) Makino produced estimates 4.7 to 6.0 times lower than one from plantation-grown trees, but was similar to the equation for urban *Zelkova* in California (Pillsbury et al. 1998). However, the allometric equations for open- and plantation-grown *Ginkgo biloba* L. were similar, implying greater architectural and genetic uniformity for this species.

Urban general equations have been developed as an alternative to applying species-specific equations when many species do not have an equation. Aguaron and McPherson (2012) compiled urban general equations from 26 urban-based equations that were species specific. They found that these direct general equations underestimated carbon storage relative to species-specific equations at the city scale. Differences between the structure of the species used to generate the urban general equations and the city's tree population may be responsible. Yoon et al. (2013) compiled species-specific urban equations into a general equation and found that the difference in values estimated using species-specific values was less than 1 percent at the citywide scale. However, Aguaron and McPherson's (2012) general equation for urban broadleaf species overestimated aboveground biomass by 50 percent. The uncertainty associated with application of urban general equations underscores the need for more urban equations that are species specific. For improved accuracy, the urban general equations in this UTD are volume equations that allow users to apply species-specific dry weight density factors.

Chapter 2: Sampling Design and Data Collection

Climate Zones and Reference Cities

The United States was divided into 16 national climate zones by aggregation of 45 Sunset climate zones (Brenzel 1997). The climate zone map demarcates each zone (fig. 9). Sunset zones were aggregated based on factors that influence plant distribution, such as length of growing season and minimum temperature, as well as cooling degree days (CDD) and heating degree days (HDD), which are indicators of the potential effects of trees on building heating and cooling loads (table 1). The CDD and HDD values are the summation of degrees of the average temperature per day above and below 18.5 °C (65 °F) for the year, respectively (McPherson 2010).

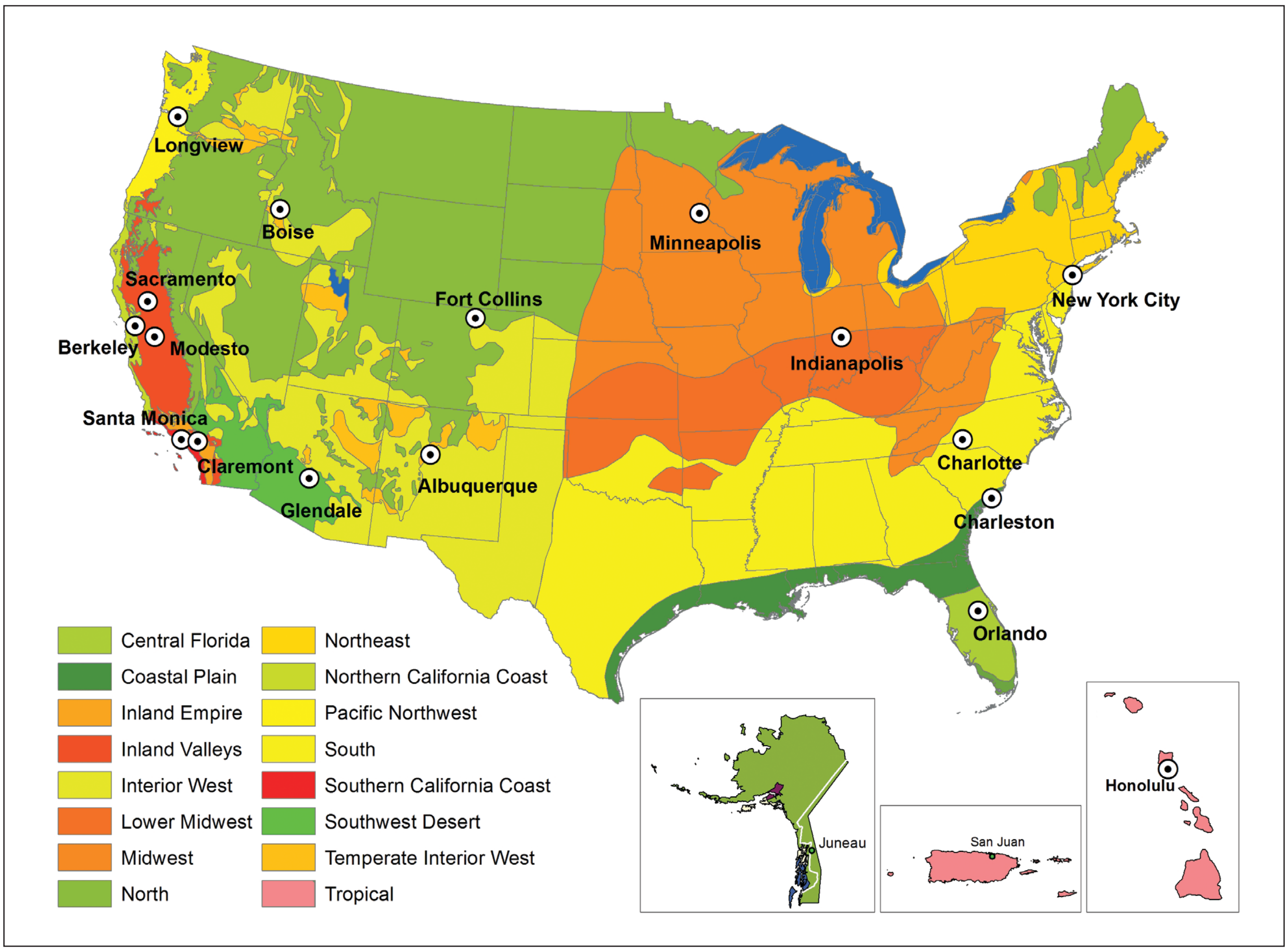

Figure 9—Climate zones were aggregated from 45 Sunset climate zones into 16 zones. Each zone has a reference city where tree growth data were collected. Sacramento, California, was added as a second reference city (with Modesto) to the Inland Valleys zone.

Table 1—Information on the reference city in each climate zone

Climate zone (code)	Reference city	Years data collected	Reference city code	Sunset zones[a]	USDA hardiness zones[b]	CDD[c]	HDD[c]	Annual precipitation
								Millimeters
Central Florida (CenFla)	Orlando, FL	2008	ORL	26	9-10	1,806	289	1367
Coastal Plain (GulfCo)	Charleston, SC	2004	CHS	27, 28	8-9	1,124	1,221	1555
Inland Empire (InlEmp)	Claremont, CA	2000	CLM	18, 19, 20, 21	9	134	872	523
Inland Valleys (InlVal)	Modesto, CA Sacramento, CA	1998 2010 2012	MOD SMF	7, 8, 9, 14,	8-9	1,052 773	1,439 1,718	315 470
Interior West (InterW)	Albuquerque, NM	2005	ABQ	2, 10	5-6	677	2,416	250
Lower Midwest (LoMidW)	Indianapolis, IN	2006	IND	35	6-7	510	3,153	392
Midwest (MidWst)	Minneapolis, MN	2004	MSP	36, 41, 43	4-6	355	4,436	622
North (NMtnPr)	Fort Collins, CO	2002	FNL	1, 44, 45	1-4	349	3,332	452
Northern California Coast (NoCalC)	Berkeley, CA	2003	JBK	15, 16, 17	9-10	39	1,786	564
Northeast (NoEast)	Queens, New York city, NY	2005	JFK	34, 37, 38, 39, 40, 42	2-5	560	2,819	1041
Pacific Northwest (PacfNW)	Longview, WA	2001	LOG	4, 5, 6	8-9	157	2,468	1059
South (Piedmt)	Charlotte, NC	2004	CLT	29, 30, 31, 32, 33	6-8	847	1,891	1426
Southern California Coast (SoCalC)	Santa Monica, CA	1999	SMA	22, 23, 24	10-11	266	710	570
Southwest Desert (SWDsrt)	Glendale, AZ	2003	GDL	11, 12, 13	9-10	2,128	637	174
Temperate Interior West (TpIntW)	Boise, ID	2005	BOI	3	7	387	3,325	417
Tropical (Tropic)	Honolulu, HA	2005	HNL	25	11	2,416	0	2206

[a] From Brenzel (1997).
[b] From http://planthardiness.ars.usda.gov/PHZMWeb/.
[c] From McPherson (2010), cooling degree days (CDD) and heating degree days (HDD) are the summation of degrees of the average temperature per day above and below 18.5 °C for the year, respectively.

"Reference city," refers to one city selected for intensive study within each climate zone (McPherson 2010). Data were collected for a second reference city in the Inland Valleys climate zone, Sacramento, California, because tree growth data were required for several ongoing studies. Criteria for selecting a reference city included (1) an updated computerized tree inventory with location information for each tree (20,000 to 250,000 street/park trees); (2) information to accurately age a sample of about 900 trees by the city forester; (3) large, old trees present in the community; and (4) an aerial lift truck available for 1 week to sample foliage.

Species and Tree Sampling

The trees sampled in each reference city were obtained from the computerized tree inventory. First, the inventory was cleaned to remove stumps, dead trees (shown as scheduled for removal), and vacant sites. It was sorted by species to identify the most abundant species for sampling. About 20 of the most abundant species were selected for sampling in each city. Appendix 1 lists the number of trees of each species sampled in each city (available for download as table S2). The sampled species accounted for 50 to 95 percent of all trees in the municipal tree inventories. To obtain information spanning the life cycle of each of the predominant tree species, a stratified random sample was drawn. The sample was stratified into nine diameter at breast height (d.b.h.) classes (0 to 7.6, 7.6 to 15.2, 15.2 to 30.5, 30.5 to 45.7, 45.7 to 61.0, 61.0 to 76.2, 76.2 to 91.4, 91.4 to 106.7, and >106.7 cm). Thirty to 70 trees of each species were randomly selected to survey, about 5 to 10 trees in each d.b.h. class. Smaller samples of 30 trees were drawn for small-growing species such as *Prunus* spp. and *Malus* spp. Seventy trees were drawn for species with individuals represented in all size classes. An equal number of alternative trees were selected as replacement trees in the event that the originally sampled trees could not be located.

Although 30 to 70 trees were randomly selected for sampling each species, the final samples ranged from 22 to 79 trees. The lower number resulted when the original and replacement trees could not be located. The higher numbers occurred when the sample trees were actually in a different size class than reported in the inventory. These trees were measured in case viable replacements could not be found. In fact, replacements were found and sample numbers became greater than expected.

Tree Data Collection

Each variable in the UTD, as well as its definition, abbreviation, and potential use, is listed in table 2. Protocols for data collection are in appendix 2. Metrics recorded for each tree sampled included species, address/location, d.b.h. (to nearest 1.0 cm by tape), tree crown, and bole height (to nearest 0.5 m by clinometer or sonar measuring device), crown diameter in two directions (parallel and perpendicular to nearest street to nearest 0.5 m by sonar measuring device) (table 2). Observational information was recorded on crown shape, land use, distance and direction from nearest air-conditioned/heated building, car shade, and conflicts with utility lines. Other data are presently being analyzed and will be added to the UTD upon publication including sidewalk damage, site type, the amount of planting space, condition of wood and foliage, whether the tree is city or privately managed, maintenance needs, and photograph numbers for the one or two photographs that were taken of each tree and processed in the laboratory to calculate leaf area and crown volume. This photographic method is described in Peper and McPherson (2003) and was found more accurate than other techniques (±25 percent of actual leaf area) for open-grown trees. The tree growth equations and raw data collected for each tree are available for download in the online supplement http://dx.doi.org/10.2737/RDS-2016-0005.

Tree age was determined from local residents, the city's urban forester, street and home construction dates, historical planting records, and aerial and historical photos. In two cases, extra effort was required to obtain age information. Tree coring was used in Queens, New York City, to estimate planting dates instead of relying solely on historical research. Unlike other cities, where streets are lined with trees of the same age because they were all planted at the time of development, street trees in Queens were of all ages because several episodes of planting had ocurred. Dendrologists at the Lamont-Doherty Earth Observatory's Tree Ring Laboratory cored 150 randomly sampled trees to establish mean tree age. These trees represented a subsample of the original 910 sample trees. One to two trees in size classes 2 through 9 were cored for each species. Cores were analyzed in the lab and tree age established. Urban foresters provided tree ages for an additional 104 sample trees in d.b.h classes 8 and 9 (91.4 to 106.7 cm and >106.7 cm), based on building records, and 34 trees in d.b.h. classes 1 and 2 based on planting records. These data were pooled with ring-count data to develop regressions based on the mean age for each d.b.h. size class. Thus, the online data for Queens, New York City, shows two sets of data, one for data directly collected from each tree and one for tree ages collected from a combination of coring a subsample of the measured trees and aging information provided by New York City Parks and Recreation. Although more accurate aging of trees is required for that region, equations relationships between d.b.h. and parameters other than age reflect actual measured data.

Table 2—Abbreviations, names, descriptions, and uses for each variable in the Urban Tree Database (UTD)

Abbreviation	Name	Description	Use
DbaseID	UTD ID number	Unique ID number for each tree	To track tree
Region	Climate region	16 U.S. climate regions, abbreviations are used (see table 1)	To identify geographic region and climate
City	Reference city/state	City/state names where data were collected	To identify city where data were collected, associated management practices, climate, etc.
Source	Original file name	.xls file name	To identify locations of original data sets
TreeID	Inventory ID number	Number assigned to each tree in inventory by city	To link to other tree inventory data
Zone	Inventory management or nursery number	Number of the management area or zone that the tree is located in within a city or nursery if young tree data are collected there	To identify where data were collected
Park/street	Inventory data for park, street, or nursery trees	Data listed as park or street or nursery (for young tree measurements)	To identify where data were collected
SpCode	Species code	Four- to six-letter code consisting of the first two letters of the genus name and the first two letters of the species name followed by two optional letters to distinguish two species with the same four-letter code	To have a stable abbreviation for each species name
ScientificName	Scientific name	Botanical name	To group by taxon
CommonName	Common name	Common name	To group by taxon
Treetype	Tree type	Three-letter code where first two letters refer to life form (BD = broadleaf deciduous, BE = broadleaf evergreen, CE = coniferous evergreen, PE = palm evergreen), and the third letter is mature height (S = small [<8 m], M = medium [8 to 15 m], (L = large [>15 m])	To assist with matching species that were not measured
Address	Address number	From inventory, street number of the building where the tree is located	To relocate the tree
Street	Street name	From inventory, the name of the street on which the tree is located	To relocate the tree
Side	Side of building or lot	From inventory, side of building or lot on which the tree is located: F = front, M = median, S = side, P = park	To relocate the tree
Cell	Tree number when multiple trees are at the same address	From inventory, the cell number (i.e., 1, 2, 3, …), where protocol determines the order trees at same address are numbered (e.g., driving direction or as street number increases)	To relocate the tree
OnStreet	Name of the street the tree is on	From inventory (omitted if not a field in city's inventory), for trees at corner addresses when tree is on cross street rather than addressed street	To relocate the tree

Table 2—Abbreviations, names, descriptions, and uses for each variable in the Urban Tree Database (UTD) (continued)

Abbreviation	Name	Description	Use
FromStreet	Name of cross street where first tree is inventoried	From inventory, the name of the first cross street that forms a boundary for trees lining unaddressed boulevards. Trees are typically numbered in order (1, 2, 3 …) on boulevards that have no development adjacent to them, no obvious parcel addresses	To relocate the tree
ToStreet	Name of last cross street	From inventory, the name of the last cross street that forms a boundary for trees lining unaddressed boulevards	To relocate the tree
Age	Tree age	Number of years since planted	For allometric equations
DBH (cm)	Trunk diameter at breast height (d.b.h.)	D.b.h. (1.37 m) measured to nearest 0.1 cm (tape). For multistemmed trees forking below 1.37 m measured above the butt flare and below the point where the stem begins forking, as per protocol	For allometric equations
TreeHt (m)	Tree height	From ground level to tree top to nearest 0.5 m (omitting erratic leader)	For allometric equations
CrnBase (m)	Height to crown base	Average distance between ground and lowest foliage layer to nearest 0.5 m (omitting erratic branch)	For allometric equations
CrnHt (m)	Height of crown from crown base to top	Calculated as TreeHT minus Crnbase to nearest 0.5 m	To calculate crown volume
CdiaPar (m)	Crown diameter measured parallel to the street	Crown diameter measurement taken to the nearest 0.5 m parallel to the street (omitting erratic branch)	For average crown diameter
CDiaPerp (m)	Crown diameter measured perpendicular to the street	Crown diameter measurement taken to the nearest 0.5 m perpendicular to the street (omitting erratic branch)	For average crown diameter
AvgCdia (m)	Average crown diameter	The average of crown diameter measured parallel and perpendicular to the street	For allometric equations
Leaf (m^2)	Leaf surface area (one side)	Estimated using digital imaging method to nearest 0.1 m^2	Air pollutant and property value effects
Setback	Tree distance from conditioned building	Distance from tree to nearest airconditioned/heated space (may not be same address as tree location): 1 = 0 to 8 m, 2 = 8.1 to 12 m, 3 = 12.1 to 18 m, 4 = >18 m.	Energy effects
TreeOr	Tree orientation (compass bearing)	Taken with compass, the coordinate of tree taken from imaginary lines extending from walls of the nearest conditioned space (may not be same address as tree location)	Energy effects
CarShade	Number of parked vehicles in tree shade	Number of parked automotive vehicles with some part under the tree's drip line. Car must be present: 0 = no autos, 1 = 1 auto, etc.	Air pollutant effects

Table 2—Abbreviations, names, descriptions, and uses for each variable in the Urban Tree Database (UTD) (continued)

Abbreviation	Name	Description	Use
LandUse	Land use type where tree is located	Predominant land use type where tree is growing: 1 = single-family residential, 2 = multifamily residential (duplex, apartments, condos), 3 = industrial/institutional/large commercial (schools, government, hospitals), 4 = park/vacant/other (agric., unmanaged riparian areas of greenbelts), 5 = small commercial (minimart, retail boutiques, etc.), 6 = transportation corridor.	Energy and property value effects
Shape	Crown shape	Visual estimate of crown shape verified from each side with actual measured dimensions of crown height and average crown diameter: 1 = cylinder (maintains same crown diameter in top and bottom thirds of tree), 2 = ellipsoid, the tree's center (whether vertical or horizontal) is the widest, includes spherical), 3 = paraboloid (widest in bottom third of crown), 4 = upside down paraboloid (widest in top third of crown).	For crown volume and energy effects
WireConf	Tree crown conflict with overhead wires	Utility lines that interfere with or appear above tree: 0 = no lines, 1 = present and no potential conflict, 2 = present and conflicting, 3 = present and potential for conflicting.	Pruning owing to conflicts may affect crown dimensions
d.b.h.1 to d.b.h.8	Trunk d.b.h.	D.b.h. (cm) for multistemmed trees; for non-multistemmed trees, d.b.h.1 is same as d.b.h.	For d.b.h. calculation

Note: "-1" for all fields except leaf area, and "-100" for leaf area indicate no data collected.

In the Lower Midwest zone, the age of 337 of the 911 sampled trees was identified across d.b.h. ranges through local resources. This represented enough data to develop age to d.b.h equations for 12 of the 20 species sampled. For the remaining eight species, analysis was run testing available measured data with the same species measured in the other 15 climate regions to find the closest relationships. Closest relationships were found for *Catalpa speciosa* and *Juglans nigra* with same species in Boise, Idaho; with *Magnolia grandiflora, Picea pungens, Pyrus* sp.*, and Ulmus pumila* in Fort Collins, Colorado; with *Celtis occidentalis* in Minneapois, Minnesota; and with *Pinus strobus* in Queens, New York City. However, these relationships were based on a comparison of minimal data from Indianapolis and should not be construed to be accurate until additional data are available for analysis from Indianapolis. These data are presented in the online UTD database and annotated in the "Notes" column as to origin. Age to d.b.h. equations shown here for these eight species, therefore, should be regarded as first-order approximations until more definitive data are available. For these reasons, tree age is probably the least accurate metric in this database.

Foliar Sampling and Data Collection

For each species, one to three trees—typical of species in age, size, and condition—were selected for foliar sampling. Sampling was done from a bucket truck that required room to maneuver to reach the areas of the crown to be sampled. Foliar samples were taken at different locations within each tree crown to capture differences between sun and shade, as well as juvenile and mature foliage. By sampling leaves of different size and maturity, it was possible to obtain relationships between leaf area and dry weight that were representative of the tree's foliar biomass over time. One set of 10 random quadrat (a cube 30 by 30 by 30 cm) samples were clipped from each tree—three from the lower one-third of the crown, four from the middle section, and three from the top one-third. Within each crown stratum, at least one sample was from the outer, middle, and inner portions. Leaves and stems were clipped along the outside of the cube, and each sample was stored in a labeled ziplock bag. The bags were stored in an ice chest and shipped by overnight delivery to the cold-storage site in Davis, California.

The foliar samples were processed to develop relationships between leaf area and foliar biomass for each tree species. The leaves in each bag were separated from stems and twigs, then weighed (fresh weight) and run through the leaf area meter to obtain the sample's total surface area (leaf area). The foliage was returned to the paper bag and dried in an oven at 65 °C (149 °F) for 3 days (72 hours minimum). On the fourth day, the bag was removed from the oven and weighed (dry weight). The bag was returned to the oven and dried 24 hours then removed from the oven and weighed. If the bag weighed less than its previous weight, it was returned to the oven and dried. This process was repeated until the weight no longer changed. The fresh weight, dry weight, and leaf area were recorded for the foliar samples in each of the 10 bags per species. Leaf area to dry weight and fresh weight to dry weight relationships were calculated for each species using standard descriptive statistics. Resulting data are shown in appendix 3.

Chapter 3: Development of Tree Growth Equations

Six models were tested for seven parameters at four weights. Predicted parameters included the following: using tree age to predict diameter at breast height (d.b.h.); and using d.b.h. to predict tree height, crown height, crown diameter, and leaf area. In addition, crown diameter was used to predict d.b.h. for use with remote sensing imagery and age predicted from d.b.h. for use in backcasting. Prior to analysis, raw data points from each region were plotted to examine potential outliers. Following methods described by Martin et al. (2012), we eliminated from our analysis those observations identified on residual plots that were greater than two units larger than the general spread of observations for that parameter. Models tested included four polynomial models (linear, quadratic, cubic, and quartic), as well as log-log and exponential:

Linear $$y_i = a + bx_i + \frac{\epsilon_i}{\sqrt{w_i}} \quad (1)$$

Quadratic $$y_i = a + bx_i + cx_i^2 + \frac{\epsilon_i}{\sqrt{w_i}} \quad (2)$$

Cubic $$y_i = a + bx_i + cx_i^2 + dx_i^3 + \frac{\epsilon_i}{\sqrt{w_i}} \quad (3)$$

Quartic $$y_i = a + bx_i + cx_i^2 + dx_i^3 + ex^4_i + \frac{\epsilon_i}{\sqrt{w_i}} \quad (4)$$

Log-log $$\text{In}(y_i) = a + b\text{In}(\text{In}(x_i + 1)) + \frac{\epsilon_i}{\sqrt{w_i}} \quad (5)$$

Exponential $$\text{In}(y_i) = a + bx_i + \frac{\epsilon_i}{\sqrt{w_i}} \quad (6)$$

Where y_i is the measurement of tree *i*, *a* is the mean intercept, *b* is the mean slope, x_i is the d.b.h. or age of tree *i*, ϵ_i is the random error for tree *i* with $\epsilon_i\, j \sim N(0,\sigma^2)$, σ^2 is the variance of the random error, and w_i is a known weight that takes on one of the following forms: $w_i = 1$, $w_i = 1/\sqrt{x_i}$, $w_i = 1/x_i$, $w_i = 1/x^2$.

Analysis was conducted using SAS® 9.2 MIXED procedure (SAS 2008). The bias-corrected Aikaike's information criterion (AIC_c) was used to compare and rank the models because of smaller sample sizes (Akaike 1974). The models with the "best" fit as indicated by having the smallest AIC_c were selected. Additional steps were needed to obtain comparable AIC_c values for log-log and exponential models (eqs. 7 and 8). Otherwise AIC_c values would not be comparable across all models. Multiplying by the geometric mean allows the AIC_c values to be compared with the models where y_i is not transformed (Draper and Smith 1998).

Log-log $$\dot{y}\ln(y_i) = a^* + b^*\ln(\ln(x_i + 1)) + \frac{\epsilon^*_i}{\sqrt{w_i}} \quad (7)$$

Exponential $$\dot{y}\ln(y_i) = a^* + b^* x_i + \frac{\epsilon^*_i}{\sqrt{w_i}} \quad (8)$$

Where $\dot{y}$ is the geometric mean of the y_i values.

All weightings for polynomials are built into the coefficients (unlike the exponential and log-log formulas). The equations are translated to Excel format in table 3 (available for download as table S4).

The resulting best fitting model is listed for each measured species and region in the online supplement, table S6 (an example is shown in app. 4), with the measured parameter, predicted tree component, model weight, equation name, the coefficients to use in each model, the minimum and maximum values to estimate between, mean square error, sample size, adjusted R^2, the raw data range, and the degrees of freedom. The model weights are already accounted for in the equation coefficients. The equation name represents the general form of the equation, the details of which are in table 3. Note that log-log and exponential models require an input for mean-squared error (mse), which is listed in table 7 (app. 4) column "c or mse" (i.e., do not calculate and use sigma^2).

For palms, there is no discernable relationship between age and d.b.h. In contrast, age is an adequate predictor of tree height. Therefore, equations were developed to predict palm height from age, and subsequently, to predict other parameters such as biomass from palm height.

Table 3—Excel-formatted equations for predicting open-grown tree growth parameters

Model name	Equation
lin	a + b × (age or dbh)
quad	a + b × x + c ×x^2
cub	a + b × x + c ×x^2 + d × x^3
quart	a + b × x + c ×x^2 + d × x^3 + e × x^4
log-logw1	EXP(a + b × LN(LN(age or dbh +1) + (mse/2)))
log-logw2	EXP(a + b × LN(LN(age or dbh +1)) + (SQRT(age or dbh) + (mse/2)))
log-logw3	EXP(a + b × LN(LN(age or dbh +1)) + (age or dbh) + (mse/2))
log-logw4	EXP(a + b × LN(LN(age or dbh +1)) + (age^2 or dbh^2) + (mse/2))
expow1	EXP(a+ b × (age or dbh) + (mse/2))
expow2	EXP(a + b × (age or dbh) + SQRT(age or dbh) + (mse/2))
expow3	EXP(a + b × (age or dbh) + (age or dbh) + (mse/2))
expow4	EXP(a + b × (age or dbh) + (age^2 or dbh^2) + (mse/2))

An important constraint to consider when applying the growth equations to measured tree data is that equations predicting d.b.h. from age may produce negative values for young ages. Negative values in d.b.h. estimates may cause continued problems for predicting tree height and other variables from d.b.h. These values should take on the first instance of a positive value.

In the Urban Tree Database (UTD), two sets of data ranges are reported. One shows the actual range of the data collected and is labelled “Data min” and “Data max.” To reduce the risk of overextending the application of the equations, we report application ranges for the equations used to predict each parameter. The “Apps min” and “Apps max” range informs users on a reasonable range for use of the equations—sometimes extending beyond collected data points, and sometimes not reaching those points. Values extending beyond the range of collected data were considered because there was sufficient knowledge of how large trees grow from measurements taken in local parks and neighborhoods.

Database Description

The core of the UTD consists of two large data tables that can be downloaded in ASCII format through the online supplement. The first table (app. 3 and available for download as table S5) shows summarized results from the foliar sampling for each species and region. The second table displays equations and coefficients for predicting tree-growth parameters by species and predicted parameter (table S6). An excerpt from table S6 for two species in one climate zone is shown in appendix 4. A User Guide (app. 5) provides step-by-step instructions and examples for applying the growth equations to trees of interest using the core data tables. In addition, appendix 5 demonstrates how to estimate dry weight biomass and carbon using allometric equations (tables S7 and S8). Table S9 provides an expanded list

Table 4—Percentage of best fitting model types for tree growth parameters by measured and predicted parameters

Relationship	cub	expow	lin	log-log	quad	quart
			Percent			
Age to diameter at breast height (d.b.h.)	27	0	31	13	28	0
Crown diameter to d.b.h.	26	1	23	35	15	0
D.b.h. to age	38	1	22	14	25	0
D.b.h. to crown diameter	22		16	23	38	0
D.b.h. to crown height	13	4	26	24	33	0
D.b.h. to leaf area	15	2	1	72	10	0
D.b.h. to tree height	16	3	14	30	35	2
Total	22	2	19	31	26	0

of dry-weight biomass density factors for common urban species. Lastly, a case study demonstrates differences in d.b.h., tree height, and total carbon across the different climate zones, highlighting the importance of developing region-specific growth models.

Data Limitations and Future Research Needs

Accurately predicting d.b.h and tree height leads to better estimates of total carbon storage and carbon sequestration. This section describes where uncertainty is greatest and additional research is needed to improve estimates.

Tails—

In the context of estimating tree size, as well as carbon storage and sequestration for applications such as calculating tree benefits, it is important to continue to improve the accuracy of the equations at the extreme ends of the age spectrum. With limited measurements at the extreme ends of the age spectrum, there is the risk of a few extreme points driving the equation form selection. It is particularly important to sample from larger/older trees because small changes in growth equations can cause large absolute differences in carbon estimates. As trees age, the differences typically increase owing to temporal autocorrelation and differences in equation form. Each additional data point obtained at the upper age range is therefore critical for increasing accuracy of growth and volumetric equations.

Age—

Sampling from large trees does not guarantee the addition of old trees to the database. One practical limitation of the age-to-d.b.h.-regression approach (from size curves instead of real growth curves) is that age data are often difficult to acquire. The lack of age information can limit the use of predictions in applications. For example, not all of the large trees randomly selected for coring in New York City were successfully cored. The length of the coring instrument and pockets of decay inside the tree limited the effectiveness of coring and thus makes this research dependent on people recording tree planting dates. Predictions for d.b.h. from the best model for *Platanus* × *acerifolia* in New York City estimated an end d.b.h. growth at and end d.b.h. of 61 cm as predicted from age, even though the largest tree measured was 165 cm d.b.h. This occurred because the largest tree was not cored successfully. Until additional data are collected to represent a larger and more robust sample of tree ages and sizes for each species, the level of inference drawn from these model fits should be limited by staying within the Apps min and Apps max ranges listed in the database.

Size—

Selecting a robust sample of trees that captures a range of sizes is important for smaller-growing species as well. We found that smaller-growing species, particularly *Prunus* and *Lagerstroemia* were problematic for model-fitting. Typically, there were few specimens smaller than 7.6 cm d.b.h. and many in the 15.2 to 30.5 cm d.b.h. range. In addition, because these trees were often pruned by homeowners, crowns rarely followed a more natural form, resulting in a large variety of forms and heights. This problem of form manipulation was even greater with *Lagerstroemia*, which also might be present as either a single- or multistemmed plant. *Lagerstroemia* were often pollarded every year, affecting height and crown measurements as well as slowing d.b.h. growth.

It was also more difficult to find good model fits for several of the small- and medium-growing conifers like *Pinus brutia*, *P. edulis*, and *P. contorta* because there were few representatives in the 0 to 15.2 cm size class or, as in the case of *P. edulis*, most representatives were in the 10.2 to 30.5 cm d.b.h. range with few samples available below or above that.

Palms—

Palms represent another sampling gap. In the UTD (app. 4), palms do not have mse or adjusted R^2 because the equations were not calculated from measurements, but from information provided by palm nurseries and experts in the region. This was done because the majority of palms were transplanted at anywhere from 5 to 40 years of age, and d.b.h. recorded in tree inventories showed no relationship to other crown dimensions. Also, city foresters had very little information on the ages of palms at time of planting. Although the UTD contains measurements for more species than ever reported, much more information is needed for truly accurate growth representation within regions of the country.

Volumetric equations—

The results from the case study (app. 5) demonstrate the differences in growth patterns among climate zones/regions. Besides improving on the growth equation database, there is work to be done to expand volumetric equations. As described in the user guide (app. 5), the volumetric equations used to predict tree volume from measured parameters are not region specific, because differences between regions have not yet been tested and localized equations have not been developed. Developing a more extensive database of volumetric equations for open-grown urban tree species is a high-priority research need.

Chapter 4: Conclusions

Information on urban tree growth underpins models such as i-Tree that calculate effects of trees on the environment and human well-being. Data about tree growth are used to create realistic animations that depict landscape change over decades. Maximum tree size and other growth data are used by urban forest managers, landscape architects, and planners to select trees most suitable to the amount of growing space, thereby reducing costly future conflicts between trees and infrastructure. Growth data may be used to characterize relationships between growth and influencing factors such as site conditions and stewardship practices. Despite the importance of tree growth data to the science and practice of urban forestry, our knowledge is scant. For example, data have been lacking to specify the range of bole and crown dimensions for an open-grown red oak (*Quercus rubra*) tree exhibiting "normal" growth in New York City.

Over a period of 14 years, the U.S. Forest Service recorded data from a consistent set of measurements on over 14,000 trees in 17 U.S. cities. This network of cities represents municipal forests with different climates, forest structures, and management histories and practices. Key information collected for each tree species includes bole and crown size, location, and age. From this Urban Tree Database (UTD), 365 sets of tree-growth equations were developed for the predominant species. Although the UTD contains measurements for more species than ever reported, much more information is needed to better model tree growth within regions of the country. Tree planting dates are seldom recorded but remain fundamental to establishing relations between age and size. Capturing the range of ages that exist within the population promises to improve the lower and upper ends of the growth predictions where most of the uncertainty currently resides. Also, the value of the UTD can be expanded with new information on site conditions (e.g., soil type, microclimate, amount of growing space) and management practices (e.g., pruning dose, irrigation regime). With such information, analysts can better predict the effects of practices on tree growth and the services their trees provide.

The UTD is not a static repository. Already remeasurements have been conducted on originally measured trees in two cities (Claremont and Santa Monica, California) to update these equations and better understand the long-term demographics of street tree populations. These new data, as well as contributions from other researchers, will be incorporated into the UTD. Continued updating will ensure that the UTD remains a valuable resource for urban and community forestry.

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English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0394	Inches (in)
Centimeters (cm)	0.394	Inches (in)
Meters (m)	3.281	Feet (ft)
Square meter (m^2)	10.76	Square feet
Cubic meters (m^3)	35.315	Cubic feet (ft^3)
Grams (g)	35.315	Ounces (oz)
Micrograms or microns (µg)	3.527×10^8	Ounces (oz)
Kilograms (kg)	2.205	Pounds (lb)
Kilograms per square meter (kg/m^2)	0.205	Pounds per square foot (lb/ft^2)
Metric tonne (t)	1.102	Tons (ton)
Degrees Celsius (°C)	°C × 1.8 + 32	Degrees Fahrenheit (°F)

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Appendix 1: Trees Sampled by Species and Region

Table 5—Numbers of trees sampled by species and region

Scientific name	Common name	SpCode	Samples
Central Florida (CenFla):			
Acer rubrum L.	red maple	ACRU	56
Cinnamomum camphora (L.) J. Presi	camphor tree	CICA	63
Eriobotrya japonica (Thunb.) Lindl.	loquat tree	ERJA	31
Juniperus virginiana L.	southern redcedar	JUSI	50
Koelreuteria elegans (Seem.) A.C. Sm.	Chinese rain tree	KOELFO	43
Lagerstroemia indica L.	common crapemyrtle	LAIN	35
Liquidambar styraciflua L.	sweetgum	LIST	48
Magnolia grandiflora L.	southern magnolia	MAGR	51
Pinus elliottii Engelm.	slash pine	PIEL	37
*Platanus occidenta*lis L.	American sycamore	PLOC	44
*Platycladus orien*talis (L.) Franco	Oriental arborvitae	THOR	37
Prunus caroliniana (Mill.) Aiton	Carolina laurelcherry	PRCA	39
Quercus laurifolia Michx.	laurel oak	QULA2	67
Quercus shumardii Buckley	Shumard oak	QUSH	37
Quercus virginiana Mill.	live oak	QUVI	65
Sabal palmetto (Walter) Lodd. ex Schult. & Schult. f.	cabbage palmetto	SAPA	45
Syagrus romanzoffiana (Cham.) Glassman	queen palm	SYRO	30
Triadica sebifera (L.) Small	tallowtree	TRSE6	40
Ulmus parvifolia Jacq.	Chinese elm	ULPA	37
Washingtonia robusta H. Wendl.	Mexican fan palm	WARO	40
Coastal Plain (GulfCo):			
Acer rubrum L.	red maple	ACRU	36
Butia capitata (Mart.) Becc.	jelly palm	BUCA	33
Carya illinoinensis (Wangenh.) K.Koch	pecan	CAIL	36
Celtis laevigata Willd.	sugarberry	CELA	37
Cornus florida L.	flowering dogwood	COFL	34
Gleditsia triacanthos L.	honeylocust	GLTR	37
Ilex opaca Aiton	American holly	ILOP	37
Juniperus virginiana L.	eastern red cedar	JUVI	43
Lagerstroemia indica L.	common crapemyrtle	LAIN	42
Liquidambar styraciflua L.	sweetgum	LIST	50
Magnolia grandiflora L.	southern magnolia	MAGR	40
Pinus taeda L.	loblolly pine	PITA	47
Platanus occidentalis L.	American sycamore	PLOC	56
Pyrus calleryana Decne.	Callery pear	PYCA	36
Quercus laurifolia Michx.	laurel oak	QULA2	79

Table 5—Numbers of trees sampled by species and region (continued)

Scientific name	Common name	SpCode	Samples
Quercus nigra L.	water oak	QUNI	68
Quercus phellos L.	willow oak	QUPH	45
Quercus virginiana Mill.	live oak	QUVI	76
Sabal palmetto (Walter) Lodd. ex Schult. & Schult. f.	cabbage palmetto	SAPA	40
Inland Empire (InlEmp):			
Brachychiton populneus (Schott & Endl.) R.Br.	kurrajong	BRPO	37
Cinnamomum camphora (L.) J. Presl	camphor tree	CICA	57
Eucalyptus sideroxylon A. Cunn. ex Woolls	red ironbark	EUSI	37
Fraxinus uhdei (Wenz.) Lingelsh.	evergreen ash	FRUH	37
Fraxinus velutina 'Modesto' Torr.	Modesto ash	FRVE_G	36
Ginkgo biloba L.	ginkgo	GIBI	37
Jacaranda mimosifolia D. Don	jacaranda	JAMI	63
Lagerstroemia indica L.	common crapemyrtle	LAIN	61
Liquidambar styraciflua L.	sweetgum	LIST	38
Liriodendron tulipifera L.	tulip tree	LITU	37
Magnolia grandiflora L.	southern magnolia	MAGR	37
Pinus brutia Ten.	Turkish pine; east Mediterranean pine	PIBR2	37
Pinus canariensis C. Sm.	Canary Island pine	PICA	39
Pistacia chinensis Bunge	Chinese pistache	PICH	40
Platanus racemosa Nutt.	California sycamore	PLRA	37
Platanus × *acerifolia* (Aiton) Willd.	London planetree	PLAC	38
Pyrus calleryana Decne.	Callery pear	PYCA	39
Quercus agrifolia Née	coastal live oak; California live oak	QUAG	37
Quercus ilex L.	holly oak	QUIL2	35
Schinus molle L.	California peppertree	SCMO	37
Schinus terebinthifolius Raddi	Brazilian pepper	SCTE	36
Washingtonia robusta H. Wendl.	Mexican fan palm	WARO	36
Inland Valleys (InlVal):			
Acer saccharinum L.	silver maple	ACSA1	29
Betula pendula Roth	European white birch	BEPE	29
Celtis sinensis Pers.	Chinese hackberry	CESI4	30
Cinnamomum camphora (L.) J. Presl	camphor tree	CICA	31
Fraxinus angustifolia 'Raywood' Vahl	Raywood ash	FRAN_R	31
Fraxinus excelsior 'Hessei' L.	Hesse ash	FREX_H	27
Fraxinus holotricha Koehne	Moraine ash	FRHO	29

Table 5—Numbers of trees sampled by species and region (continued)

Scientific name	Common name	SpCode	Samples
Fraxinus pennsylvanica Marshall	Marshall ash	FRPE_M	28
Fraxinus velutina Torr.	Modesto ash	FRVE_G	28
Ginkgo biloba L.	ginkgo	GIBI	32
Gleditsia triacanthos L.	honeylocust	GLTR	27
Koelreuteria paniculata Laxm.	goldenrain tree	KOPA	29
Lagerstroemia indica L.	common crapemyrtle	LAIN	26
Liquidambar styraciflua L.	sweetgum	LIST	30
Magnolia grandiflora L.	southern magnolia	MAGR	29
Pinus thunbergii Parl.	Japanese black pine	PITH	26
Pistacia chinensis Bunge	Chinese pistache	PICH	30
Platanus × *acerifolia* (Aiton) Willd.	London planetree	PLAC	27
Prunus cerasifera Ehrh.	cherry plum	PRCE	27
Pyrus calleryana 'Bradford' Decne.	Callery pear 'Bradford'	PYCA_B	30
Quercus ilex L.	holly oak	QUIL2	28
Zelkova serrata (Thunb.) Makino	Japanese zelkova	ZESE	31
Interior West (InterW):			
Chilopsis linearis (Cav.) Sweet	desert willow	CHLI	30
Elaeagnus angustifolia L.	Russian olive	ELAN	30
Fraxinus americana L.	white ash	FRAM	28
Fraxinus angustifolia 'Raywood' Vahl	Raywood ash	FRAN2	30
Fraxinus pennsylvanica Marshall	green ash	FRPE	31
Fraxinus velutina Torr.	velvet ash	FRVE	69
Gleditsia triacanthos L.	honeylocust	GLTR	68
Koelreuteria paniculata Laxm.	goldenrain tree	KOPA	28
Malus sp.	apple	MA2	30
Pinus edulis Engelm.	pinyon pine	PIED	29
Pinus nigra Arnold	Austrian pine	PINI	28
Pinus ponderosa Douglas ex P. Lawson & C. Lawson	ponderosa pine	PIPO	30
Pinus sylvestris L.	Scotch pine	PISY	30
Pistacia chinensis Bunge	Chinese pistache	PICH	30
Platanus × *acerifolia* (Aiton) Willd.	London planetree	PLAC	70
Populus angustifolia E. James	narrowleaf cottonwood	POAN	70
Populus fremontii S. Watson	Fremont cottonwood	POFR	70
Prunus cerasifera Ehrh.	cherry plum	PRCE	30
Pyrus calleryana Decne.	Callery pear	PYCA	32
Ulmus pumila L.	Siberian elm	ULPU	70

Table 5—Numbers of trees sampled by species and region (continued)

Scientific name	Common name	SpCode	Samples
Lower Midwest (LoMidW):			
Acer platanoides L.	Norway maple	ACPL	34
Acer rubrum L.	red maple	ACRU	35
Acer saccharinum L.	silver maple	ACSA1	54
Acer saccharum Marsh.	sugar maple	ACSA2	37
Catalpa speciosa (Warder) Warder ex Engelm.	northern catalpa	CASP	49
Celtis occidentalis L.	northern hackberry	CEOC	56
Cercis canadensis L.	eastern redbud	CECA	33
Fraxinus americana L.	white ash	FRAM	55
Fraxinus pennsylvanica Marshall	green ash	FRPE	49
Gleditsia triacanthos L.	honeylocust	GLTR	35
Juglans nigra L.	black walnut	JUNI	34
Malus sp.	apple	MA2	36
Morus sp.	mulberry	MO	48
Picea pungens Engelm.	blue spruce	PIPU	35
Pinus strobus L.	eastern white pine	PIST	39
Populus deltoides Bartram ex Marsh	eastern cottonwood	PODE	59
Pyrus calleryana 'Bradford' Decne.	Callery pear 'Bradford'	PYCA_B	39
Quercus rubra L.	northern red oak	QURU	60
Tilia cordata Mill.	littleleaf linden	TICO	36
Ulmus pumila L.	Siberian elm	ULPU	54
Midwest (MidWst):			
Acer negundo L.	Boxelder	ACNE	43
Acer platanoides L.	Norway maple	ACPL	48
Acer rubrum L.	red maple	ACRU	46
Acer saccharinum L.	silver maple	ACSA1	41
Acer saccharum Marsh.	sugar maple	ACSA2	48
Celtis occidentalis L.	northern hackberry	CEOC	49
Fraxinus americana L.	white ash	FRAM	38
Fraxinus pennsylvanica Marshall	green ash	FRPE	46
Ginkgo biloba L.	ginkgo	GIBI	48
Gleditsia triacanthos L.	honeylocust	GLTR	48
Malus sp.	apple	MA2	50
Quercus palustris Münchh.	pin oak	QUPA	47
Quercus rubra L.	northern red oak	QURU	45
Tilia americana L.	American basswood	TIAM	46
Tilia cordata Mill.	littleleaf linden	TICO	38
Ulmus americana L.	American elm	ULAM	42

Table 5—Numbers of trees sampled by species and region (continued)

Scientific name	Common name	SpCode	Samples
Ulmus pumila L.	Siberian elm	ULPU	37
North (NMtnPr):			
Acer platanoides L.	Norway maple	ACPL	60
Acer saccharinum L.	silver maple	ACSA1	66
Acer saccharum Marsh.	sugar maple	ACSA2	22
Celtis occidentalis L.	northern hackberry	CEOC	67
Fraxinus americana L.	white ash	FRAM	31
Fraxinus pennsylvanica Marshall	green ash	FRPE	65
Gleditsia triacanthos L.	honeylocust	GLTR	64
Gymnocladus dioicus (L.) K. Koch	Kentucky coffeetree	GYDI	31
Malus sp.	apple	MA2	31
Picea pungens Engelm.	blue spruce	PIPU	34
Pinus nigra Arnold	Austrian pine	PINI	33
Pinus ponderosa Douglas ex P. Lawson & C. Lawson	ponderosa pine	PIPO	31
Populus sargentii Dode	plains cottonwood	POSA	54
Prunus sp.	plum	PR	25
Pyrus sp.	pear	PY	29
Quercus macrocarpa Michx.	bur oak	QUMA1	34
Tilia americana L.	American basswood	TIAM	33
Tilia cordata Mill.	littleleaf linden	TICO	34
Ulmus americana L.	American elm	ULAM	61
Ulmus pumila L.	Siberian elm	ULPU	62
Northern California Coast (NoCalC):			
Acacia melanoxylon R. Br.	black acacia	ACME	35
Acer palmatum Thunb.	Japanese maple	ACPA	38
Cinnamomum camphora (L.) J. Presl	camphor tree	CICA	70
Eucalyptus globulus Labill.	blue gum eucalyptus	EUGL	67
Fraxinus velutina Torr.	velvet ash	FRVE	33
Ginkgo biloba L.	ginkgo	GIBI	36
Liquidambar styraciflua L.	sweetgum	LIST	37
Liriodendron tulipifera L.	tulip tree	LITU	34
Magnolia grandiflora L.	southern magnolia	MAGR	38
Pinus radiata D. Don	Monterey pine	PIRA	35
Pistacia chinensis Bunge	Chinese pistache	PICH	37
Pittosporum undulatum Vent.	Victorian box	PIUN	31
Platanus × acerifolia (Aiton) Willd.	London planetree	PLAC	70

Table 5—Numbers of trees sampled by species and region (continued)

Scientific name	Common name	SpCode	Samples
Prunus cerasifera Ehrh.	cherry plum	PRCE	31
Pyrus calleryana Decne.	Callery pear	PYCA	30
Pyrus kawakamii Hayata	evergreen pear	PYKA	35
Quercus agrifolia Née	coastal live oak; California live oak	QUAG	66
Robinia pseudoacacia L.	black locust	ROPS	34
Sequoia sempervirens (Lamb. ex D. Don) Endl.	coast redwood	SESE	62
Ulmus americana L.	American elm	ULAM	60
Ulmus parvifolia Jacq.	Chinese elm	ULPA	33
Northeast (NoEast):			
Acer platanoides L.	Norway maple	ACPL	42
Acer rubrum L.	red maple	ACRU	46
Acer saccharinum L.	silver maple	ACSA1	53
Acer saccharum Marsh.	sugar maple	ACSA2	31
Aesculus hippocastanum L.	horsechestnut	AEHI	33
Fraxinus pennsylvanica Marshall	green ash	FRPE	44
Ginkgo biloba L.	ginkgo	GIBI	33
Gleditsia triacanthos L.	honeylocust	GLTR	34
Liquidambar styraciflua L.	sweetgum	LIST	41
Malus sp.	apple	MA2	32
Pinus strobus L.	eastern white pine	PIST	32
Platanus × *acerifolia* (Aiton) Willd.	London planetree	PLAC	53
Pyrus calleryana Decne.	Kwanzan cherry	PRSE2	34
Quercus palustris Münchh.	Callery pear	PYCA	33
Quercus phellos L.	pin oak	QUPA	54
Quercus rubra L.	willow oak	QUPH	33
Tilia cordata Mill.	northern red oak	QURU	51
Tilia tomentosa Moench	littleleaf linden	TICO	48
Ulmus americana L.	silver linden	TITO	30
Zelkova serrata (Thunb.) Makino	American elm	ULAM	40
Acer platanoides L.	Japanese zelkova	ZESE	34
Pacific Northwest (PacfNW):			
Acer macrophyllum Pursh	bigleaf maple	ACMA	40
Acer platanoides L.	Norway maple	ACPL	74
Acer rubrum L.	red maple	ACRU	39
Acer saccharum Marsh.	sugar maple	ACSA2	37
Betula pendula Roth	European white birch	BEPE	41

Table 5—Numbers of trees sampled by species and region (continued)

Scientific name	Common name	SpCode	Samples
Calocedrus decurrens (Torr.) Florin	incense cedar	CADE2	38
Carpinus betulus 'Fastigiata' L.	columnar hornbeam	CABEF	39
Crataegus × *lavallei* Hérincq ex Lavallée	Carriere hawthorn	CRLA	74
Fagus sylvatica L.	European beech	FASY	38
Fraxinus latifolia Benth.	Oregon ash	FRLA	39
Liquidambar styraciflua L.	sweetgum	LIST	73
Malus angustifolia (Aiton) Michx.	southern crabapple	PYAN	39
Morus alba L.	white mulberry	MOAL	38
Pinus contorta var. *bolanderi* (Parl.) Vasey	Bolander beach pine	PICO5	39
Populus balsamifera subsp. *Trichocarpa* L.	black cottonwood	POTR2	36
Prunus cerasifera Ehrh.	cherry plum	PRCE	74
Prunus serrulata Lindl.	Kwanzan cherry	PRSE2	38
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir	PSME	39
Quercus rubra L.	northern red oak	QURU	39
Tilia americana L.	American basswood	TIAM	39
Tilia cordata Mill.	littleleaf linden	TICO	40
Ulmus americana L.	American elm	ULAM	41
South (Piedmt):			
Acer rubrum L.	red maple	ACRU	44
Acer saccharinum L.	silver maple	ACSA1	48
Acer saccharum Marsh.	sugar maple	ACSA2	41
Betula nigra L.	river birch	BENI	39
Cornus florida L.	flowering dogwood	COFL	34
Ilex opaca Aiton	American holly	ILOP	34
Juniperus virginiana L.	eastern red cedar	JUVI	39
Lagerstroemia sp.	common crapemyrtle	LA6	40
Liquidambar styraciflua L.	sweetgum	LIST	43
Magnolia grandiflora L.	southern magnolia	MAGR	42
Malus sp.	apple	MA2	29
Pinus echinata Mill.	shortleaf pine	PIEC	36
Pinus taeda L.	loblolly pine	PITA	37
Prunus sp.	plum	PR	36
Prunus yedoensis Matsum.	Yoshino flowering cherry	PRYE	39
Pyrus calleryana Decne.	Callery pear	PYCA	34
Quercus alba L.	white oak	QUAL	47
Quercus nigra L.	water oak	QUNI	45
Quercus phellos L.	willow oak	QUPH	49
Quercus rubra L.	northern red oak	QURU	40

Table 5—Numbers of trees sampled by species and region (continued)

Scientific name	Common name	SpCode	Samples
Ulmus alata Michx.	winged elm	ULAL	32
Inland Valleys (SacVal):			
Cedrus deodara (Roxb. ex D. Don) G. Don	deodar cedar	CEDE	61
Celtis occidentalis L.	northern hackberry	CEOC	37
Celtis sinensis Pers.	Chinese hackberry	CESI4	60
Cinnamomum camphora (L.) J. Presl	camphor tree	CICA	63
Fraxinus velutina Torr.	Modesto ash	FRVE_G	40
Ginkgo biloba L.	ginkgo	GIBI	60
Lagerstroemia indica L.	common crapemyrtle	LAIN	28
Liquidambar styraciflua L.	sweetgum	LIST	44
Liriodendron tulipifera L.	tulip tree	LITU	64
Magnolia grandiflora L.	southern magnolia	MAGR	67
Pistacia chinensis Bunge	Chinese pistache	PICH	38
Platanus × acerifolia (Aiton) Willd.	London planetree	PLAC	54
Prunus cerasifera Ehrh.	cherry plum	PRCE	34
Pyrus calleryana Decne.	callery pear	PYCA	31
Quercus agrifolia Née	coastal live oak; California live oak	QUAG	65
Quercus lobata Née	valley oak	QULO	53
Quercus rubra L.	northern red oak	QURU	41
Sequoia sempervirens (Lamb. ex D. Don) Endl.	coast redwood	SESE	52
Ulmus parvifolia Jacq.	Chinese elm	ULPA	62
Zelkova serrata (Thunb.) Makino	Japanese zelkova	ZESE	47
Southern California Coast (SoCalC):			
Callistemon citrinus (Curtis) Skeels	lemon bottlebrush	CACI	31
Cedrus deodara (Roxb. ex D. Don) G. Don	deodar cedar	CEDE	28
Ceratonia siliqua L.	algarrobo Europeo	CESI3	31
Cinnamomum camphora (L.) J. Presl	camphor tree	CICA	29
Cupaniopsis anacardioides (A. Rich.) Radlk.	carrotwood	CUAN	30
Eucalyptus ficifolia F.Muell	red flowering gum	EUFI81	32
Ficus thonningii Blume	figueira benjamin	FIMI	34
Jacaranda mimosifolia D. Don	jacaranda	JAMI	33
Liquidambar styraciflua L.	sweetgum	LIST	33
Magnolia grandiflora L.	southern magnolia	MAGR	33
Melaleuca quinquenervia (Cav.) S.T. Blake	punk tree	MEQU	31
Metrosideros excelsa Sol. ex Gaertn.	New Zealand christmas tree	MEEX	32
Phoenix canariensis Chabaud	Canary Island date palm	PHCA	32

Table 5—Numbers of trees sampled by species and region (continued)

Scientific name	Common name	SpCode	Samples
Pinus canariensis C. Sm.	Canary Island pine	PICA	30
Pittosporum undulatum Vent.	Victorian box	PIUN	36
Podocarpus macrophyllus (Thunb.) Sweet	yew podocarpus	POMA	31
Prunus caroliniana (Mill.) Aiton	Carolina laurelcherry	PRCA	32
Schinus terebinthifolius Raddi	Brazilian pepper	SCTE	31
Tristaniopsis conferta L.A.S.Johnson & K.D.Hill	Brisbane box	TRCO	28
Washingtonia robusta H. Wendl.	Mexican fan palm	WARO	30
Southwest Desert (SWDsrt):			
Acacia farnesiana L.	sweet acacia	ACFA	31
Acacia salicina Lindl.	willow acacia	ACSA3	37
Brachychiton populneus (Schott & Endl.) R.Br.	kurrajong	BRPO	35
Chilopsis linearis (Cav.) Sweet	desert willow	CHLI	34
Eucalyptus microtheca F. Muell.	coolibah tree	EUMI2	36
Fraxinus uhdei (Wenz.) Lingelsh.	evergreen ash	FRUH	32
Fraxinus velutina Torr.	velvet ash	FRVE	59
Morus alba L.	white mulberry	MOAL	39
Olea europaea L.	olive	OLEU	36
Parkinsonia aculeata L.	Jerusalem thorn	PAAC	34
Parkinsonia florida (Benth. ex A. Gray) S. Watson	blue paloverde	CEFL	32
Phoenix dactylifera L.	date palm	PHDA4	56
Pinus eldarica Medw.	Afghan pine	PIEL2	30
Pinus halepensis Mill.	Aleppo pine	PIHA	34
Pistacia chinensis Bunge	Chinese pistache	PICH	33
Prosopis chilensis (Molina) Stuntz	algarrobo	PRCH	31
Quercus virginiana Mill.	live oak	QUVI	36
Rhus lancea L.f.	African sumac	RHLA	32
Ulmus parvifolia Jacq.	Chinese elm	ULPA	36
Washintonia filifera (Linden) Wendl.	California palm	WAFI	71
Washingtonia robusta H. Wendl.	Mexican fan palm	WARO	63
Temperate Interior West (TpIntW):			
Acer platanoides L.	Norway maple	ACPL	62
Acer saccharinum L.	silver maple	ACSA1	58
Acer saccharum Marsh.	sugar maple	ACSA2	30
Catalpa speciosa (Warder) Warder ex Engelm.	northern catalpa	CASP	59
Crataegus sp.	hawthorn	CR	33
Fraxinus americana L.	white ash	FRAM	32
Fraxinus pennsylvanica Marshall	green ash	FRPE	60

Table 5—Numbers of trees sampled by species and region (continued)

Scientific name	Common name	SpCode	Samples
Gleditsia triacanthos L.	honeylocust	GLTR	33
Juglans nigra L.	black walnut	JUNI	57
Liquidambar styraciflua L.	sweetgum	LIST	33
Malus sp.	apple	MA2	30
Picea pungens Engelm.	blue spruce	PIPU	29
Pinus sylvestris L.	Scotch pine	PISY	29
Platanus × *acerifolia* (Aiton) Willd.	London planetree	PLAC	64
Platanus occidentalis L.	American sycamore	PLOC	48
Pyrus calleryana Decne.	Callery pear	PYCA	34
Quercus rubra L.	northern red oak	QURU	56
Robinia pseudoacacia L.	black locust	ROPS	62
Tilia americana L.	American basswood	TIAM	59
Ulmus pumila L.	Siberian elm	ULPU	55
Tropical (Tropic):			
Bauhinia × *blakeana* Dunn	Hong Kong orchid tree	BABL	37
Calophyllum inophyllum L.	kamani	CAIN4	62
Cassia × *nealiae* H. S. Irwin & Barneby	rainbow shower tree	CANE33	41
Casuarina equisetifolia L.	Australian pine	CAEQ	62
Citharexylum spinosum L.	fiddlewood	CISP2	35
Cocos nucifera L.	coconut palm	CONU	34
Conocarpus erectus L. var. *argenteus* Millsp.	silver buttonwood	COERA2	37
Cordia subcordata Lam.	kou	COSU2	33
Delonix regia (Bojer) Raf.	royal poinciana	DERE	59
Elaeodendron orientale Jacq.	false olive	ELOR2	34
Ficus benjamina L.	Benjamin fig	FIBE	60
Filicium decipiens (Wight & Arn.) Thwaites	fern tree	FIDE6	35
Ilex paraguariensis A. St.-Hil.	Paraguay tea	ILPA2	36
Lagerstroemia speciosa (L.) Pers.	giant crapemyrtle	LASP	37
Melaleuca quinquenervia (Cav.) S.T. Blake	punk tree	MEQU	59
Samanea saman (Jacq.) Merr.	monkeypod	PISA2	62
Swietenia mahagoni (L.) Jacq.	West Indian mahogany	SWMA	54
Tabebuia aurea (Silva Manso) Benth. & Hook. f. ex S.	silver trumpet tree	TAAR	37
Tabebuia heterophylla (DC.) Britton	pink trumpet tree	TAPA	36
Tabebuia ochracea (Cham.) Standl. subsp. *neochrysantha* (A.H. Gentry) A.H. Gentry	golden trumpet tree	TACH	36
Veitchia merrillii H.E. Moore	Christmas palm	VEME	32
Total			14,487

SpCode = four- to six-letter code consisting of the first two letters of the genus name and the first two letters of the species name followed by two optional letters to distinguish two species with the same four-letter code.

Appendix 2: Field Data Collection Protocols

The following data will be recorded for each tree (note: highlighted fields 1 through 9 will be uploaded from inventory onto your palmtop and are for locating trees. You will collect data for the remaining items:

1. TreeID—from inventory, unique number assigned to each tree by city in inventory.
2. SpCode—four- to six-letter code consisting of the first two letters of the genus name and the first two letters of the species name followed by two optional letters to distinguish two species with the same four-letter code.
3. AddressNum–from inventory, street number of building where tree is located.
4. Street–from inventory, the name of the street on which the tree is located–from inventory.
5. Side—from inventory, indicates side of building or lot on which the tree is located (see fig. 10):
   F = front
   M = median
   S = side
   P = park
6. Cell—from inventory, the cell number where the tree is located (1, 2, 3, etc). Obtain city inventory protocols to determine what order the trees are numbered in (e.g., sometimes they are assigned in driving direction or, alternatively, as street number increases, depending upon city).
7. OnStree—from inventory (omit if not included as a field in city's inventory), for trees at corner addresses when the tree is actually on a cross street rather than the addressed street (see fig. 10).
8. FromStreet/ToStreet—from inventory, the names of the cross streets that form boundaries for trees lining unaddressed boulevards. For example, on boulevards that have no development adjacent to them, therefore no obvious parcel addressing, trees are typically numbered in order. By including closest cross streets in the inventory, one will not have to begin counting trees from No. 1 in order to locate No. 333, which is 10 blocks up the boulevard from No. 1.

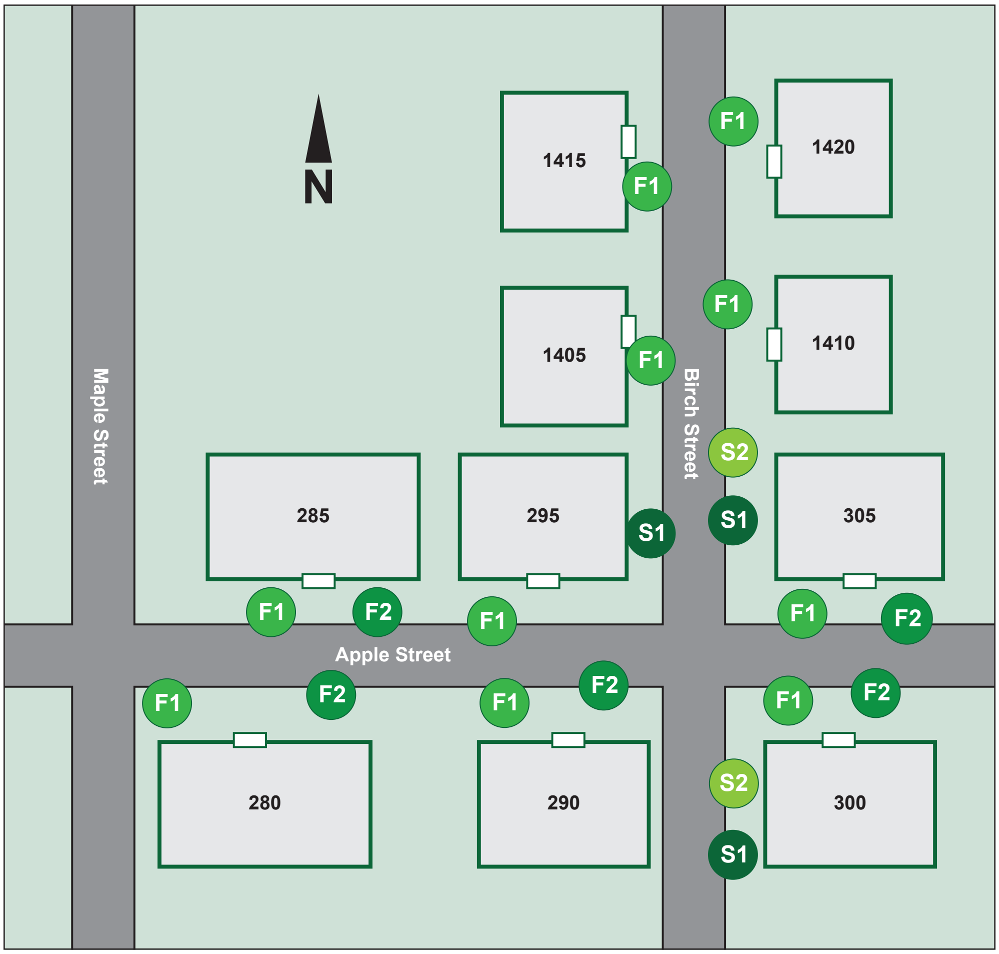

Figure 10—Treeloc tree 295 Apple S1 is actually the first tree (in driving direction) on Birch Street side of house.

9. DBHinv—the diameter at breast height (d.b.h.) from the city inventory, usually expressed as classes from one to nine, but class system specific to city. Sometimes expressed as d.h.h. to nearest inch or centimeter. Data are used to help locate the desired size of tree in the field for sampling.
10. Diameter at breast height—measure the d.b.h. (1.37 m) to nearest 0.1 cm (tape). Where possible for multistemmed trees forking below 1.37 m, measure above the butt flare and below the point where the stem begins forking. When this is not possible, measure diameter root collar (DRC) as described below. Saplings (d.b.h./DRC 2.54 to 12.5 cm) will be measured at 1.37 m unless falling under multistemmed/unusual stem categories requiring DRC measurements (per Forest Health Monitoring (FHM) Field Methods Guide).

DIAMETER at ROOT COLLAR–adapted from Forest Health and Monitoring (FHM) Field Methods Guide:
For species requiring DRC, measure the diameter at the ground line or at the stem root collar, whichever is higher. For these trees, treat clumps of stems having a unified crown and common rootstock as a single tree; examples include mesquite and juniper. For multistemmed trees, compute and record a cumulative DRC (see below); record individual stem diameters and a stem status (live or dead) on a separate form or menu as required.

Measuring DRC: Before measuring DRC, remove the loose material on the ground (e.g., litter) but not mineral soil. Measure just above any swells present, and in a location where the diameter measurements are reflective of the volume above the stems (especially when trees are extremely deformed at the base).

Stems must be at least 0.3 m in length and 2.54 cm in diameter at breast height to qualify for measurement; stems that are missing owing to cutting or damage are not included in measurement.

Additional instructions for DRC measurements are illustrated in figure 11.

Computing and recording DRC: For all tally trees requiring DRC, with at least one stem 2.54 cm in diameter or larger at the root collar, DRC is computed as the square root of the sum of the squared stem diameters. For a single-stemmed DRC tree, the computed DRC is equal to the single diameter measured.

Use the following formula to compute DRC:

DRC = SQRT [SUM (stem diameter^2)]

Round the result to the nearest 2.54 cm. For example, a multistemmed woodland tree with stems of 12.2, 13.2, 3.8, and 22.1 would be calculated as:

DRC = SQRT ($12.2^2 + 13.2^2 + 3.8^2 + 22.1^2$)

= SQRT (825.93)

= 28.74

= 28.7

11. TreeHt—from ground level to treetop to nearest 0.5 m (omit erratic leader as shown in fig. 12 with rangefinder).
12. CrnBase—with rangefinder, average distance between ground and lowest foliage layer (omitting erratic branch) to nearest 0.5 m.
13. CDiaPar—(crown diameter) crown diameter measurement taken to the nearest 0.5 m parallel to the street. The occasional erratic branch should not be included (see fig. 13).
14. CDiaPerp—(crown diameter) crown diameter measurement taken to the nearest 0.5 m perpendicular to the treet. The occasional erratic branch should not be included (see fig. 13).

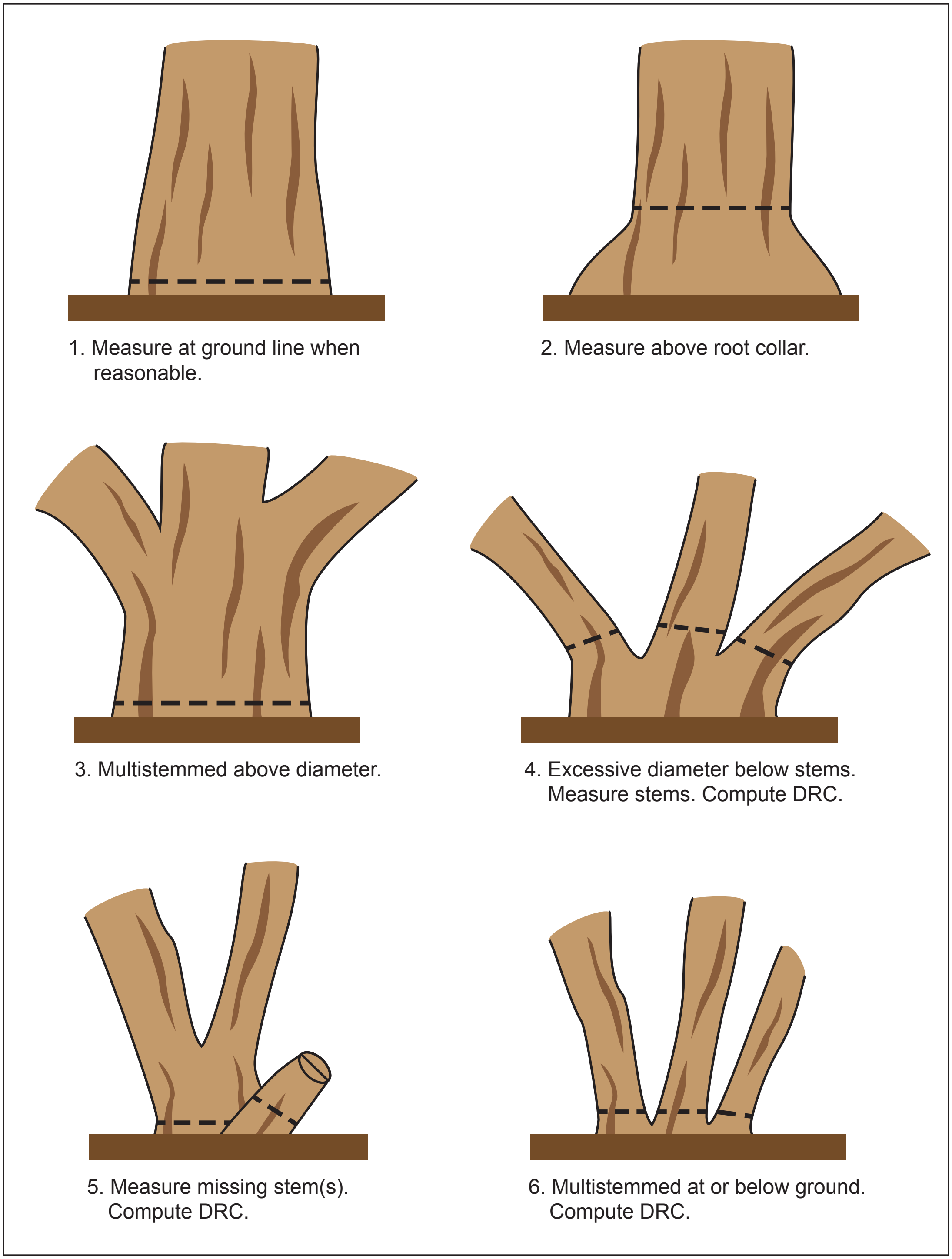

Figure 11—How to measure Diameter at Root Collar (DRC) in a variety of situation.

Pacific Southwest Research Station

Figure 12—Tree with erratic leader that should not be included in height measurement.

Pacific Southwest Research Station

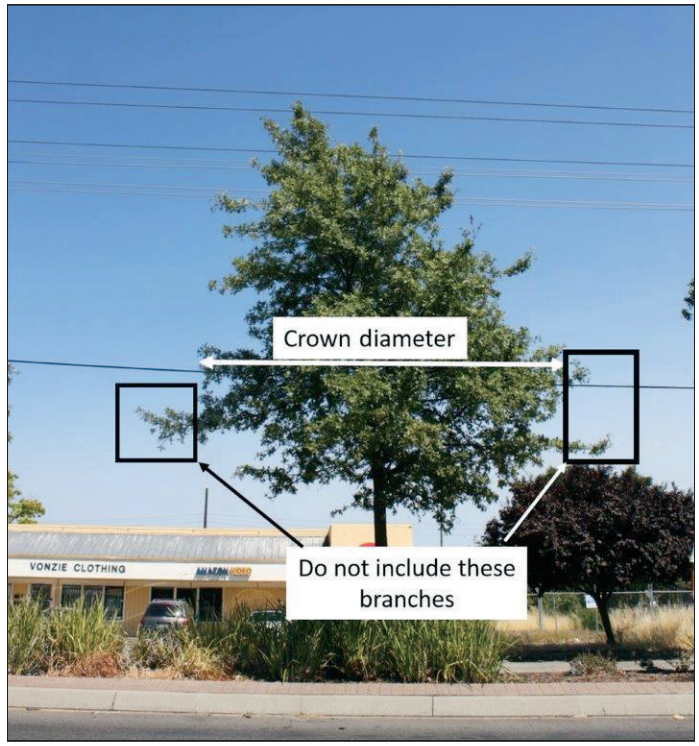

Figure 13—Erratic branch (in box at left) is omitted from crown diameter measurement. Distance measured is represented by white line.

15. Setback—distance from the tree to the nearest air conditioned/heated space (be aware that this may not be the same address as the tree location).
    Evaluate as:
    1 = 0 to 8 m
    2 = 8.1 to 12 m
    3 = 12.1 to 18 m
    4 = >18 m
    Use: assess effects of shade on energy use.
16. TreeOr—Tree orientation—taken with compass, as in figure 14 the coordinate of tree taken from imaginary lines extending from walls of the nearest conditioned space (heated or airconditioned space—may not be same address as tree location):
17. CarShade—Number of autos where any portion of any parked automotive vehicle is under the tree's drip line. Car must be present:
    0 = no autos
    1 = one auto
    2 = two autos, etc.
    Use: vehicle hydrocarbon emissions reduction.

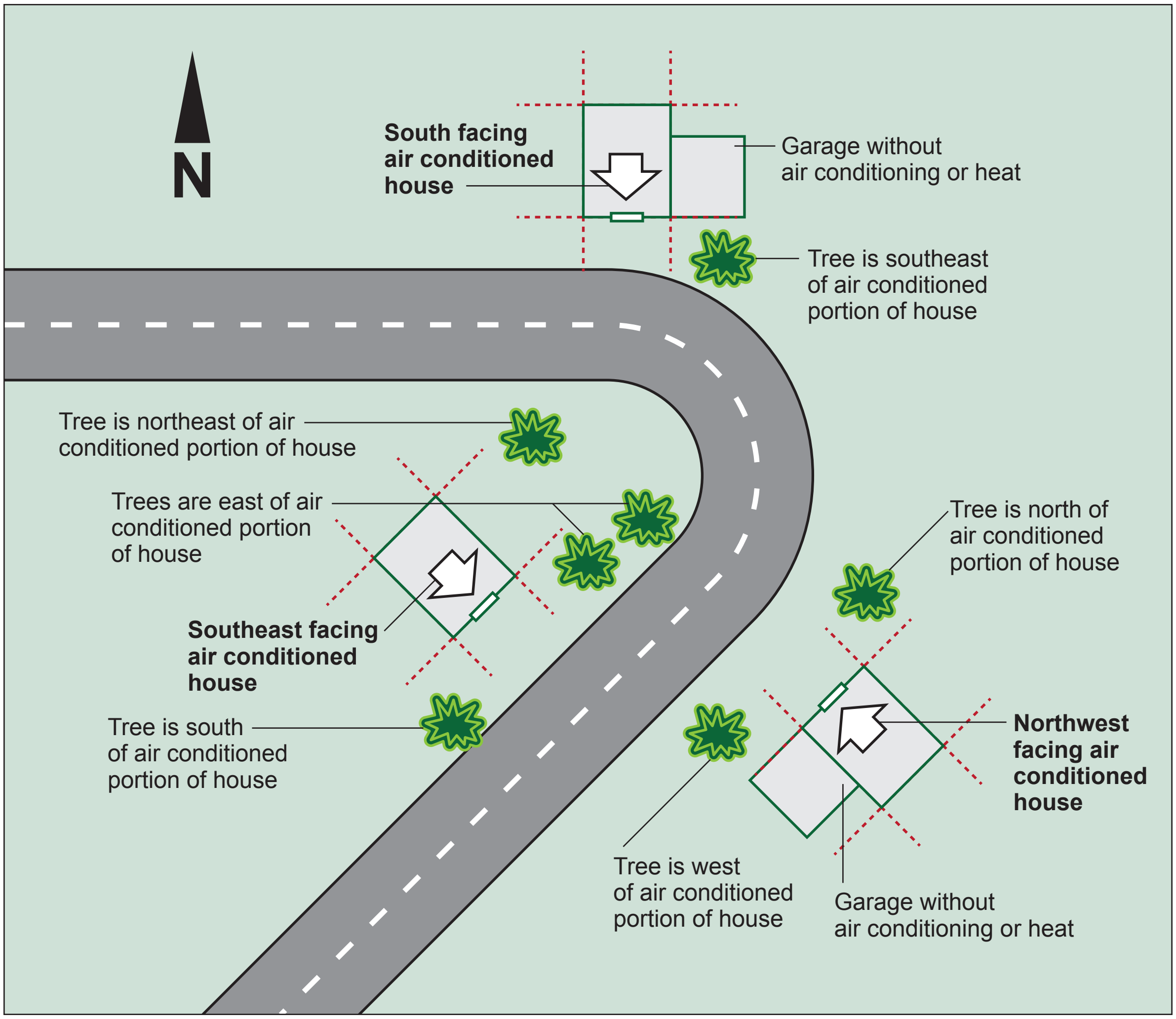

Figure 14—Shows imaginary lines extending from walls and associated tree orientation

18. Land use—Area where tree is growing:
    1 = single-family residential
    2 = multifamily residential (duplex, apartments, condos)
    3 = industrial/institutional/large commercial (schools, government, hospitals)
    4 = park/vacant/other (agricultural, unmanaged riparian areas of greenbelts)
    5 = small commercial (minimart, retail boutiques, etc.)
    6 = transportation corridor.
    Use: energy, property value.

19. Shape–visual estimate of crown shape verified when different from each side with actual measured dimensions of crown height and average crown diameter. If in doubt, determine shape using average crown diameter and crown height measurements. See figure 15. Use: energy (shadow patterns)
20. 1 = cylinder = maintains same crown diameter in top and bottom thirds of tree
21. 2 = ellipsoid (horizontal or vertical; also includes spherical)—for ellipse the tree's center (whether vertical or horizontal) should be the widest)
22. 3 = paraboloid—widest in bottom third of crown
23. 4 = upside down paraboloid—widest in top third of crown
24. WireConf—utility lines that interfere with or appear above tree
    0 = no lines
    1 = present and no potential conflict
    2 = present and conflicting
    3 = present and potential for conflicting
25. Image1—select position for best possible photo of tree crown, keeping in mind that you must try to obtain two perpendicular views of the tree that are as free of background noise as possible. Try to position yourself so the tree crown is as isolated as possible from neighboring tree crowns and other crowns in background:
26. Distance from tree that photo is taken at increments of 5 m (5, 10, 15, 20 m, etc) and accurate within 0.05 m.
27. Camera zoom should be set to full wide angle
28. First image must include entire tree (bole and crown) for backup measurements and should fill as much of viewfinder as possible
29. Kneel to take images so more sky is included in background
30. Dist1—Measure distance from camera back (the point where image is actually recorded) to point equivalent to center of tree bole (fig. 16). Measure accurately within 0.05 m.
31. Image2—taken as perpendicularly (90°) as possible to Image 1.
32. Dist2—distance as per Dist1 for Image 2.
33. PlantDate—Date tree was planted. As you collect data, talk with residents and see if you can find name and address of the oldest person on street or in neighborhood, or if residents know age of tree. We will review methods for aging trees during training.
34. Notes: any pertinent notes—if tree is replacement and what tree was replaced—give address of replacement tree.
35. dbh1, dbh2, dbh3, etc., are for individual stem diameter entries for multi-stemmed trees being recorded using DRC methods. These cells are linked to the formula in field #10 (d.b.h.) column calculating the final d.b.h.

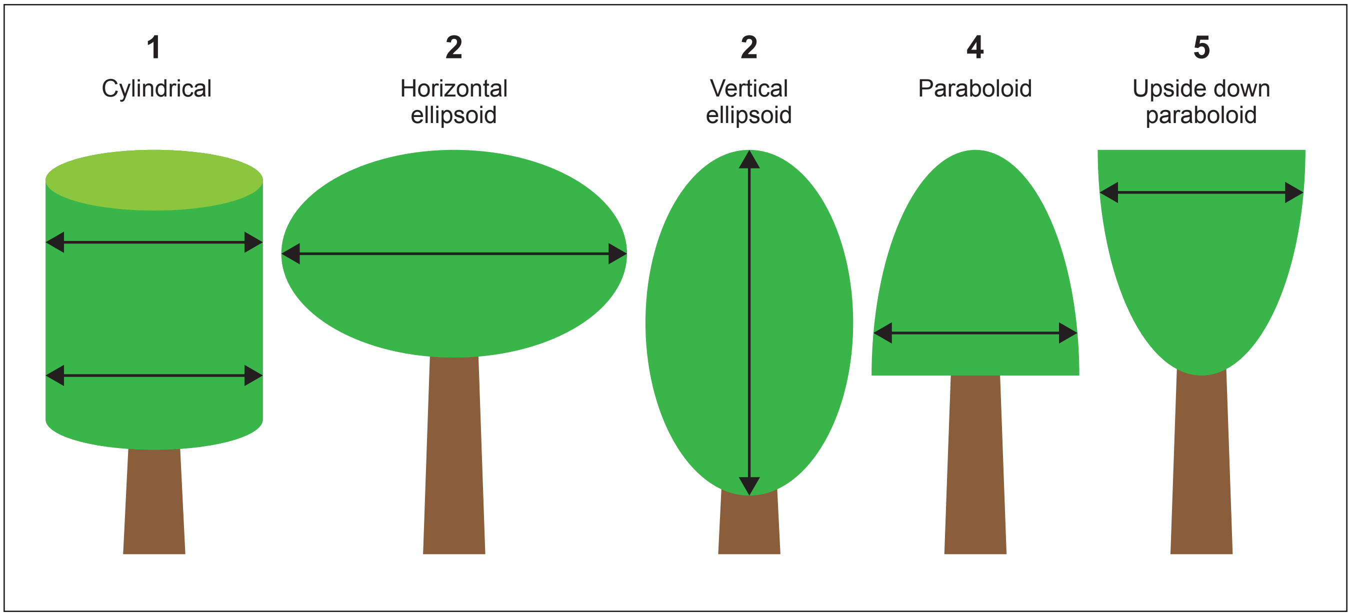

Figure 15—Shapes of tree crowns.

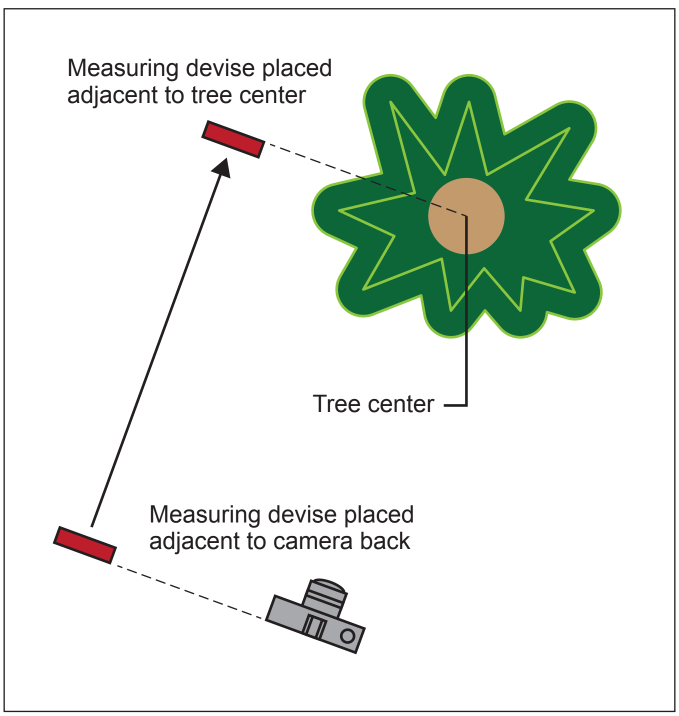

Figure 16—Showing how to measure distance (in 5-m increments) between camera back and tree center.

Appendix 3: Foliar Biomass

Table 6 shows the mean and standard deviations for dry-weight to fresh-weight ratios for foliar biomass and the average foliar biomass factors (gram of dry weight per square meter of leaf area) for each species and region. Average foliar biomass factors range from a low of 76.1 g/m^2 for climate zone MidWst to a high of 222.7 g/m^2 for TpIntW. Across climate zones, there is a range of average foliar biomass factor values by species tree type from a high of 481.9 g/m^2 in large conifer evergreen species to a low of 99.3 g/m^2 in large broadleaf deciduous species. Within climate zones, there is also high variability, influenced by tree type. For example, although the average foliar biomass factor for NoCalC is 214.4 g/m^2, the range is from a high of 659.7 g/m^2 (driven by *Sequoia sempervirens* and *Pinus radiata*, both factors over 500.0 g/m^2) to a low of 73.2 g/m^2 *Prunus cerasifera*. It is important to note the sample number (n) and documented sampling notes when applying these data. Foliar samples were not collected in four of the reference cities (InlVal, InterW, PacfNW, SacVal).

Table 6—Average dry-weight to fresh-weight (dw:fw) ratios for foliar biomass and average foliar biomass factors (gram of dry weight per square meter of leaf area) for each species and region

Region[a]	SpCode[b]	Avg dw/fw (g)	dw/fw SD	Avg dw g/m^2	dw g/m^2 SD	No.
CenFla	ACRU	0.46	0.04	102.75	12.28	10
CenFla	CICA	0.48	0.04	116.42	6.64	10
CenFla	ERJA	0.41	0.06	162.48	26.87	10
CenFla	JUSI	0.50	0.03	405.68	48.08	10
CenFla	KOELFO	0.49	0.04	68.35	12.55	10
CenFla	LAIN	0.34	0.03	81.38	18.16	10
CenFla	LIST	0.31	0.02	93.74	15.48	10
CenFla	MAGR	0.35	0.03	144.87	22.25	10
CenFla	PIEL	0.44	0.01	107.74	11.50	10
CenFla	PLOC	0.38	0.04	74.60	13.45	10
CenFla	THOR	0.42	0.01	207.09	29.85	10
CenFla	PRCA	0.45	0.05	118.66	19.20	10
CenFla	QULA2	0.48	0.01	117.81	37.87	10
CenFla	QUSH	0.50	0.02	110.12	16.49	10
CenFla	QUVI	0.49	0.04	135.18	51.85	10
CenFla	SAPA	0.41	0.16	207.21	83.86	7
CenFla	SYRO	0.46	0.03	132.76	59.85	7
CenFla	TRSE6	0.36	0.03	73.87	10.81	10
CenFla	ULPA	0.42	0.04	130.78	37.30	10

Table 6—Average dry-weight to fresh-weight (dw:fw) ratios for foliar biomass and average foliar biomass factors (gram of dry weight per square meter of leaf area) for each species and region (continued)

Region[a]	SpCode[b]	Avg dw/fw (g)	dw/fw SD	Avg dw g/m^2	dw g/m^2 SD	No.
CenFla	WARO	0.42	0.07	149.50	18.68	4
GulfCo	ACRU	0.32	0.02	72.68	14.58	10
GulfCo	BUCA	0.71		331.74		1
GulfCo	CAIL	0.45	0.03	104.35	16.85	10
GulfCo	CELA	0.33	0.04	58.41	11.16	10
GulfCo	COFL	0.39	0.03	78.34	21.27	10
GulfCo	GLTR	0.40	0.03	159.31	142.22	10
GulfCo	ILOP	0.52	0.02	206.95	13.51	10
GulfCo	JUVI	0.45	0.02	357.56	46.51	10
GulfCo	LAIN	0.30	0.03	78.58	13.71	10
GulfCo	LIST	0.35	0.04	98.90	24.22	10
GulfCo	MAGR	0.43	0.02	221.77	17.98	10
GulfCo	PITA	0.39	0.01	572.86	25.14	10
GulfCo	PLOC	0.40	0.06	71.94	15.67	10
GulfCo	PYCA	0.49	0.02	154.87	22.36	10
GulfCo	QULA2	0.53	0.02	135.55	14.41	10
GulfCo	QUNI	0.53	0.01	147.77	14.32	10
GulfCo	QUPH	0.50	0.03	100.79	10.68	10
GulfCo	QUVI	0.52	0.01	255.19	197.58	10
GulfCo	SAPA	0.63		303.42		1
InlEmp	BRPO	0.35		122.79		20
InlEmp	CICA	0.46		176.12		20
InlEmp	EUSI	0.47		179.20		20
InlEmp	FRUH	0.45		164.23		20
InlEmp	FRVE	0.53		144.64		20
InlEmp	GIBI	0.41		176.63		20
InlEmp	JAMI	0.36		114.76		20
InlEmp	LAIN	0.46		256.51		20
InlEmp	LIST	0.46		145.46		20
InlEmp	LITU	0.34		89.61		20
InlEmp	MAGR	0.54		289.27		20
InlEmp	PIBR2	0.36		446.89		20
InlEmp	PICA	0.50		342.79		20
InlEmp	PICH	0.45		118.87		20
InlEmp	PLAC	0.55		128.41		20
InlEmp	PLRA	0.56		139.39		20
InlEmp	PYCA	0.59		186.43		20
InlEmp	QUAG	0.52		358.25		20

Table 6—Average dry-weight to fresh-weight (dw:fw) ratios for foliar biomass and average foliar biomass factors (gram of dry weight per square meter of leaf area) for each species and region (continued)

Region[a]	SpCode[b]	Avg dw/fw (g)	dw/fw SD	Avg dw g/m^2	dw g/m^2 SD	No.
InlEmp	QUIL2	0.60		202.39		20
InlEmp	SCMO	0.31		166.69		20
InlEmp	SCTE	0.43		153.77		20
InlEmp	WARO	0.47	0.05	271.45	52.90	4
LoMidW	ACPL	0.31	0.12	101.52	53.63	10
LoMidW	ACRU	0.32	0.05	108.69	16.68	10
LoMidW	ACSA1	0.29	0.07	85.92	15.37	10
LoMidW	ACSA2	0.38	0.06	122.58	30.86	10
LoMidW	CASP	0.25	0.03	72.01	16.29	10
LoMidW	CEOC	0.31	0.05	72.60	13.00	10
LoMidW	CECA	0.27	0.04	95.05	9.89	10
LoMidW	FRAM	0.37	0.02	102.43	16.89	10
LoMidW	FRPE	0.33	0.04	116.06	22.56	10
LoMidW	GLTR	0.32	0.07	114.58	29.89	10
LoMidW	JUNI	0.30	0.03	87.52	10.82	10
LoMidW	MA2	0.23	0.07	105.13	21.14	10
LoMidW	MO	0.26	0.04	99.88	22.03	10
LoMidW	PIPU	0.42	0.04	340.97	169.38	10
LoMidW	PIST	0.34	0.03	250.60	32.06	10
LoMidW	PODE	0.28	0.03	122.01	20.47	10
LoMidW	PYCA	0.30	0.03	115.70	25.59	10
LoMidW	QURU	0.34	0.05	109.22	21.66	10
LoMidW	TICO	0.28	0.06	100.13	37.61	10
LoMidW	ULPU	0.26	0.05	106.42	13.37	10
MidWst	ACNE	0.30	0.03	52.94	10.21	10
MidWst	ACPL	0.39	0.03	49.84	7.50	10
MidWst	ACRU	0.46	0.02	83.29	11.79	10
MidWst	ACSA1	0.44	0.03	85.83	14.78	10
MidWst	ACSA2	0.42	0.04	53.62	11.55	10
MidWst	CEOC	0.40	0.02	68.23	6.79	10
MidWst	FRAM	0.40	0.03	71.40	15.16	10
MidWst	FRPE	0.34	0.03	68.62	13.05	10
MidWst	GIBI	0.31	0.03	91.24	14.10	10
MidWst	GLTR	0.39	0.02	89.52	12.86	10
MidWst	MA2	0.40	0.05	67.53	20.50	10
MidWst	QUPA	0.44	0.02	84.97	10.85	10
MidWst	QURU	0.45	0.02	85.06	16.44	10

Table 6—Average dry-weight to fresh-weight (dw:fw) ratios for foliar biomass and average foliar biomass factors (gram of dry weight per square meter of leaf area) for each species and region (continued)

Region[a]	SpCode[b]	Avg dw/fw (g)	dw/fw SD	Avg dw g/m^2	dw g/m^2 SD	No.
MidWst	TIAM	0.37	0.03	77.04	22.04	10
MidWst	TICO	0.35	0.03	57.33	15.11	10
MidWst	ULAM	0.36	0.02	82.30	9.63	10
MidWst	ULPU	0.41	0.02	124.67	18.41	10
NMtnPr	ACPL	0.40	0.03	68.23	19.36	10
NMtnPr	ACSA1	0.48	0.09	83.03	29.01	10
NMtnPr	ACSA2	0.36	0.06	75.73	11.58	10
NMtnPr	CEOC	0.45	0.04	76.18	16.71	10
NMtnPr	FRAM	0.42	0.06	74.91	11.40	10
NMtnPr	FRPE	0.39	0.08	84.76	20.89	10
NMtnPr	GLTR	0.44	0.03	96.98	21.79	10
NMtnPr	GYDI	0.36	0.03	58.25	13.26	10
NMtnPr	MA2	0.31	0.09	54.94	13.70	10
NMtnPr	PIPU	0.45	0.01	428.00	29.51	10
NMtnPr	PINI	0.43	0.04	411.32	41.37	10
NMtnPr	PIPO	0.44	0.02	399.01	31.95	10
NMtnPr	POSA	0.27	0.04	70.73	12.52	10
NMtnPr	PR	0.41	0.09	71.12	15.74	10
NMtnPr	PY	0.42	0.02	120.06	14.26	10
NMtnPr	QUMA1	0.53	0.11	122.42	14.97	10
NMtnPr	TIAM	0.33	0.03	69.46	8.30	10
NMtnPr	TICO	0.33	0.07	57.75	14.78	10
NMtnPr	ULAM	0.43	0.04	84.33	22.85	10
NMtnPr	ULPU	0.33	0.04	70.29	15.34	10
NoCalC	ACME	0.56	0.05	219.54	23.17	10
NoCalC	ACPA	0.51	0.02	90.67	10.69	10
NoCalC	CICA	0.53	0.05	167.57	18.93	9
NoCalC	EUGL	0.55	0.03	338.48	28.62	10
NoCalC	FRVE	0.60	0.05	184.02	18.19	10
NoCalC	GIBI	0.38	0.02	156.00	60.01	10
NoCalC	LIST	0.48	0.04	125.75	18.38	10
NoCalC	LITU	0.36	0.01	83.00	5.16	10
NoCalC	MAGR	0.48	0.02	232.77	15.65	10
NoCalC	PIRA	0.52	0.03	762.71	127.18	10
NoCalC	PICH	0.51	0.04	143.94	25.88	10
NoCalC	PIUN	0.49	0.01	149.41	11.55	10
NoCalC	PLAC	0.42	0.14	107.74	12.69	10

Table 6—Average dry-weight to fresh-weight (dw:fw) ratios for foliar biomass and average foliar biomass factors (gram of dry weight per square meter of leaf area) for each species and region (continued)

Region[a]	SpCode[b]	Avg dw/fw (g)	dw/fw SD	Avg dw g/m^2	dw g/m^2 SD	No.
NoCalC	PRCE	0.45	0.02	73.19	27.38	10
NoCalC	PYCA	0.57	0.03	175.06	34.38	10
NoCalC	PYKA	0.58	0.09	243.93	48.81	10
NoCalC	QUAG	0.60	0.02	251.98	9.65	10
NoCalC	ROPS	0.42	0.03	86.20	8.34	10
NoCalC	SESE	0.52	0.03	556.77	94.40	10
NoCalC	ULAM	0.79	1.19	160.98	243.30	9
NoCalC	ULPA	0.46	0.01	192.29	16.69	10
NoEast	ACPL	0.41	0.04	62.05	18.87	10
NoEast	ACRU	0.37	0.13	72.68	16.10	10
NoEast	ACSA1	0.41	0.04	89.82	18.86	10
NoEast	ACSA2	0.44	0.02	80.77	13.07	10
NoEast	AEHI	0.43	0.06	85.38	10.89	10
NoEast	FRPE	0.44	0.02	109.44	12.42	10
NoEast	GIBI	0.35	0.08	130.59	31.82	10
NoEast	GLTR	0.44	0.03	124.66	21.56	10
NoEast	LIST	0.35	0.08	93.78	25.84	10
NoEast	MA2	0.50	0.05	109.68	23.11	10
NoEast	PIST	0.38	0.10	717.94	376.53	10
NoEast	PLAC	0.41	0.01	110.02	20.02	10
NoEast	PRSE2	0.43	0.03	99.32	19.35	10
NoEast	PYCA	0.46	0.06	130.15	35.72	10
NoEast	QUPA	0.45	0.05	88.17	28.31	10
NoEast	QUPH	0.46	0.03	183.61	278.65	10
NoEast	QURU	0.46	0.03	96.79	24.42	10
NoEast	TICO	0.38	0.04	141.78	236.15	10
NoEast	TITO	0.38	0.01	73.85	8.99	10
NoEast	ULAM	0.40	0.01	99.77	20.85	10
NoEast	ZESE	0.45	0.05	73.05	39.55	10
Piedmt	ACRU	0.44	0.04	86.92	21.30	10
Piedmt	ACSA1	0.40	0.03	84.77	9.26	10
Piedmt	ACSA2	0.36	0.12	57.99	30.52	10
Piedmt	BENI	0.35	0.07	69.63	15.32	10
Piedmt	COFL	0.35	0.05	54.49	14.71	10
Piedmt	ILOP	0.34	0.05	124.53	32.68	10
Piedmt	JUVI	0.40	0.02	559.08	78.10	10
Piedmt	LA6	0.32	0.03	112.76	18.18	10

Table 6—Average dry-weight to fresh-weight (dw:fw) ratios for foliar biomass and average foliar biomass factors (gram of dry weight per square meter of leaf area) for each species and region (continued)

Region[a]	SpCode[b]	Avg dw/fw (g)	dw/fw SD	Avg dw g/m^2	dw g/m^2 SD	No.
Piedmt	LIST	0.33	0.04	80.11	20.74	10
Piedmt	MAGR	0.40	0.04	165.31	26.11	10
Piedmt	MA2	0.28	0.06	57.71	19.52	10
Piedmt	PIEC	0.38	0.02	706.35	201.79	10
Piedmt	PITA	0.39	0.03	525.79	98.03	10
Piedmt	PR	0.29	0.05	57.86	17.15	10
Piedmt	PRYE	0.40	0.05	116.85	28.23	10
Piedmt	PYCA	0.37	0.08	113.74	41.72	10
Piedmt	QUAL	0.42	0.05	73.03	17.37	10
Piedmt	QUNI	0.44	0.08	91.73	20.63	10
Piedmt	QUPH	0.42	0.04	86.21	18.50	10
Piedmt	QURU	0.42	0.06	71.81	16.01	10
Piedmt	ULAL	0.50	0.03	84.65	16.63	10
SoCalC	CACI			204.01		10
SoCalC	CEDE			390.93	11.19	3
SoCalC	CESI3			233.23	22.20	3
SoCalC	CICA			129.86		1
SoCalC	CUAN			178.53	20.01	3
SoCalC	FIMI			141.50	7.04	3
SoCalC	JAMI			115.85		1
SoCalC	LIST			124.00	4.85	3
SoCalC	MAGR			235.45	13.78	3
SoCalC	MEQU			201.99		1
SoCalC	MEEX			219.06		1
SoCalC	PHCA			226.15		1
SoCalC	PIBR2	0.36		446.89		1
SoCalC	PICA			371.31		1
SoCalC	PIUN			143.46		1
SoCalC	POMA			200.41	13.34	2
SoCalC	SCTE			121.99		1
SoCalC	TRCO			174.30		1
SoCalC	WARO			216.16		1
SWDsrt	ACFA	0.48	0.08	178.75	42.23	10
SWDsrt	ACSA3	0.32	0.02	187.23	16.85	10
SWDsrt	BRPO	0.37	0.02	86.14	6.40	10
SWDsrt	CHLI	0.40	0.02	159.62	25.89	10
SWDsrt	EUMI2	0.48	0.08	145.29	12.16	10

Table 6—Average dry-weight to fresh-weight (dw:fw) ratios for foliar biomass and average foliar biomass factors (gram of dry weight per square meter of leaf area) for each species and region (continued)

Region[a]	SpCode[b]	Avg dw/fw (g)	dw/fw SD	Avg dw g/m^2	dw g/m^2 SD	No.
SWDsrt	FRUH	0.47	0.02	126.35	11.21	10
SWDsrt	FRVE	0.44	0.02	120.11	13.48	10
SWDsrt	MOAL	0.49	0.04	153.46	30.14	10
SWDsrt	OLEU	0.52	0.02	256.39	18.88	10
SWDsrt	PAAC	0.40	0.06	586.32	126.61	10
SWDsrt	CEFL	0.51	0.05	181.85	40.64	10
SWDsrt	PHDA4	0.68	0.02	309.49	5.62	2
SWDsrt	PIEL2	0.43	0.02	452.68	142.21	10
SWDsrt	PIHA	0.47	0.02	515.04	199.92	10
SWDsrt	PICH	0.47	0.06	132.31	27.57	10
SWDsrt	PRCH	0.45	0.03	177.36	21.06	10
SWDsrt	QUVI	0.52	0.10	185.64	29.68	10
SWDsrt	RHLA	0.46	0.04	132.57	15.47	10
SWDsrt	ULPA	0.53	0.01	203.71	20.19	10
SWDsrt	WAFI	0.52	0.01	193.01	27.01	2
SWDsrt	WARO	0.54	0.06	192.46	2.98	2
TpIntW	ACPL	0.43	0.02	68.37	13.43	10
TpIntW	ACSA1	0.46	0.12	83.03	11.59	7
TpIntW	ACSA2	0.43	0.03	59.23	12.41	10
TpIntW	CASP	0.32	0.05	81.09	35.25	10
TpIntW	CR	0.48	0.03	113.36	25.49	10
TpIntW	FRAM	0.41	0.03	101.97	12.78	10
TpIntW	FRPE	0.39	0.02	78.97	15.26	10
TpIntW	GLTR	0.45	0.03	113.71	30.52	10
TpIntW	JUNI	0.41	0.03	97.23	21.33	10
TpIntW	LIST	0.38	0.03	99.82	17.96	10
TpIntW	MA2	0.42	0.06	81.29	21.26	10
TpIntW	PIPU	0.49	0.03	562.63	28.25	10
TpIntW	PISY	0.46	0.02	477.71	70.45	10
TpIntW	PLAC	0.40	0.02	101.34	18.50	10
TpIntW	PLOC	0.38	0.03	91.63	21.75	10
TpIntW	PYCA	0.42	0.03	93.42	14.80	10
TpIntW	QUAL	0.47	0.02	91.68	16.86	10
TpIntW	QURU	0.47	0.06	89.61	13.81	10
TpIntW	ROPS	0.42	0.11	64.84	14.25	10
TpIntW	TIAM	0.37	0.03	60.00	13.58	10
TpIntW	TICO	0.39	0.03	63.38	16.17	10

Table 6—Average dry-weight to fresh-weight (dw:fw) ratios for foliar biomass and average foliar biomass factors (gram of dry weight per square meter of leaf area) for each species and region (continued)

Region[a]	SpCode[b]	Avg dw/fw (g)	dw/fw SD	Avg dw g/m^2	dw g/m^2 SD	No.
TpIntW	ULPU	0.40	0.02	118.79	27.30	10
Tropic	BABL	0.43	0.03	121.05	10.66	10
Tropic	CAIN4	0.41	0.06	173.82	16.25	10
Tropic	CANE33	0.45	0.03	99.05	10.73	10
Tropic	CAEQ	0.45	0.17	1466.27	561.35	10
Tropic	CISP2	0.35	0.02	109.36	19.44	10
Tropic	CONU	0.45	0.06	200.91	28.09	2
Tropic	COERA2	0.34	0.02	194.06	87.11	10
Tropic	COSU2	0.20	0.02	50.06	9.58	10
Tropic	DERE	0.38	0.02	125.06	26.21	10
Tropic	ELOR2	0.44	0.01	216.18	14.57	10
Tropic	FIBE	0.39	0.02	130.09	22.03	10
Tropic	FIDE6	0.42	0.02	151.57	27.80	10
Tropic	ILPA2	0.42	0.02	164.33	12.96	10
Tropic	LASP	0.31	0.04	99.35	26.17	10
Tropic	MEQU	0.40	0.14	189.66	48.45	10
Tropic	PISA2	0.41	0.03	118.04	21.74	10
Tropic	SWMA	0.45	0.02	110.92	15.42	10
Tropic	TAAR	0.34	0.02	155.75	18.22	10
Tropic	TAPA	0.36	0.02	136.29	21.70	10
Tropic	TACH	0.48	0.03	154.16	31.80	10
Tropic	VEME	0.41	0.02	170.11	10.17	2

SD = standard deviation.

[a] CenFla = Central Florida, GulfCo = Coastal Plain, InlEmp = Inland Empire, LoMidW = Lower Midwest, MidWst = Midwest, NMtnPr = North, NoCalC = Northern California Coast, NoEast = Northeast, Piedmt = South, SoCalC = Southern California Coast, SWDsrt = Southwest Desert, TpIntW = Temperate Interior West, Tropic = Tropical.

[b] SpCodes = Four- to six-letter code consisting of the first two letters of the genus name and the first two letters of the species name followed by two optional letters to distinguish two species with the same four-letter code.

Appendix 4: Growth Equation Coefficients and Application Information

Appendix 4 and the corresponding online supplement report the growth equation coefficients from the best fitting models for each species and region. Table 7 illustrates the parameters predicted by the growth equations for two species, ACME and ACPA, in the Northern California Coast climate zone. The full table of coefficients for all species measured in each reference city is available in table S6 of the online supplement.

Twelve combinations of equation forms and model weights were tested for predicting seven parameters for each species and region. Thirty-one percent of all region-species combinations are best-fit (as measured by AIC_c values) by log-log (primarily unweighted) equations, followed closely by polynomial quadratic (26 percent), cubic (22 percent), and linear (19 percent) equations (app. 4, table 8). However, there is considerable variation in best-fit equation form among measured and predicted parameter types. For example, d.b.h. to leaf area relationship are typically best described by a log-log relationship (72 percent of the best-fit models across species are log-log equations), while d.b.h. to age relationships are most frequently described by cubic equations (38 percent). There is also variation in best-fit model frequency based on tree type, such as evergreen or deciduous, large, medium or small, and broadleaf, conifer, or palm. For example, the relationship between d.b.h. and tree height is most frequently best fit with quadradic models (50 percent) in medium coniferous evergreen species, but small coniferous evergreen species are best fit with linear models (83 percent). Meanwhile, log-log models are the most frequently chosen models for medium broadleaf deciduous species (43 percent).

Table 7—Example of equations for predicting tree-growth parameters by species and predicted parameter in Northern California Coast climate zone

Species	Ind. var.	Pred.[a]	Model weight[b]	EqName[c]	A	b	c or mse	d	e	Apps min	Apps max	Sigma	No.	adj R2	DF
ACME	dbh	age	1/dbh	quad	-0.07717	1.03847	-0.00387			1	74	1.13403	35	0.941	32
ACME	cdia	dbh	1/cdia^2	quad	0.48486	2.88322	0.17048			2.78	99.02	1.28772	31	0.927	28
ACME	dbh	crown dia	1/sqrt(dbh)	quad	0.72517	0.23255	-0.00072			1.37	16.71	0.31444	31	0.941	28
ACME	dbh	crown ht	1/sqrt(dbh)	log-logw2	0.33845	1.43614	0.01374			2.14	13.47	0.1172	31	0.911	29
ACME	age	dbh	1/age^2	cub	2.85114	-0.12224	0.05596	-0.0005		2.78	99.03	0.11337	35	0.907	31
ACME	dbh	leaf area	1	log-logw1	0.38175	3.72792	0.30567			6.38	491.2	0.55287	25	0.895	23
ACME	dbh	tree ht	1/sqrt(dbh)	log-logw2	0.50713	1.54757	0.00894			2.6	18.45	0.09454	31	0.948	29
ACPA	dbh	age	1/dbh	cub	-2.14827	1.39244	0.00738	-0.00021		0	64	0.70595	38	0.97	34
ACPA	cdia	dbh	1/cdia^2	lin	-0.767	4.15225				2.85	47.38	0.67011	35	0.931	33
ACPA	dbh	crown dia	1	log-logw1	-1.01932	2.48188	0.03998			0.78	10.57	0.19994	35	0.928	33
ACPA	dbh	crown ht	1/dbh	lin	0.90353	0.11475				1.23	6.34	0.05462	35	0.771	33
ACPA	age	dbh	1/age^2	cub	2.84767	0.23083	0.02511	-0.00028		2.85	47.39	0.02437	38	0.944	34
ACPA	dbh	leaf area	1	log-logw1	-2.21556	5.79413	0.37159			1.3	368.78	0.60958	33	0.888	31
ACPA	dbh	tree ht	1/sqrt(dbh)	lin	2.02054	0.15818				2.47	9.52	0.36403	35	0.819	33

ACME, ACPA = *Acacia melanoxylon* and *Acer palmatum*, respectively.

[a] Units of predicted components: age = years, dbh = centimeters, crown dia = meters, crown height = meters, la = m^2.

[b] Model components: dbh = diameter at breast height, crown dia = crown diameter, crown ht = crown height, tree ht = tree height, la = leaf area, Ind.var. = independent variable; Pred. = predicts component; EqName = equation name referring to equations in table 3.

[c] Log-log and exponential models require an input for mean-squared-error (mse), which is listed in column "c or mse" (do not calculate and use $sigma^2$).

Table 8—Percentage frequency of best-fit equation forms by measured/predicted parameter and tree type

Relationship	BDL	BDM	BDS	BEL	BEM	BES	CEL	CEM	CES	PEL	PEM	PES	Total
							Percent						
Age to d.b.h.:													
cub	33	26	16	33	25	5	12	67	6				27
expow	0	2	0	0	0	0	0	0	0				0
lin	24	35	50	33	36	58	36	6	12				31
log-log	9	11	18	3	3	0	16	22	82				13
quad	34	26	16	30	36	37	36	6	0				28
quart	0	0	0	0	0	0	0	0	0				0
Total													100
Crown diameter to d.b.h.:													
cub	35	25	8	21	33	21	28	22	0				26
expow	1	0	5	0	0	0	0	0	0				1
lin	11	21	39	24	33	26	36	50	12				23
log-log	35	33	34	42	28	37	28	17	82				35
quad	19	21	13	12	6	16	8	11	6				15
quart	0	0	0	0	0	0	0	0	0				0
Total													100
D.b.h. to age:													
cub	43	37	32	27	42	32	28	6	94				38
expow	1	0	5	0	0	0	4	0	0				1
lin	23	19	29	21	17	21	24	28	6				22
log-log	7	14	18	12	17	26	12	50	0				14
quad	26	30	16	39	25	21	32	17	0				25
quart	0	0	0	0	0	0	0	0	0				0
Total													100
D.b.h. to crown diameter:													
cub	29	21	24	12	3	0	16	0	0	14	93	33	22
expow	0	0	0	3	0	0	0	0	0	0	0	0	0
lin	6	25	26	9	25	32	36	28	18	7	0	0	16
log-log	31	26	24	15	25	47	24	17	0	0	0	0	23
quad	34	28	26	61	47	21	24	56	82	79	7	53	38
quart	0	0	0	0	0	0	0	0	0	0	0	13	0
Total													100

Table 8—Percentage frequency of best-fit equation forms by measured/predicted parameter and tree type (continued)

Relationship	BDL	BDM	BDS	BEL	BEM	BES	CEL	CEM	CES	PEL	PEM	PES	Total
							Percent						
D.b.h. to crown height													
cub	13	9	3	15	6	0	8	22	0	14	73	33	13
expow	0	2	8	0	8	21	8	0	12	0	0	0	4
lin	17	25	45	18	36	42	40	22	82	7	0	0	26
log-log	29	35	29	36	25	26	16	6	6	0	0	0	24
quad	40	30	16	30	25	11	28	50	0	79	27	53	33
quart	0	0	0	0	0	0	0	0	0	0	0	13	0
Total													100
D.b.h. to leaf area:													
cub	5	5	5	9	3	0	8	39	0	100	73	93	15
expow	1	2	0	3	6	5	0	0	12	0	0	0	2
lin	1	2	5	3	0	0	0	0	0	0	0	0	1
log-log	85	75	87	67	81	89	84	44	88	0	0	0	72
quad	8	16	3	18	11	5	8	17	0	0	27	7	10
quart	0	0	0	0	0	0	0	0	0	0	0	0	0
Total													100
D.b.h. to tree height:													
cub	18	12	5	15	6	0	24	17	0	7	93	33	16
expow	0	0	8	3	8	21	0	6	0	0	0	0	3
lin	10	12	29	9	8	5	16	22	82	0	0	0	14
log-log	33	33	42	36	36	47	28	6	18	7	0	0	30
quad	39	42	16	36	42	26	32	50	0	86	7	20	35
quart	0	0	0	0	0	0	0	0	0	0	0	47	2
Total													100

Tree types: BDL = broadleaf deciduous large, BDM = broadleaf deciduous medium, BDS = broadleaf deciduous small, BEL = broadleaf evergreen large, BEM = broadleaf evergreen medium, BES = broadleaf evergreen small, CEL = conifer evergreen large, CEM = conifer evergreen medium, CES = conifer evergreen small, PEL = palm evergreen large, PEM = palm evergreen medium, PES= palm evergreen small.

Appendix 5: User Guide

This guide provides step-by-step instructions on how to use the allometric equations to estimate tree component dimensions. Predicted parameters included using tree age to predict diameter at breast height (d.b.h.); using d.b.h. to predict tree height, crown height, crown diameter, and leaf area. In addition, crown diameter was used to predict d.b.h., and age from d.b.h. The guide is divided into sections based on the tree components that are to be estimated. In the first section, we show tree diameter, height, crown dimensions, and leaf area from d.b.h. and/or tree height. In the second section, we demonstrate how to estimate dry-weight biomass and carbon using the table of equations presented in appendix 5. Lastly, we present a case study that illustrates the importance of developing region-specific growth models.

Calculating Bole Diameter and Height, Crown Dimensions, and Leaf Area

Example 1. Calculating d.b.h. and tree height from tree age (d.b.h. and height not measured).

In this example, we aim to predict tree dimensions d.b.h., tree height, crown diameter, crown height, and leaf area for a 33-year-old *Liquidambar styraciflua* (American sweetgum) in the Northern California Coast (NoCalC) region.

Step 1. Look up the species and region specific age to d.b.h. equation in table S5 in the online supplement at http://dx.doi.org/10.2737/RDS-2016-0005. The equation name is "quad" for which the equation form is listed in table 3:

d.b.h. (*Liquidambar styraciflua* in NoCalC) = $a + b \times age + c \times age^2$

d.b.h. = $2.80359 + 1.29151 \times 33 + 0.00299 \times (33)^2 = 42.2$ cm

Step 2. Calculate tree height (ht) from d.b.h. by looking up the equation name and coefficients in table S5 and equation form (cubic) in table 3:

ht (*Liquidambar styraciflua* in NoCalC) = $a + b \times dbh + c \times dbh^2 + d \times dbh^3$

ht = $0.57478 + 0.62687 \times 42.16 + (-0.00837) \times (42.2)^2 + 0.00004 \times (42.2)^3 = 15.1$ m

Having calculated tree d.b.h (and in some cases tree height), it is now possible to skip ahead to section 2 if the goal is to estimate dry-weight biomass and carbon storage/sequestration. To estimate other tree dimensions, continue with steps 3 through 6.

Step 3. Calculate crown diameter (cdia) from d.b.h. by looking up the equation name and coefficients in table S5 and equation form (cubic) in table 3:

cdia (*Liquidambar styraciflua* in NoCalC) = $a + b \times dbh + c \times dbh^2$

cdia = $0.42238 + 0.29796 \times 42.2 + (-0.00131) \times 42.2^2 = 10.7$ m

Step 4. Calculate crown height (cht) from d.b.h. by looking up the equation name and coefficients in table S5 and equation form in table 3:

cht (*Liquidambar styraciflua* in NoCalC) = $a + b \times dbh + c \times dbh^2 + d \times dbh^3$

$cht = (-0.54095) + 0.53287 \times 42.2 + (-0.00872) \times 42.2^2 + 0.00005 \times 42.2^3 = 10.2$ m

Step 5. Calculate leaf area (la) from d.b.h. by looking up the equation name and coefficients in table S5 and equation form (log-log) in table 3:

$la = e^{(a + b \times \ln(\ln(dbh + 1)) + (mse/2))}$

$la = e^{(-1.47634) + 5.49634 \times LN(LN(42.2+1)) + (0.29671/2))} = 413.2\ m^2$

where e is a mathematical constant equal to 2.71828182845904, the base of the natural logarithm.

Step 6. To calculate foliar biomass (fb), multiply leaf area (m^2) from step 4 by the average foliar biomass factor (g/m^2 leaf area) in appendix 3:

fb = leaf area × average foliar biomass factor

fb = 413.2 m^2 × 125.75 (g/m^2) = 51959.9 g

Estimating Dry-Weight Biomass and Carbon

To estimate the aboveground volume of wood in a tree, measured tree size data are used with biomass equations. While the growth equations are region-specific, biomass equations are not. Biomass equations are presented for 26 open-grown urban trees species (table 9). Most of these equations are compiled from literature sources described in the table, while the general equations (Urb Gen Broadleaf and Urb Gen Conifer) were developed through data collection and analyses. To be consistent with equations used in the Urban Forest Project Protocols (Climate Action Reserve 2008) for carbon projects, mass is not included in the formulations. All urban equations predict aboveground volume in square meters per tree. To convert from volume to dry-weight (DW) biomass, the predicted volume is multiplied by a DW density factor (table 9).

In addition to equations developed specifically for urban trees, biomass equations have been adapted from literature on rural forest biomass and applied for use in the urban setting (table 10). These equations may produce either volume or DW biomass directly. Equations predicting DW biomass directly do not need to be multiplied by a DW density factor.

Complete listings of equations are available in tables 9 and 10 (downloadable as tables S6 and S7). All equations are listed in an Excel-ready form so they may be copied and pasted into an Excel cell. Measurements required for using the biomass equations are either d.b.h. and tree height, or d.b.h. alone. If data availability permits, it is recommended that users select the d.b.h. and height equations over the d.b.h. only equations as they tend to produce more accurate results, particularly for trees with crowns that have been heavily pruned or topped.

Table 9—Volume equations for 26 urban tree species requiring diameter at breast height (d.b.h.) (cm) only or d.b.h. (cm) and height (m) measurements to calculate volume

Equation species	SpCode	D.b.h. range	Equation[a]	Predicts[b]	DW density	Equation source[c]
D.b.h. and height:		*Centimeters*				
Acacia longifolia	ACLO	15 to 57	=0.0000904 × dbhcm^2.18649 × htm^0.46736	V	510	3
Acer platanoides	ACPL	10 to 102	=0.001011 × dbhcm^1.533 × htm^0.657	V	520	2
Acer saccharinum	ACSA1	13 to 135	=0.0002383 × dbhcm^1.998 × htm^0.596	V	440	2
Celtis occidentalis	CEOC	11 to 119	=0.0022451 × dbhcm^2.118 × htm^ to 0.447	V	490	2
Ceratonia siliqua	CESI3	16 to 74	=0.0001368 × dbhcm^1.79584 × htm^0.92667	V	520	3
Cinnamomum camphora	CICA	13 to 69	=0.0000807 × dbhcm^2.1348 × htm^0.63404	V	520	3
Cupressus macrocarpa	CUMA	16 to 147	=0.0000419 × dbhcm^2.2604 × htm^0.6301	V	410	3
Eucalyptus globulus	EUGL	116 to 130	=0.0000318 × dbhcm^2.15182 × htm^0.83573	V	620	3
Fraxinus pennsylvanica	FRPE	15 to 123	=0.0004143 × dbhcm^1.847 × htm^0.646	V	530	2
Fraxinus velutina 'Modesto'	FRVE_G	15 to 85	=0.0000385 × dbhcm^1.76296 × htm^1.42782	V	510	3
Gleditsia triacanthos	GLTR	9 to 98	=0.0004891 × dbhcm^2.132 × htm^0.142	V	600	2
Gymnocladus dioicus	GYDI	10 to 37	=0.000463 × dbhcm^1.545 × htmet^0.792	V	530	2
Jacaranda mimosifolia	JAMI	17 to 60	=0.0000801 × dbhcm^2.18578 × htm^0.548045	V	490	3
Liquidambar styraciflua	LIST	14 to 54	=0.0000631 × dbhcm^2.31582 × htm^0.41571	V	460	3
Magnolia grandiflora	MAGR	15 to 74	=0.0000504 × dbhcm^2.07041 × htm^0.84563	V	460	3
Pinus radiata	PIRA	17 to 105	=0.0000419 × dbhcm^2.226808 × htm^0.668993	V	400	3
Pistacia chinensis	PICH	13 to 51	=0.0000329 × dbhcm^2.19157 × htm^0.94367	V	685	3
Platanus × acerifolia	PLAC	16 to 74	=0.0000485 × dbhcm^2.43642 × htm^0.39168	V	500	3
Populus sargentii	POSA	6 to 137	=0.0019055 × dbhcm^1.806 × htm^0.134	V	370	2
Quercus ilex	QUIL2	13 to 52	=0.0000789 × dbhcm^1.82158 × htm^1.06269	V	820	3
Quercus macrocarpa	QUMA1	11 to 100	=0.0001689 × dbhcm^1.956 × htm^0.842	V	580	2
Tilia cordata	TICO	11 to 65	=0.0009453 × dbhcm^1.617 × htm^0.59	V	420	2
Ulmus americana	ULAM	18 to 114	=0.0012 × dbhcm^1.696 × htm^0.405	V	460	2
Ulmus parvifolia	ULPA	17 to 56	=0.0000609 × dbhcm^2.32481 × htm^0.49317	V	730	3
Ulmus pumila	ULPU	16 to 132	=0.000338 × dbhcm^0.855 × htm^2.041	V	540	2
Zelkova serrata	ZESE	15 to 86	=0.0000401 × dbhcm^2.36318 × htm^0.5519	V	520	3
Urban Gen broadleaf	UGEB	6 to 135	=0.0001967 × dbhcm^1.951853 × htm^0.664255	V	Jenkins, DRYAD[d]	1
Urban Gen conifer	UGEC	16 to 147	=0.0000426 × dbhcm^2.24358 × htm^0.64956	V	Jenkins, DRYAD[d]	1

Table 9—Volume equations for 26 urban tree species requiring diameter at breast height (d.b.h.) (cm) only or d.b.h. (cm) and height (m) measurements to calculate volume (continued)

Equation species	SpCode	D.b.h. range	Equation[a]	Predicts[b]	DW density	Equation source[c]
D.b.h. only:						
Acacia longifolia	ACLO	15 to 57	=0.000154 × dbhcm^2.34725	V	510	3
Acer platanoides	ACPL	10 to 102	=0.0019421 × dbhcm^1.785	V	520	2
Acer saccharinum	ACSA1	13 to 135	=0.000363 × dbhcm^2.292	V	440	2
Celtis occidentalis	CEOC	11 to 119	=0.0014159 × dbhcm^1.928	V	490	2
Ceratonia siliqua	CESI3	16 to 74	=0.0002579 × dbhcm^2.128861	V	520	3
Cinnamomum camphora	CICA	13 to 69	=0.0000839 × dbhcm^2.53466	V	520	3
Cupressus macrocarpa	CUMA	16 to 147	=0.0000985 × dbhcm^2.495263	V	410	3
Eucalyptus globulus	EUGL	116 to 130	=0.000161 × dbhcm^2.43697	V	620	3
Fraxinus pennsylvanica	FRPE	15 to 123	=0.0005885 × dbhcm^2.206	V	530	2
Fraxinus velutina 'Modesto'	FRVE_G	15 to 85	=0.000054 × dbhcm^2.633462	V	510	3
Gleditsia triacanthos	GLTR	9 to 98	=0.0005055 × dbhcm^2.22	V	600	2
Gymnocladus dioicus	GYDI	10 to 37	=0.0004159 × dbhcm^2.059	V	530	2
Jacaranda mimosifolia	JAMI	17 to 60	=0.0001005 × dbhcm^2.486248	V	490	3
Liquidambar styraciflua	LIST	14 to 54	=0.0000799 × dbhcm^2.560469	V	460	3
Magnolia grandiflora	MAGR	15 to 74	=0.0000559 × dbhcm^2.622015	V	460	3
Pinus radiata	PIRA	17 to 105	=0.0000469 × dbhcm^2.666079	V	400	3
Pistacia chinensis	PICH	13 to 51	=0.0000392 × dbhcm^2.808625	V	685	3
Platanus × *acerifolia*	PLAC	16 to 74	=0.000059 × dbhcm^2.673578	V	500	3
Populus sargentii	POSA	6 to 137	=0.0020891 × dbhcm^1.873	V	370	2
Quercus ilex	QUIL2	13 to 52	=0.0000627 × dbhcm^2.607285	V	820	3
Quercus macrocarpa	QUMA1	11 to 100	=0.0002431 × dbhcm^2.415	V	580	2
Tilia cordata	TICO	11 to 65	=0.0009359 × dbhcm^2.042	V	420	2
Ulmus americana	ULAM	18 to 114	=0.0018 × dbhcm^1.869	V	460	2
Ulmus parvifolia	ULPA	17 to 56	=0.000069 × dbhcm^2.639347	V	730	3
Ulmus pumila	ULPU	16 to 132	=0.0048879 × dbhcm^1.613	V	540	2
Zelkova serrata	ZESE	15 to 86	=0.0000502 × dbhcm^2.674757	V	520	3
Urban Gen broadleaf	UGEB	6 to 135	=0.0002835 × dbhcm^2.310647	V	Jenkins, DRYAD[d]	1
Urban Gen conifer	UGEC	16 to 147	=0.0000698 × dbhcm^2.578027	V	Jenkins, DRYAD[d]	1

[a] dbhcm = diameter at breast height in centimeters; htm = tree height in meters; dwdensity = dry weight-density factor.
[b] DWdensity = dry weight biomass in kg/ m^3 ; V = aboveground volume in cubic meters per tree.
[c] Equation source: 1 = Aguaron and McPherson 2012; 2 = Lefsky and McHale 2008; 3 = Pillsbury et al. 1998.
[d] Look up the dw density factor in McHale et al. (2009) first, but if not available, then the Global Wood Density Database (Zeng 2003).

Table 10—Dry-weight biomass and volume equations derived from rural forests

Equation species	SpCode	D.b.h. range (cm)	Equation[a]	Predicts[b]	Dry-weight density	Equation source[c]
Acer rubrum	ACRU	0 to 35	=0.1970 × dbhcm^2.1933	DW	N/A	6
Fagus grandifolia	FAGR	1 to 60	=0.1957 × dbhcm^2.3916	DW	N/A	6
Fraxinus americana	FRAM	5 to 50	=0.1063 × dbhcm^2.4798-EXP(-4.0813+5.8816/dbhcm)	DW	N/A	6,A
Juniperus virginiana	JUVI	14 to 43	=dbhcm+0.1632 × dbhcm^2.2454-(dbhcm+0.1244 × dbhcm^1.5549)	DW	440	4,B
Liriodendron tulipifera	LITU	5 to 50	=0.0365 × (dbhcm)^2.7324-EXP(-4.0813+5.8816/dbhcm)	DW	N/A	6,A
Melaleuca quinquenervia	MEQU	0.5 to 39	=EXP(-1.83+2.01 × LN(dbhcm))	DW	N/A	7
Quercus agrifolia	QUAG	20 to 140	=0.0000447 × (dbhcm)^2.31958 × (htm)^0.62528	V	590	5
Quercus garryana	QUGA4	20 to 140	=0.0000674 × (dbhcm)^2.14321 × (htm)^0.74220	V	640	5
Quercus lobata	QULO	20 to 140	=0.0000763 × (dbhcm)^1.94165 × (htm)^0.86562	V	550	5
Quercus rubra	QURU	5 to 50	=0.1130 × (dbhcm)^2.4572-EXP(-4.0813+5.8816/dbhcm)	DW	N/A	6,A
Umbellularia californica	UMCA	20 to 140	=0.0000763 × (dbhcm)^1.94553) × (htm)^0.88389	V	510	5
Gen Hdwd aspen/alder/cottonwood/ willow	GNHDAA	12 to 50	=EXP(-2.2094+2.3867 × LN(dbhcm))-EXP(-4.0813+5.8816/dbhcm)	DW	N/A	4,B
Gen Hdwd Harris	GNHDH	>10	=EXP(-2.437+2.418 × LN(dbhcm))+EXP(-3.188+2.226 × LN(dbhcm))	DW	N/A	3
Gen Hdwd maple/oak/hickory/beech	GNHDHM	14 to 34	=EXP(-2.0127+2.4342 × LN(dbhcm))-EXP(-4.0813+5.8816/dbhcm)	DW	N/A	4,B
Gen Hdwd soft maple/birch	GNHDSM	12 to 42	=EXP(-1.9123+2.3651 × LN(dbhcm))-EXP(-4.0813+5.8816/dbhcm)	DW	N/A	4,B
Gen Sftwd cedar/larch	GNSWCL	3 to 61	=EXP(-2.0336+2.2592 × LN(dbhcm))-EXP(-2.9584+4.4766/dbhcm)	DW	N/A	4,B
General Sftwd doug-fir	GNSWDF	3 to 190	=EXP(-2.2304+2.4435 × LN(dbhcm))-EXP(-2.9584+4.4766/dbhcm)	DW	N/A	4,B
Gen Sftwd pine	GNSWP	3 to 99	=EXP(-2.5356+2.4349 × LN(dbhcm))-EXP(-2.9584+4.4766/dbhcm)	DW	N/A	4,B
Gen Sftwd spruce	GNSWS	3 to 78	=EXP(-2.0773+2.3323 × LN(dbhcm))-EXP(-2.9584+4.4766/dbhcm)	DW	N/A	4,B
Gen Sftwd truefir/hemlock	GNSWTF	3 to 111	=EXP(-2.5384+2.4814 × LN(dbhcm))-EXP(-2.9584+4.4766/dbhcm)	DW	N/A	4,B
Gen Trop Chave	GNTRC	4 to 148	=0.112 × ((dw density/1000) × dbhcm^2 × htm)^0.916	DW	Jenkins, DRYAD[d]	1
Gen Wdlnd juniper/oak/mesquite	GNWDJO	NA	=EXP(-0.7152+1.7029 × LN(dbhcm))-EXP(-4.0813+5.8816/dbhcm)	DW	N/A	4,B
Genl palms	GNP	to 17 m ht	=(6 × htm+0.8)+(0.8 × htm+0.9)	DW	N/A	2
Gen spiny dry climate	GNHDV	2 to 32	=EXP(-1.103+1.994 × LN(dbhcm)+0.317 × LN(htm)+1.303 × LN(dwdensity/1000))	DW	Jenkins, DRYAD[d]	8

N/A = not applicable.
[a] dbhcm = diameter at breast height in centimeters; htm = tree height in meters; dwdensity = dry-weight density factor.
[b] DW density = dry-weight biomass in kiligrams per cubic meter; V = aboveground volume in cubic meters per tree.
[c] Equation source: 1 = Chave et al. 2005, 2 = Frangi and Lugo (1985), 3 = Harris et al. (1973), 4 = McHale et al. (2009), 5 = Pillsbury and Kirkley (1984), 6 = Ter-Mikaelian and Korzukhin 1997, 7 = Van et al. 2000, 8 = Vieilledent et al. 2012, A = minus Jenkins foliage, B = minus foliage ratio.
[d] Look up the dry-weight density factor in McHale et al. (2009) first, but if not available, then look it up in the Global Wood Density Database (Zeng 2003).

We developed two general volume equations from the urban species equations, one for urban broadleaf species and one for conifers. These equations can be used if the species of interest cannot be matched taxonomically or through wood form to the species listed in the tables of biomass equations derived from urban or rural forests (table 10). The general equations predict cubic meters of fresh-wood volume. Fresh-wood volume is then multiplied by the species' DW density factor to obtain aboveground DW biomass. The urban general equations require looking up a dry-weight density factor (in Jenkins et al. 2004 first, but if not available then the Global Wood Density Database).

To estimate total carbon and stored carbon dioxide (CO_2) equivalents, dry-weight biomass (either calculated directly or from fresh-wood volume) is converted using constants. The DW biomass is multiplied by 1.28 to incorporate belowground biomass (Husch et al. 2003, Tritton and Hornbeck 1982, Wenger 1984), multiplied by the constant 0.5 to convert to total carbon stored (Leith 1963, Whittaker et al. 1973), and multiplied by the constant 3.67 (molecular weight of CO_2) to convert to total CO_2 stored.

Dry-weight densities are unique to each tree species and can vary extensively among species. Volume equations can be applied to other species based on taxonomy if a species-specific DW density factor is not known. For example, because many of the species measured in each of the reference cities were not represented in tables 9 and 10, it was necessary to assign biomass equations to species for which there were no available data. Table 11 provides examples of species matching for volume or biomass estimation (see column "Equation Species Code" for species to which species without information are matched). If the form of the tree is completely different than any species listed, we recommend using the general equations for urban broadleaf and conifer trees and look up the species-specific dry-weight-wood density value in DRYAD, the Global Wood Density Database (Chave et al. 2005, Frangi and Lugo 1985, Harris et al. 1973, Higuchi et al. 2005, Jenkins et al. 2004, Pillsbury and Kirkley 1984, Ter-Mikaelian and Korzuhkhin 1997, Van et al. 2000, Vieilledent et al. 2012, Zanne et al. 2009, Zeng 2003) available as a downloadable Excel spreadsheet at http://datadryad.org/repo/handle/10255/dryad.235.

Table 11— Expanded list of biomass density factors for common urban species

SpCode	Scientific name	DW density[a]	Matched equation SpCode	Equation source[b]
ACFA	*Acacia farnesiana*	520	ACLO	8
ACLO	*Acacia longifolia*	520	ACLO	8
ACMA	*Acer macrophyllum*	440	ACPL	6
ACME	*Acacia melanoxylon*	573	ACLO	8
ACNE	*Acer negundo*	420	ACPL	6
ACPA	*Acer palmatum*	450	ACPL	6
ACPL	*Acer platanoides*	520	ACPL	6
ACRU	*Acer rubrum*	490	ACRU	9
ACSA1	*Acer saccharinum*	440	ACSA1	6
ACSA2	*Acer saccharum*	560	ACPL	6
ACSA3	*Acacia salicina*	473	ACLO	8
AEHI	*Aesculus hippocastanum*	500	UGEB	1
BABL	*Bauhinia* x *blakeana*	527	GNTRC	2
BENI	*Betula nigra*	490	UGEB	1
BEPE	*Betula pendula*	530	UGEB	1
BRPO	*Brachychiton populneus*	387	UGEB	1
BUCA	*Butia capitata*	370	PRACM	3
CABEF	*Carpinus betulus* 'Fastigiata'	598	UGEB	1
CACI	*Callistemon citrinus*	690	UGEB	1
CADE2	*Calocedrus decurrens*	350	GNSWCL	5,B
CAEQ	*Casuarina equisetifolia*	728	GNTRC	2
CAIL	*Carya illinoinensis*	600	UGEB	1
CAIN4	*Calophyllum inophyllum*	560	GNTRC	2
CANE33	*Cassia* x *nealiae*	670	GNTRC	2
CASP	*Catalpa speciosa*	380	UGEB	1
CECA	*Cercis canadensis*	520	UGEB	1
CEDE	*Cedrus deodara*	410	GNSWCL	5,B
CEFL	*Parkinsonia florida*	619	GNHDV	11
CELA	*Celtis laevigata*	490	CEOC	6
CEOC	*Celtis occidentalis*	490	CEOC	6
CESI3	*Ceratonia siliqua*	520	CESI3	8
CESI4	*Celtis sinensis*	490	CEOC	6
CHLI	*Chilopsis linearis*	600	GNHDV	11
CICA	*Cinnamomum camphora*	520	CICA	8
CISP2	*Citharexylum spinosum*	700	GNTRC	2
COERA2	*Conocarpus erectus* var. *argenteus*	690	GNTRC	2
COFL	*Cornus florida*	640	UGEB	1
CONU	*Cocos nucifera*	520	PRACM	3
COSU2	*Cordia subcordata*	640	GNTRC	2

Table 11— Expanded list of biomass density factors for common urban species (continued)

SpCode	Scientific name	DW density[a]	Matched equation SpCode	Equation source[b]
CR	*Crataegus* species	520	UGEB	1
CRLA80	*Crataegus laevigata*	620	UGEB	1
CUAN	*Cupaniopsis anacardioides*	520	UGEB	1
CUMA	*Cupressus macrocarpa*	410	CUMA	8
DERE	*Delonix regia*	479	GNTRC	2
ELAN	*Elaeagnus angustifolia*	520	UGEB	1
ELOR2	*Elaeodendron orientale*	676	GNTRC	2
ERJA	*Eriobotrya japonica*	520	UGEB	1
EUFI81	*Eucalyptus ficifolia*	794	EUGL	8
EUGL	*Eucalyptus globulus*	620	EUGL	8
EUMI2	*Eucalyptus microtheca*	994	EUGL	8
EUSI	*Eucalyptus sideroxylon*	932	EUGL	8
FAGR	*Fagus grandifolia*	585	FAGR	9
FASYAT	*Fagus sylvatica* 'Atropunicea'	585	FAGR	9
FIBE	*Ficus benjamina*	460	GNTRC	2
FIDE6	*Filicium decipiens*	805	GNTRC	2
FIMI	*Ficus thonningii*	432	GNTRC	2
FRAM	*Fraxinus americana*	550	FRAM	9,A
FRAN_R	*Fraxinus angustifolia* 'Raywood'	510	FRVE_G	8
FRAN2	*Fraxinus angustifolia*	510	FRVE_G	8
FREX_H	*Fraxinus excelsior* 'Hessei'	560	FRVE_G	8
FRHO	*Fraxinus holotricha*	510	FRVE_G	8
FRLA	*Fraxinus latifolia*	500	FRAM	9,A
FRPE	*Fraxinus pennsylvanica*	530	FRPE	6
FRPE_M	*Fraxinus pennsylvanica* 'Marshall'	530	FRPE	6
FRUH	*Fraxinus uhdei*	510	FRPE	6
FRVE	*Fraxinus velutina*	510	FRVE_G	8
FRVE_G	*Fraxinus velutina* 'Modesto'	510	FRVE_G	8
GIBI	*Ginkgo biloba*	520	UGEB	1
GLTR	*Gleditsia triacanthos*	600	GLTR	6
GNHDAA	General hardwood jenkins	N/A	GNHDAA	5,B
GNHDH	General hardwood harris	N/A	GNHDH	4
GNHDHM	General hardwood jenkins	N/A	GNHDHM	5,B
GNHDSM	General hardwood jenkins	N/A	GNHDSM	5,B
GNHDV	General spiny dry vieilledent	N/A	GNHDV	11
GNSWCL	General softwood jenkins	N/A	GNSWCL	5,B
GNSWDF	General softwood jenkins	N/A	GNSWDF	5,B
GNSWP	General softwood jenkins	N/A	GNSWP	5,B
GNSWS	General softwood jenkins	N/A	GNSWS	5,B

Table 11— Expanded list of biomass density factors for common urban species (continued)

SpCode	Scientific name	DW density[a]	Matched equation SpCode	Equation source[b]
GNSWTF	General softwood jenkins	N/A	GNSWTF	5,B
GNTRC	General tropical chave	N/A	GNTRC	2
GNWDJO	General woodland jenkins	N/A	GNWDJO	5,B
GYDI	*Gymnocladus dioicus*	530	UGEB	1
ILOP	*Ilex opaca*	500	UGEB	1
ILPA2	*Ilex paraguariensis*	565	GNTRC	2
JAMI	*Jacaranda mimosifolia*	490	JAMI	8
JUNI	*Juglans nigra*	510	UGEB	1
JUSI	*Juniperus virginiana* var. *silicicola*	420	JUVI	5,B
JUVI	*Juniperus virginiana*	440	JUVI	5,B
KOEL	*Koelreuteria elegans*	595	UGEB	1
KOPA	*Koelreuteria paniculata*	620	UGEB	1
LA6	*Lagerstroemia* species	571	UGEB	1
LAIN	*Lagerstroemia indica*	571	UGEB	1
LASP	*Lagerstroemia speciosa*	612	GNTRC	2
LIST	*Liquidambar styraciflua*	460	LIST	8
LITU	*Liriodendron tulipifera*	400	LITU	9,A
MA2	*Malus* species	610	UGEB	1
MAGR	*Magnolia grandiflora*	460	MAGR	8
MEEX	*Metrosideros excelsa*	1150	UGEB	1
MEQU	*Melaleuca quinquenervia*	520	MEQU	10
MO	*Morus* species	520	UGEB	1
MOAL	*Morus alba*	520	UGEB	1
OLEU	*Olea europaea*	700	UGEB	1
PAAC	*Parkinsonia aculeata*	610	GNHDV	11
PHCA	*Phoenix canariensis*	370	PRACM	3
PHDA4	*Phoenix dactylifera*	370	PRACM	3
PIBR2	*Pinus brutia*	430	UGEC	1
PICA	*Pinus canariensis*	610	UGEC	1
PICH	*Pistacia chinensis*	685	PICH	8
PICO5	*Pinus contorta* var. *bolanderi*	380	UGEC	1
PIEC	*Pinus echinata*	470	UGEC	1
PIED	*Pinus edulis*	500	UGEC	1
PIEL2	*Pinus eldarica*	540	UGEC	1
PIHA	*Pinus halepensis*	460	UGEC	1
PINI	*Pinus nigra*	430	UGEC	1
PIPO	*Pinus ponderosa*	380	UGEC	1
PIPU	*Picea pungens*	360	UGEC	1
PIRA	*Pinus radiata*	400	PIRA	8

Table 11— Expanded list of biomass density factors for common urban species (continued)

SpCode	Scientific name	DW density[a]	Matched equation SpCode	Equation source[b]
PISA2	*Samanea saman*	520	GNTRC	2
PIST	*Pinus strobus*	340	UGEC	1
PISY	*Pinus sylvestris*	430	UGEC	1
PITA	*Pinus taeda*	470	UGEC	1
PITH	*Pinus thunbergiana*	430	UGEC	1
PIUN	*Pittosporum undulatum*	745	UGEB	1
PLAC	*Platanus* × *acerifolia*	500	PLAC	8
PLOC	*Platanus occidentalis*	480	PLAC	8
PLRA	*Platanus racemosa*	480	PLAC	8
POAN	*Populus angustifolia*	350	POSA	6
PODE	*Populus deltoides*	370	POSA	6
POFR	*Populus fremontii*	410	POSA	6
POMA	*Podocarpus macrophyllus*	470	UGEB	1
POSA	*Populus sargentii*	370	POSA	6
POTR2	*Populus balsamifera* ssp. *trichocarpa*	310	POSA	6
PR	*Prunus* species	560	UGEB	1
PRACM	*Prestoea montana*	370	PRACM	3
PRCA	*Prunus caroliniana*	560	UGEB	1
PRCE	*Prunus cerasifera*	470	UGEB	1
PRCEKW	*Prunus cerasifera* ‘Thundercloud’	560	UGEB	1
PRCH	*Prosopis chilensis*	740	GNHDV	11
PRSE2	*Prunus serrulata*	560	UGEB	1
PRYE	*Prunus yedoensis*	470	UGEB	1
PSME	*Pseudotsuga menziesii*	450	GNSWDF	5,B
PY	*Pyrus* species	600	UGEB	1
PYAN	*Malus angustifolia*	610	UGEB	1
PYCA	*Pyrus calleryana*	600	UGEB	1
PYCA_B	*Pyrus calleryana* ‘Bradford’	600	UGEB	1
PYKA	*Pyrus kawakamii*	600	UGEB	1
QUAG	*Quercus agrifolia*	590	QUAG	7
QUAL	*Quercus alba*	600	QUGA4	7
QUGA4	*Quercus garryana*	640	QUGA4	7
QUIL2	*Quercus ilex*	820	QUIL2	8
QULA2	*Quercus laurifolia*	560	QULO	7
QULO	*Quercus lobata*	550	QULO	7
QUMA1	*Quercus macrocarpa*	580	QUMA1	6
QUNI	*Quercus nigra*	560	QUAG	7
QUPA	*Quercus palustris*	580	QUAG	7
QUPH	*Quercus phellos*	560	QUAG	7

Table 11— Expanded list of biomass density factors for common urban species (continued)

SpCode	Scientific name	DW density[a]	Matched equation SpCode	Equation source[b]
QURU	*Quercus rubra*	560	QURU	9,A
QUSH	*Quercus shumardii*	590	QUAG	7
QUVI	*Quercus virginiana*	800	QUGA4	7
RHLA	*Rhus lancea*	540	GNHDV	11
ROPS	*Robinia pseudoacacia*	660	GLTR	6
SAPA	*Sabal palmetto*	520	PRACM	3
SCMO	*Schinus molle*	650	UGEB	1
SCTE	*Schinus terebinthifolius*	650	UGEB	1
SESE	*Sequoia sempervirens*	360	GNSWCL	5,B
SWMA	*Swietenia mahagoni*	750	GNTRC	2
SYRO	*Syagrus romanzoffiana*	370	PRACM	3
TAAR	*Tabebuia aurea*	520	GNTRC	2
TACH	*Tabebuia ochracea* subsp. *neochrysantha*	960	GNTRC	2
TAPA	*Tabebuia heterophylla*	520	GNTRC	2
THOR	*Platycladus orientalis*	527	UGEC	1
TIAM	*Tilia americana*	320	TICO	6
TICO	*Tilia cordata*	420	TICO	6
TITO	*Tilia tomentosa*	320	TICO	6
TRCO	*Tristaniopsis conferta*	750	UGEB	1
TRSE6	*Triadica sebifera*	520	UGEB	1
UGEB	Urban general broadleaf	DRYAD[c]	UGEB	1
UGEC	Urban general conifer	DRYAD[c]	UGEC	1
ULAL	*Ulmus alata*	600	ULPU	6
ULAM	*Ulmus americana*	460	ULAM	6
ULPA	*Ulmus parvifolia*	730	ULPA	8
ULPU	*Ulmus pumila*	540	ULPU	6
UMCA	*Umbellularia californica*	510	UMCA	7
VEME	*Veitchia merrillii*	370	PRACM	3
WAFI	*Washingtonia filifera*	370	PRACM	3
WARO	*Washingtonia robusta*	370	PRACM	3
ZESE	*Zelkova serrata*	520	ZESE	8

Notes: Species without a specific equation or dry-weight density factor are matched to known species. N/A = not applicable.

[a] DW density = dry-weight biomass kilograms per cubic meter.

[b] Equation source: 1 = Aguaron and McPherson 2012, 2 = Chave et al. 2005, 3 = Frangi and Lugo 1985, 4 = Harris et al. 1973, 5 = Jenkins et al. 2004, 6 = Lefsky and McHale 2008, 7 = Pillsbury and Kirkley 1984, 8 = Pillsbury et al. 1998, 9 = Ter-Mikaelian and Korzukhin 1997, 10 = Van et al. 2000, 11 = Vieilledent et al. 2012, A = minus Jenkins foliage, B = minus foliage ratio.

[c] For equations UGEC and UGEB, look up correct dry-weight density factor for species of interest in DRYAD (the Global Wood Density Database).

Example 2. Calculating dry-weight biomass and carbon stored based on either calculated or measured d.b.h. and/or tree height.

Once d.b.h. and height have been measured or calculated (as in example 1), the next step entails using either d.b.h. or d.b.h. and height to calculate the dry-weight biomass. For species assigned biomass equations, skip to example 3. For species assigned volumetric equations, follow this example.

In this example, we continue with a sample tree *Liquidambar styraciflua* (sweetgum) located in the Northern California Coast region. It is 33 years of age and has an estimated d.b.h. equal to 42.2 cm and tree height equal to 15.3 m, as calculated in example 1.

Step 1. Select the equation for d.b.h. and height to calculate aboveground fresh wood volume (table 9). Fresh-wood volume in cubic meters (V) for a 15.3-m tall sweetgum with a 42.2-cm d.b.h. is calculated as:

$$V = 0.0000631 \times (42.2)^{2.31582} \times (15.1)^{0.41571} = 1.13 \text{ m}^3$$

Note that the volumetric equations are not region specific, so the fact that our sample tree is located in the Northern California Coast region does not play a role in this example. If the tree had not been measured and we were predicting d.b.h. and/or ht from age or d.b.h., we would need to select a region-specific growth equation.

Step 2. Convert from fresh-wood volume to dry-weight biomass by multiplying V by the species-specific DW density factor, which for sweetgum is 460 kg/m^3 (from table 9)

$$DW = 1.13 \text{ m}^3 \times 460 \text{ kg/m}^3 = 519.80 \text{ kg}$$

Step 3. Thus far, we have calculated the biomass for the aboveground portion of the tree. To convert from DW biomass to carbon stored, the belowground biomass should be incorporated. The biomass stored belowground is calculated by multiplying the DW biomass by 1.28:

$$\text{Total DW} = 519.80 \text{ kg} \times 1.28 = 665.34 \text{ kg}$$

Step 4. Next, the DW biomass is converted into kilograms of carbon (C) by multiplying by the constant 0.5:

$$C = 665.34 \text{ kg} \times 0.5 = 332.67 \text{ kg}$$

Step 5. Convert stored carbon into stored carbon dioxide (CO_2) by multiplying by the constant 3.67 as follows:

$$CO_2 = 332.67 \text{ kg} \times 3.67 = 1220.89 \text{ kg}$$

Note that in this case, results were rounded at each step. Users will achieve slightly different results when using Excel or programming language to calculate the final amounts.

Example 3. Estimating DW biomass directly from tree size parameters.

In this variation of example 2, we measure a *Liriodendron tulipifera*, which has a d.b.h. of 35.0 cm. Select the equation from table 10 for estimating the direct DW biomass of this species. The calculation is as follows:

$DW = 0.0365 \times (35.0)^{2.7324} - e^{(-4.0813+5.8816/35.0)} = 604.4$ kg

where e is a mathematical constant equal to 2.71828182845904.

To estimate total DW, total carbon stored, and CO_2 stored, continue with steps 3 through 5 in example 2.

Error in Predicting Future Growth, Carbon, and Biomass

The volume equations were developed from trees that may differ in size from the trees in the user's sample or inventory. The d.b.h. ranges for trees sampled to develop the volume and biomass equations are listed in columns labelled "Dbh lower (cm)" and "Dbh upper (cm)" (tables 9 and 10). Applying the equations to trees with d.b.h. outside of this range may increase the prediction error. Tree growth as modelled or estimated by the user may deviate significantly from tree growth models generalized here. In general, it is better to err on the side of underestimating carbon stocks rather than overestimating. Recommended ways of evaluating the growth data presented here include contacting local arborists and other tree experts (e.g., university extension offices, city tree managers) or from repeated measurements of inventoried trees.

Case Study

To demonstrate the species-level differences in d.b.h., tree height, and total carbon across regions, we selected the top three species most commonly measured in the 17 reference cities (16 reference cities and SacVal): *Acer saccharinum* (silver maple), *Liquidambar styraciflua (*sweetgum), and *Magnolia grandiflora* (southern magnolia). We estimated the d.b.h., tree height, and total carbon at 10-year intervals up to the maximum age recommended for the application of the developed equations (i.e., "AppMax"). Silver maple was measured in 7 reference cities, southern magnolia in 8 cities, and sweetgum in 12 cities.

At age 40, the oldest age for which data were available across regions, the estimated total carbon stored in silver maple was between 378.1 kg in the Northeast and 4505.6 kg in the Midwest regions, an 11-fold difference (fig. 17). Estimated d.b.h range was between 34.8 cm in Northeast and 101.6 cm in the Midwest; tree height ranged from 13.3 m in Northeast and 23.4 m in Midwest (table 12). The growth patterns of silver maple are similar in three regions: Inland Valley, North, Tropical Interior West and Lower Midwest, where there is only a twofold difference at age 40. Over the same time period, the quickest accumulation of carbon in silver

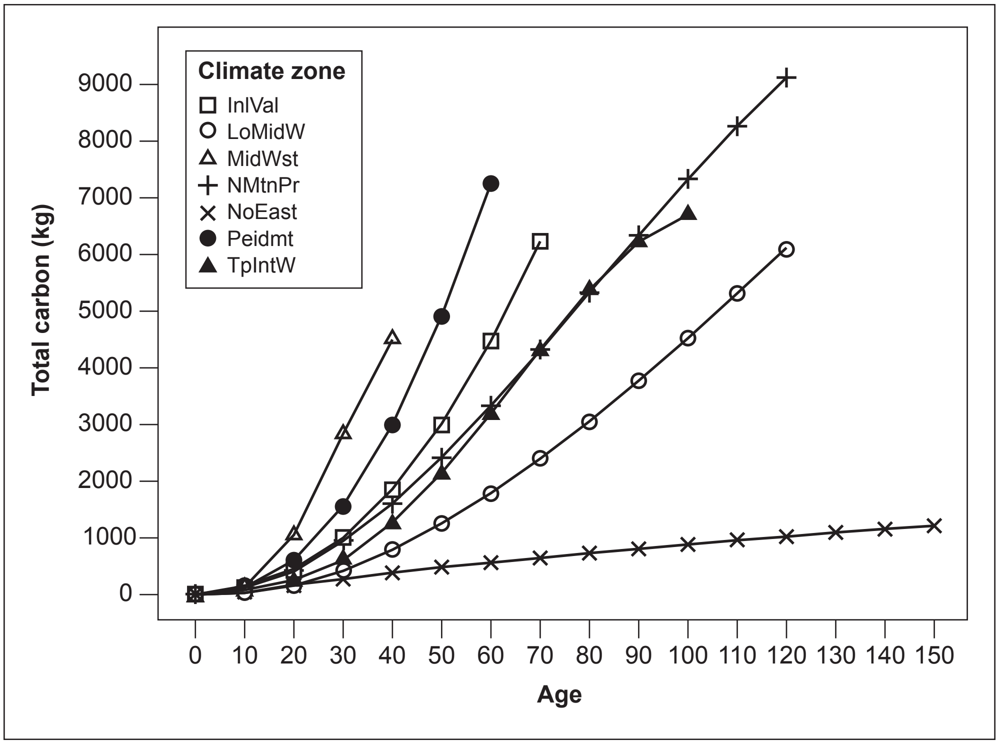

Figure 17—Total stored carbon by age for silver maple in regions where it was measured.

maple occurred in the Midwest and South. Silver maple growing in the Northeast is on the lowest trajectory for carbon stored, amounting to only 1222.3 kg at the oldest age for which the growth equations could be applied, age 150.

Of the regions and reference cities in which sweetgum is planted abundantly, the highest amount of carbon stored was in the southeastern region of the United States followed by regions in California (Northern California Coast; Inland Valleys including Sacramento Valley; Inland Empire) (fig. 18). Sweetgum in the Northeast and Southern California Coast stored noticeably less carbon than in the other regions as trees grew older. At age 60, the difference between highest and lowest estimates of carbon storage was ninefold, ranging from 238.6 kg in Southern California Coast (d.b.h. = 37.3; tree height = 13.3 m) to 5451.5 kg in the South region (d.b.h. = 121.4 cm; tree height = 34.8 m (fig. 18; table 13).

The regional differences in total carbon stored by magnolia become evident within 30 years of planting, with trees in Central Florida, South (Piedmont), Coastal Plain, and Sacramento Valley increasing at a faster rate than in Southern California Coast, Northern California Coast, and Inland Valleys (fig. 19). It takes magnolia approximately 30 additional years in Northern California Coast to attain similar levels of total carbon storage amount as in Central Florida and South regions. By age 50, the oldest age for which estimates were available across regions, magnolia is

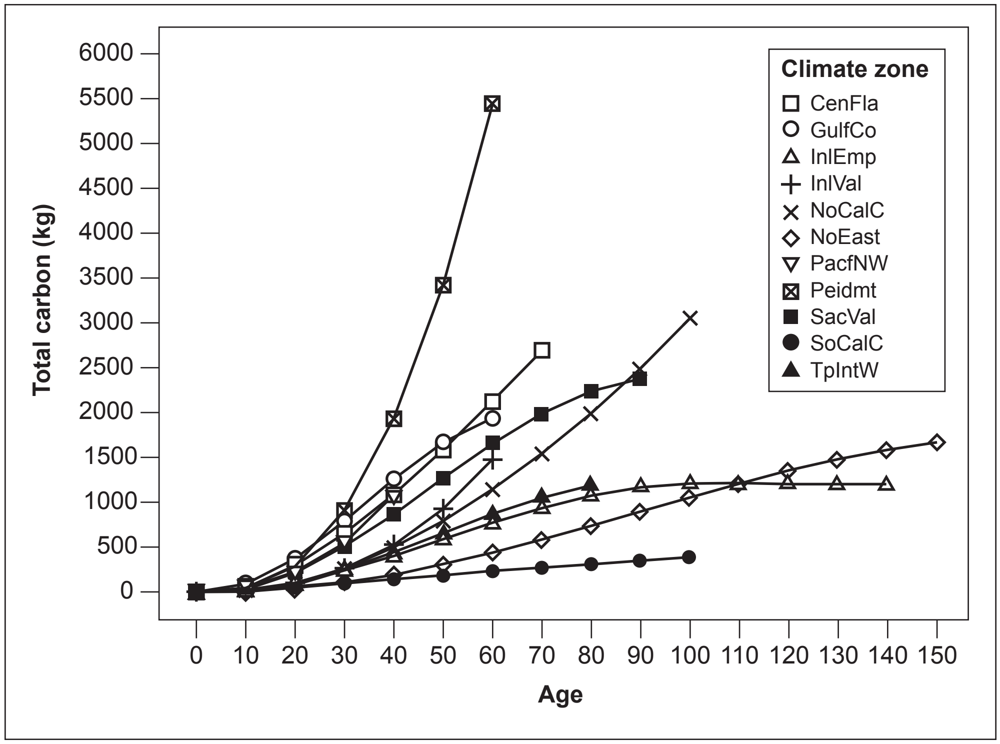

Figure 18—Total stored carbon by age for sweetgum in regions where it was measured.

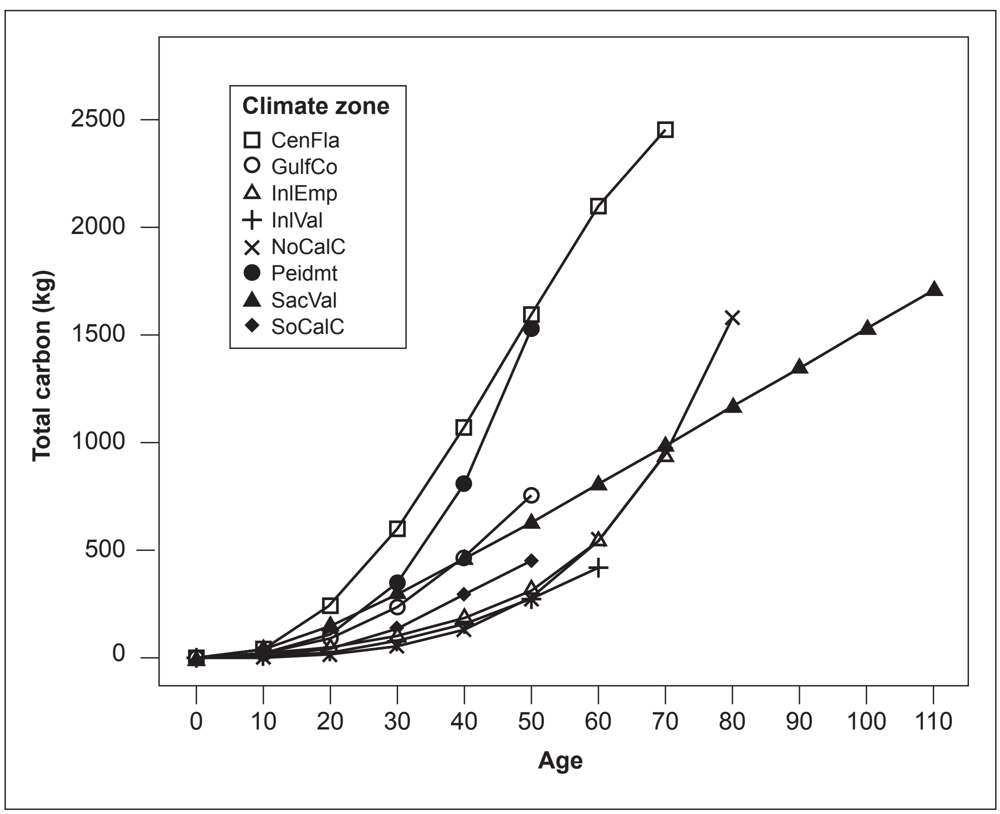

Figure 19—Total stored carbon by age for southern magnolia in regions where it was measured.

expected to accumulate six times more carbon in the Central Florida (1596.2 kg) than in the Inland Valleys region (271.9 kg), nearly a sixfold difference. Estimated d.b.h ranged from 41.2 cm (tree height = 12.2 m) in the Inland Valleys to 97.8 cm in Central Florida region (tree height = 15.7 m) (table 14).

Species that are highly abundant in the reference cities (i.e., silver maple, sweetgum, and magnolia) accumulated carbon at a higher rate in the southeastern regions of the Unites States, namely South, Central Florida, and Coastal Plain regions. The ability of trees to store a large amount of carbon in the southeastern United States is likely due in part to the combination of high precipitation (>1300 mm per year), high temperatures in the summer and relatively warm temperatures in the winter (cooling degree days [CDD] > 847; heating degree days [HDD] < 2000), and long growing seasons. Central Florida, for example, has low HDD and high CDD, signifying a warm climate year round, where cooling would be required in the summers, but heating would not be needed as much in the winter.

Another region in which our case study species have accumulated relatively large amounts of carbon is the Midwest. This is surprising owing to the shorter growing seasons and cooler temperatures. One factor that likely played a role was the lack of limitations on growing space in Minneapolis, Minnesota. Very few sites had visible limitations on growth. In contrast, in Queens, New York city, only 44 percent of the sites had no apparent limitations. The species analyzed in our case study accumulated consistently less carbon in Queens than in the other reference cities. Santa Monica, reference city for the Southern California Coast region, also had lower estimates of carbon storage by sweetgum, likely resulting from too heavy pruning owing to hazard potentials (e.g., trees planted very close to curbs on busy commercial boulevards) (personal communication, P. Peper). Additional regions that had lower total carbon storage were the Inland Empire, Inland Valleys, and Lower Midwest. Although the inland regions of California have many warm days conducive to plant growth, low precipitation can result in high evaporative demand. Prolonged drought stress can restrict tree growth and carbon storage (Anderegg et al. 2015). For example, in the Inland Valleys region, CDD is 3153 mm, but annual precipitation is only 315 mm, most of which comes during the leaf-off season.

Table 12—Diameter at breast height (d.b.h.) and tree height estimates for *Acer saccharinum* in regions where these species were measured

Age	Inland Valleys	Lower Midwest	Midwest	North	Northeast	South	Temperate Interior West
Year	*Diameter at breast height (cm)*						
0	2.5	1.4	2.2	2.8	2.2	1.3	4
10	19	10	22.5	19.6	16.5	22.4	15.2
20	35.5	23.5	52.6	35.5	24.8	43.5	28.4
30	52	36.2	81.4	50.3	30.4	64.6	42.8
40	68.5	48	101.6	64.2	34.8	85.7	57.9
50	85	58.9		77.2	38.4	106.7	72.8
60	101.5	69.1		89.1	41.5	127.8	87
70	118	78.7		100.1	44.1		99.7
80		87.8		110.2	46.5		110.3
90		96.4		119.2	48.7		118
100		104.7		127.3	50.6		122.2
110		112.6		134.4	52.4		
120		120.1		140.6	54.1		
130					55.7		
140					57.1		
150					58.5		
	Tree height (m)						
0	2.2	1.3	3	2.8	2	2.6	6.4
10	10.6	6.9	10.4	11.2	9.1	8.7	9.3
20	14.7	11.2	18.3	15	11.3	13.7	12.4
30	17.5	13.8	22.5	17.5	12.5	17.8	15.4
40	19.8	15.7	23.4	19.3	13.3	20.9	18.1
50	21.6	17.1		20.8	13.9	23	20.4
60	23.2	18.2		21.9	14.4	24.2	22.1
70	24.5	19.2		22.9	14.8		23.3
80		20		23.7	15.2		24
90		20.7		24.4	15.5		24.4
100		21.3		24.9	15.7		24.6
110		21.9		25.4	16		
120		22.4		25.8	16.2		
130					16.4		
140					16.6		
150					16.7		

Table 13—Diameter at breast height (d.b.h.) and tree height estimates for *Liquidambar styraciflua* in regions where these species were measured

Age	Central Florida	Coastal Plain	Inland Empire	Inland Valleys	Northeast	Northern CA Coast	Pacific Northwest	Sacramento Valley	South	Southern CA Coast	Temperate Interior West
Year	*Diameter at breast height (cm)*										
0	0.9	2.6	2.5	2.5	3.4	2.8	2	3.7	2.3	1.8	2.8
10	21.9	24.5	15.1	14.5	12.1	15.4	18.4	20.4	18.7	14.9	13.7
20	41	42.9	26.4	26.4	20.2	27.4	34.8	35.3	39.3	22.3	26.1
30	56.2	58	36.3	38.4	27.8	38.9	51.3	48.4	59.8	27.4	36.8
40	68.9	69.7	45	50.3	35	49.7	67.7	59.6	80.3	31.4	46.1
50	80.1	77.9	52.4	62.3	41.6	59.9		69	100.8	34.6	53.8
60	90	82.8	58.4	74.2	47.7	69.5		76.5	121.4	37.3	60
70	99		63.2		53.4	78.5		82.2		39.7	64.7
80			66.6		58.5	87		86		41.9	67.9
90			68.8		63.1	94.8		88.1		43.8	
100			69.6		67.2	102				45.5	
110			69.6		70.8						
120			69.6		73.9						
130			69.6		76.5						
140			69.6		78.6						
150					80.1						
	Tree height (m)										
0	0.6	1.8	2.9	4.8	2.7	2.3	2.4	3.5	1.8	2.6	1.6
10	9.9	12.7	9.2	7.9	5.9	8.4	9.5	10	12.6	7.3	8.1
20	13.6	17.7	12.9	11.1	8.5	12.4	14.5	15.2	19.9	9.6	12.9
30	15.7	20.7	15.2	14.2	10.6	14.8	17.6	19.2	24.9	11	16.2
40	17.2	22.7	16.6	17.4	12.3	16.3	18.6	22.2	28.8	12	18.6
50	18.3	23.9	17.7	20.5	13.7	17.3		24.5	32	12.7	20.3
60	19.2	24.6	18.6	23.7	14.9	18		26.1	34.8	13.3	21.6
70	19.9		19.4		15.9	18.8		27.3		13.8	22.5
80			20		16.8	19.8		28		14.2	23.1
90			20.5		17.6	21.1		28.3		14.6	
100			20.6		18.3	22.7				14.9	
110			20.6		18.9						
120			20.6		19.4						
130			20.6		19.9						
140			20.6		20.2						
150					20.5						

Table 14—Diameter at breast height (d.b.h.) and tree height estimates for *Magnolia grandiflora* in regions where these species were measured

Age	Central Florida	Coastal Plain	Inland Empire	Inland Valleys	Lower Midwest	Midwest	North	Northeast	Northern California Coast	Sacramento Valley	South
Year	*Diameter at breast height (cm)*										
0	3	2.5	2.2	2.5	3.1	3.1	3.1	3.1	3	1.2	3.1
10	21.2	14.7	13.3	10.3	14.5	14.5	14.5	14.5	7.7	18.8	14.5
20	41.6	26.9	21.9	18	27.9	27.9	27.9	27.9	14.1	32.4	27.9
30	59.4	39.1	29.3	25.7	43.2	43.2	43.2	43.2	22.3	42.6	43.2
40	74.7	51.3	36.7	33.5	60.5	60.5	60.5	60.5	32.3	50.9	60.5
50	87.5	63.5	45.6	41.2	79.6	79.6	79.6	79.6	44.1	57.9	79.6
60	97.8		57.1	49					57.6	64.1	
70	105.5		72.6						72.9	69.6	
80									90.1	74.6	
90										79.2	
100										83.4	
110										87.4	
	Tree height (m)										
0	1.1	1.2	2.8	1.8	1.6	1.6	1.6	1.6	1.9	0.7	1.6
10	6.6	5.7	5.6	4.4	6.1	6.1	6.1	6.1	4.1	8	6.1
20	10.3	9.2	7.5	6.8	10.5	10.5	10.5	10.5	6	10.8	10.5
30	12.7	11.8	8.9	8.9	14.4	14.4	14.4	14.4	7.8	12.4	14.4
40	14.4	13.5	10.2	10.7	17.3	17.3	17.3	17.3	9.4	13.4	17.3
50	15.7	14.2	11.4	12.2	18.7	18.7	18.7	18.7	10.8	14.3	18.7
60	16.5		12.5	13.5					12.1	14.9	
70	16.5		13.2						13.3	15.5	
80									14.5	15.9	
90										16.3	
100										16.7	
110										17	

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