EQUATIONS FOR PREDICTING DIAMETER, HEIGHT, CROWN WIDTH, AND LEAF AREA OF SAN JOAQUIN VALLEY STREET TREES

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Abstract. Although the modeling of energy-use reduction, air pollution uptake, rainfall interception, and microclimate modification associated with urban trees depends on data relating diameter at breast height (dbh), crown height, crown diameter, and leaf area to tree age or dbh, scant information is available for common municipal tree species. In this study, tree height, crown width, crown height, dbh, and leaf area were measured for 12 common street tree species in the San Joaquin Valley city of Modesto, California, U.S. The randomly sampled trees were planted from 2 to 89 years ago. Using age or dbh as explanatory variables, parameters such as dbh, tree height, crown width, crown height, and leaf area responses were modeled using two equations. There was strong correlation (adjusted $R^2 > 0.70$) for total height, crown diameter, and leaf area with dbh. Correlations for dbh with age and crown height for several species were weaker. The equations for predicting tree sizes and leaf area are presented and applied to compare size and growth for all species 15 and 30 years after planting. Tree height, crown diameter, and dbh growth rates tended to slow during the second 15 years, but the leaf area growth rate increased for most species. Comparisons of predicted sizes for three species common to Modesto and Santa Monica trees suggest that pruning has a significant impact on tree size and leaf area, potentially more than climate and soil characteristics.

Key Words. Urban forest; tree growth; predictive equations; size relationships; leaf area.

In rural forest stands and plantations, growth and yield are modeled using diameter-at-breast-height (dbh) relationships with tree height, crown height, and crown diameter (Furnival 1961; Curtis 1967; Stage 1973). Shinozaki et al. (1964) presented a pipe model theory showing a strong relationship between conducting tissues (the "pipes" running from roots to branch tips) and the tissues that receive water and nutrients in the crown. This theory provided the basis for equations predicting leaf area from dbh and sapwood area. For urban forests, the development of equations to predict dbh, height, crown diameter, crown height, and leaf area of dominant municipal tree species will enable arborists, researchers, and urban forest managers to model costs and benefits, analyze alternative management scenarios, and determine the best management practices for sustainable urban forests (McPherson et al. 2000). For instance, pollutant uptake by open-grown trees depends on the leaf area because leaves absorb pollutants such as ozone and nitrogen oxides through leaf stomata and intercept particulate matter (e.g., dust, ash, pollen, smoke) on leaf surfaces (Scott et al. 1998). Shade simulators used to determine energy savings associated with the shading of homes require estimates of tree heights and crown diameters (Simpson 1998). Similarly, the modeling of carbon sequestration, rainfall interception, and microclimate modification also depends on the availability of data relating dbh, height, crown height, crown diameter, and leaf area to tree age or dbh (Huang et al. 1987; Simpson 1998; Xiao et al. 1998). Unfortunately, equations developed for rural forests have not been directly transferable to open-grown municipal trees (Nowak 1994; Peper and McPherson 1998), and references currently available in the

United States for predicting size and leaf area of common municipal tree species at particular ages are limited.

Nowak's (1996) allometric method for estimating leaf area is based on data collected on 54 open-grown park trees in Chicago, Illinois, that were selected with full crowns in excellent condition and additional data on 34 smaller trees obtained from Gacka-Grzesikiewicz (1980) in Warsaw, Poland. Frelich (1992) measured only healthy trees (221 trees representing 12 species) growing in Twin Cities, Minnesota, to predict size relationships. Similarly, to develop linear relationships between dbh, height, crown spread, and age, Fleming (1988) measured trees in New Jersey having full healthy crowns. In each of these studies, sampling methods were neither random nor designed to address the broad range of tree conditions and locations along city streets. In addition, the data were collected from USDA climate zones 3 to 6 (USDA 1990) having 150 to 180 frost-free days, representing a significantly shorter growing season than those in many southern and western states. They may not predict tree size at a given age in warmer climate zones with longer growing seasons.

Equations to predict total height, crown height, crown diameter, and leaf area from dbh, or to predict dbh from age after transplant, for 16 common street tree species growing in the coastal southern California city of Santa Monica (USDA climate zone 10) represent the only predictive models for urban tree species growing in warmer climate zones of the United States. Although Modesto and Santa Monica have similar rainfall [315 mm (12.4 in.) and 322 mm (12.7 in.), respectively], Santa Monica has a year-round growing season (Brenzel 1997). The Modesto growing season extends from early March through mid-November, with 20-year average lows ranging from −3°C to −9°C (26°F to 16°F), compared to Santa Monica's average lows of 7°C to −4°C (44°F to 24°F). Modesto is located in the San Joaquin Valley, a northern California inland area that is one of the world's five Mediterranean climate regions (Dallman 1998).

The objective of this study was to develop regression equations to predict dbh from tree age, and to predict total height, crown diameter, crown height, and leaf area from dbh for 12 common street tree species growing in Modesto, California (USDA zone 9).

METHODS

Field Data Collection Procedures

Modesto manages 75,649 street trees belonging to 184 species (McPherson et al. 1999). However, the 12 species sampled in this study account for 41% of the entire street tree population. Computerized street tree inventories and handwritten documents containing planting records for trees were utilized to randomly sample common street tree species. Ginkgo *(Ginkgo biloba)* were 3 years old at planting, silver maple *(Acer saccharinum)*, European ash (*Fraxinus excelsior* 'Hessei'), crapemyrtle *(Lagerstroemia indica)*, London plane (*Platanus* × *acerifolia*), Bradford pear (*Pyrus calleryana* 'Bradford'), and zelkova *(Zelkova serrata)* were 1-year-old whips at planting, and all other species were 2-year-old whips at planting. To obtain size information spanning the life cycle of each of the 12 species, stratified random sampling was conducted in different-aged neighborhoods with trees of known planting age. Stratification consisted of two groups, a "young tree" group (planted from 1970s through 1990s) and an "old tree" group (planted prior to 1970). Fifteen trees of known age were randomly drawn for each group for each species. Five additional trees were drawn as substitutes if original trees could not be located.

Data collected for each tree from June through September 1998 included species, age, address, dbh [to nearest 0.1 cm (0.39 in.) by tape], and tree height [to nearest 0.5 m (1.64 ft) by clinometer or range pole], crown diameter in two directions [maximum and minimum axis, to the nearest 0.5 m (1.64 ft) by tape], height to the base of crown (to nearest 0.5 m by clinometer or range pole), and leaf area. Observational data included a visual estimate of crown shape, pruning level, tree condition code (explained in paragraph below), and planting location (i.e., front lawn, planting strip, sidewalk cutout).

Condition code (to nearest 5%) was calculated per the *Guide for Plant Appraisal* (Council of Tree and Landscape Appraisers 1992). Pruning level estimation, recorded on a scale of 0 to 3, where 0 = no pruning, 1= less than 10% of crown pruned, 2 = 10% to 39% pruned, and 3 = 40% or more pruned, was based on total percentage of crown removed due to crown raising, reduction, thinning, and heading during the last 4-year pruning cycle. Modesto's municipal trees were on a 4-year inspection and pruning cycle with all work conducted by city crews. Young tree pruning followed the American National Standard Institute A300-1995 guidelines for tree maintenance (National Arborist Association 1995). As trees matured, pruning included crown raising. Mature tree maintenance typically consisted of crown cleaning and thinning.

Two digital photos of each tree crown, taken at perpendicular angles (chosen to provide the most unobstructed view of the crown), were used to estimate leaf area using an image processing method (Peper and McPherson 1998; Peper and Mori, forthcoming). Focal length of the camera (5 cm [1.97 in.]) and distance from camera to the tree were recorded to nearest 0.1 m (0.33 in.) using the Sonin® Combo Pro CST distance measuring device. Clinometer and sonar device measurements were checked for accuracy several times per week by measuring heights and distances with a tape or range pole.

Due to limited resources and the time required for data collection and verification of tree ages, we were unable to collect a sufficient amount of data for validation of the equations. Initially it was assumed that planting ages could be determined from the city tree inventory and development ages. However, ages of trees for which age data were missing or entered incorrectly in the database were verified through searching handwritten planting records, interviewing residents and city arborists, or increment coring to count growth rings. Crown height was calculated by subtracting the bole height (distance to base of crown) from total tree height.

Data Analysis

Of the original 360 trees selected for sampling, 341 were used in the analyses. Trees were excluded if they could not be located in the field (felled and removed), or if photos revealed that the tree was incorrectly identified or entered into the database. Therefore, eight species have fewer than the 30 trees originally drawn for sampling.

Typically, street tree databases include dbh size classes but rarely any age information for each tree. Therefore, in this study only dbh is regressed on age; all other variables are regressed on dbh, enabling users to predict the other dimensions using measures of dbh alone. Three curve-fitting models were tested, including a modified Weibull model fitted by Frelich (1992) to a small sample of healthy trees. The logarithmic regression model provided the best fit for predicting all parameters except leaf area, for which the nonlinear exponential model was used (see appendix). Visual observation of the data revealed increasing variability with age and size of the trees; therefore, we assumed the error to be multiplicative as is indicated by the confidence intervals shown in Figure 1. A brief description of the models is in the appendix. A complete description of the analysis and models, including the necessary standard error of estimates, response sample mean, and correlation values needed for calculating confidence intervals is available on the Center for Urban Forest Research web site at http://wcufre.ucdavis.edu/urbanforestinventoryandmonitoring.htm.

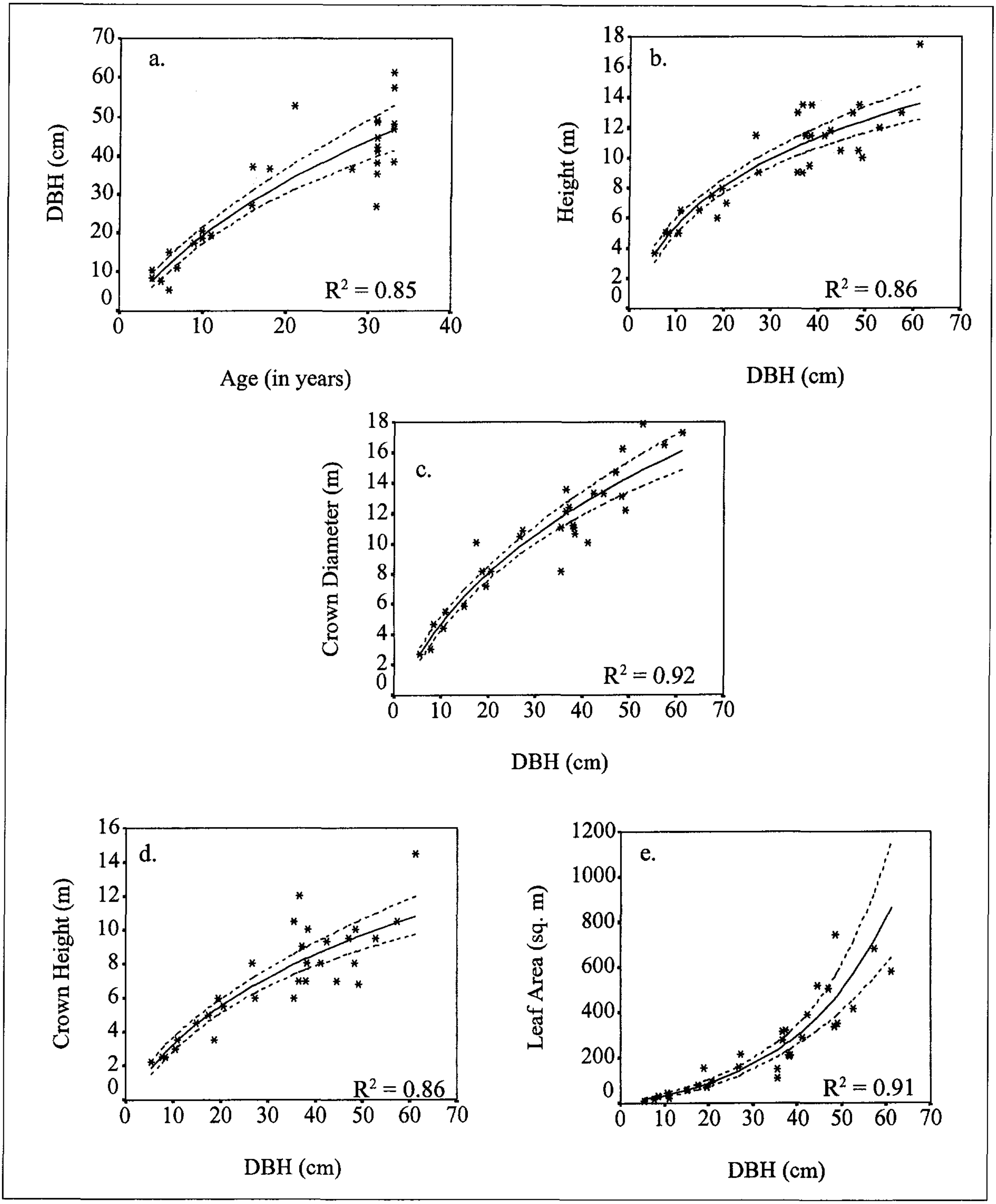

Figure 1. Actual measurements (asterisks), predicted responses (solid line), and confidence intervals (dotted lines) for zelkova growing in Modesto, California. Equation (2), $E(\text{leaf area}_i) = a*(e^{b*dbh_i} - 1)$ where E = expected value and a and b are parameters to be estimated, was used to model leaf area for 12 species. Equation (1), $E(y_i) = a*[\log(x_i + 1)]^b$ was used to predict all other dimensions.

RESULTS AND DISCUSSION

The Sample

The majority (61%) of Modesto's street trees were growing in front lawns within 3.5 m (11.5 ft) of a sidewalk or street. Twenty-three percent were in planting strips wider than 1.2 m (4 ft). Only 16% of the trees grew in restricted locations, either in sidewalk cutouts measuring 1.2 by 1.2 m or smaller or planting strips of less than 1.2 m width. Trees planted in lawns usually received irrigation, and the amount varied widely, depending on the home owner (front yards) or business owner (planting strips). Typically, irrigation was for the lawn rather than deep-watering for trees. Table 1 shows the age range sampled for each species. Eighty-one percent of the trees sampled were in good to excellent condition, 17% fair, and 2% poor, dead, or dying.

Table 1. The range of years included in sample for each species along with the minimum and maximum ages are shown.

Common name	Min. age	Max. age	No. of years
Silver maple	5	67	62
Camphor tree	6	73	67
European ash	2	48	46
Ginkgo	8	35	27
Goldenrain tree	3	37	34
Crape myrtle	5	48	43
Sweetgum	15	39	24
Southern magnolia	8	49	41
Chinese pistache	4	36	32
London plane	4	89	85
Bradford pear	8	48	40
Zelkova	3	33	30

With the exception of crapemyrtle, sweetgum *(Liquidambar styraciflua)*, and eight trees (representing six species) growing beneath power lines, crown reduction and heading were rarely observed within the sample. Perhaps because of its accessibility, the small-statured crapemyrtle often was shaped by home owners rather than city tree crews. Crown reduction to reduce weight on sweetgums having weak secondary branch attachments was also observed within the sample. Otherwise, maintenance pruning appeared conservative, conducted when necessary to maintain the health and structure of the trees.

Dbh, Height, and Crown Diameter

The regression coefficients (A = y-intercept and b = slope) for predicting dbh from age, and height and crown diameter from dbh are presented in Table 2 along with the mean standard error (MSE) and adjusted coefficients of determination (adjusted R^2). All equations were significant ($P < 0.01$). The dbh model displayed good fit ($R^2 = 0.70$) for seven species. The R^2 values are a direct measure of the strength of association between variables such as dbh and height. The higher the R^2, the stronger the association. Tree height and crown diameter displayed good fit for ten of the 12 species (Table 2). The model explained the most variation in the data for silver maple, camphor tree *(Cinnamomum camphora)*, ginkgo, goldenrain tree *(Koelreutaria paniculata)*, and zelkova. The age range for these species spanned a minimum of 30 years (Table 1). An example of the fitted models for zelkova is shown in Figure 1. Since the data were fitted with a statistical model that accounted for the increase of the variability with the increase of the mean values, one notices the confidence bounds expand with increasing tree age and size. This trend represents a common effect and was evident for all species, expressing the increasing variability within species due to the cumulative effects of differences in genotype, culture, site condition, biotic, and abiotic factors that influence tree health.

Species with the lowest R^2 were sweetgum and southern magnolia *(Magnolia grandiflora)*. Several factors contributed to this low R^2. The Modesto municipal tree inventory did not differentiate among cultivars for either of these species, and their inclusion in the sample contributed to greater variation in dbh, height, and crown size. During our inventory, we noted several cultivars

Table 2. Sample size, estimated regression coefficients, and mean standard error (MSE) values for predicting dbh from age, or tree height, crown diameter, or crown height from dbh, along with adjusted coefficients of determination for the modeling data set. Height, crown diameter, crown height, or dbh can be predicted by $\hat{y}_i = EXP\left\{MSE/2\left(\hat{A} + \hat{b}\log\left(\log\left(x_i + 1\right)\right)\right)\right\}$, where $\hat{y}_i$ = the tree parameter to be estimated, *EXP* = the inverse of the natural logarithm, and x_i = age or dbh.

			Dbh vs. Age				Height vs. dbh				Crown diameter vs. dbh				Crown height vs. dbh			
Species	Common name	*n*	$\hat{A}$	*b*	MSE	R^2	$\hat{A}$	*b*	MSE	R^2	$\hat{A}$	*b*	MSE	R^2	$\hat{A}$	*b*	MSE	R^2
Acer saccharinum	Silver maple	28	-0.365	3.502	0.21332	0.79	0.406	1.778	0.03789	0.90	-0.205	1.995	0.03091	0.93	-0.109	2.023	0.05484	0.88
Cinnamomum camphora	Camphor tree	30	0.385	2.723	0.11999	0.76	-0.165	1.959	0.05145	0.79	-1.150	2.615	0.02691	0.93	-1.207	2.513	0.08081	0.80
Fraxinus excelsior 'Hessei'	European ash	27	0.995	2.072	0.15637	0.74	0.972	1.031	0.02168	0.79	-0.960	2.483	0.01828	0.96	0.725	0.991	0.05596	0.57
Ginkgo biloba	Ginkgo	31	-2.717	5.015	0.10769	0.83	0.534	1.465	0.03802	0.82	-0.471	1.989	0.03490	0.90	0.174	1.542	0.07857	0.71
Koelreutaria paniculata	Goldenrain tree	28	0.340	2.559	0.05686	0.94	0.461	1.454	0.02356	0.92	-0.232	1.873	0.02793	0.94	-0.262	1.719	0.10639	0.78
Lagerstroemia indica	Crapemyrtle	25	-0.160	2.249	0.15280	0.64	0.560	1.080	0.02942	0.72	-0.236	1.679	0.04358	0.81	-0.573	1.805	0.06868	0.76
Liquidambar styraciflua	Sweetgum	30	-0.720	3.509	0.07674	0.51	0.092	1.973	0.03924	0.55	-1.256	2.606	0.03890	0.68	-0.234	2.074	0.06311	0.45
Magnolia grandiflora	Southern magnolia	28	-0.010	2.609	0.09677	0.45	-0.553	2.280	0.03663	0.69	-0.609	2.095	0.03918	0.64	-1.402	2.733	0.06863	0.63
Pistacia chinensis	Chinese pistache	28	1.008	1.997	0.08051	0.71	0.033	1.898	0.03921	0.72	-0.237	2.081	0.02925	0.81	-0.541	2.078	0.10162	0.54
Platanus × *acerifolia*	London plane	27	1.941	1.441	0.10575	0.66	-0.090	2.066	0.04352	0.72	-0.569	2.286	0.03315	0.81	-0.569	2.245	0.04604	0.74
Pyrus calleryana 'Bradford'	Bradford pear	29	1.396	1.719	0.12057	0.40	0.429	1.525	0.00488	0.90	-0.782	2.383	0.02399	0.81	-0.258	1.843	0.02628	0.69
Zelkova serrata	Zelkova	30	0.921	2.294	0.06311	0.85	0.222	1.676	0.02015	0.86	-0.438	2.259	0.02014	0.92	-0.784	2.218	0.03537	0.86

for each of these species. For example, the sweetgum sample included 'Palo Alto' and 'Burgundy' cultivars. There were three or four southern magnolia cultivars. Additionally, sweetgum had not been planted in the past 15 years, and the southern magnolia sample contained only two trees that were planted within the past 25 years.

The model fit crapemyrtle dimensions well, with the exception of dbh and age. The sample contained both multi- and single-stemmed specimens. Stems in several multi-stemmed trees had been removed. This reduced dbh and contributed to the variability in dbh–age relationships. However, there was no obvious explanation for the even higher variability (low R^2) between Bradford pear dbh and tree age.

Generally, the relationship between crown diameter and dbh was stronger than the relationship between height, crown height, and leaf area and dbh, most likely because the forms are more subject to cultural practices. Municipal tree pruning affects tree height and height to the base of the crowns more than crown diameter due to crown raising for vehicular and pedestrian traffic and crown reduction around utilities and signs. The R^2 for crown diameter and dbh for ten of 12 species was greater than 0.80. For six species it was greater than 0.90. The best correlations in the Santa Monica study were also between crown diameter and dbh.

Crown Height and Leaf Area

The predictive model for crown height showed good fit ($R^2 = 0.70$) for seven species (Table 2), and all equations were highly significant ($P < 0.01$). The crown height adjusted R^2 was generally lower for most species than tree height and crown values for the same species. This may be related to pruning since crown height measurements were affected by both crown raising and crown reduction. Many of the crowns had been raised in previous pruning cycles, but we had data only for the past 4 years; therefore, we were unable to account for differences in crown height based on pruning history.

For leaf area, a nonlinear exponential model showed good fit ($R^2 > 0.70$) for nine of the 12 species, with R^2 greater than 0.65 for two additional species (Table 3). Sweetgum and southern magnolia were planted over a shorter time span relative to other species and showed weaker correlations. Variability in leaf area for crapemyrtle was probably higher due to the pruning of crowns by home owners.

Growth Comparison

Fifteen years after planting, estimated dbh for Modesto trees ranged from 10 to 38 cm (4.1 to 15 in.), and tree height ranged from 5 to 14 m (15.7 to 45.8 ft) (Table 4). The fastest-growing trees by dbh were London plane, zelkova, Bradford pear, and silver maple, while the slowest

Table 3. The coefficient and mean standard error values (MSE) for predicting tree leaf area from dbh using Equation (2) for the modeling data set. Leaf area can be predicted by: $LA = EXP\left(\hat{A}\right) * EXP\left(\left(\hat{b}DBH\right) - 1\right) * EXP\left(MSE/2\right)$, where LA = estimated leaf area and EXP = the inverse of the natural logarithm.

		Leaf area vs. dbh			
Common name	*n*	*A*	*b*	MSE	R^2
Silver maple	27	5.465	0.017	0.14538	0.93
Camphor	28	3.482	0.046	0.21453	0.87
European ash	27	3.198	0.056	0.26392	0.88
Ginkgo	30	3.410	0.053	0.30207	0.86
Goldenrain tree	28	3.139	0.054	0.37021	0.87
Crape myrtle	25	2.634	0.073	0.55388	0.64
Sweetgum	30	4.547	0.034	0.22762	0.68
Southern magnolia	27	4.264	0.029	0.22067	0.66
Chinese pistache	24	3.421	0.065	0.13464	0.89
London plane	27	5.198	0.021	0.23508	0.74
Bradford pear	29	5.115	0.021	0.16544	0.71
Zelkova	30	4.033	0.045	.012706	0.91

Table 4. Predicted sizes for 12 species at 15 and 30 years after planting are shown sorted by fastest growth (dbh) in first 15 years after planting.

	Dbh (cm)		Height (m)		Crown diameter (m)		Leaf area (m^2)	
Common name	15	30	15	30	15	30	15	30
London plane	38.11	48.17	13.97	15.51	11.48	12.89	262.22	353.87
Zelkova	37.89	53.38	11.36	12.85	12.64	14.91	297.44	589.15
Bradford pear	31.30	40.90	10.47	11.48	9.27	10.70	174.29	240.18
Silver maple	27.47	58.12	13.11	18.62	9.22	13.67	151.03	427.56
Chinese pistache	27.15	38.12	10.70	12.41	10.17	11.96	179.18	358.48
Camphor tree	26.60	46.05	9.12	12.21	7.38	10.90	86.67	264.01
European ash	24.19	39.12	9.18	10.27	7.54	9.89	93.92	220.47
Sweetgum	23.77	45.77	11.89	15.94	6.60	9.71	152.27	387.07
Goldenrain tree	21.87	37.15	8.77	10.50	7.17	9.04	72.43	175.21
Southern magnolia	18.98	30.19	7.55	9.80	5.80	7.38	65.83	113.87
Ginkgo	12.94	38.77	7.92	11.74	4.98	8.50	45.15	235.29
Crapemyrtle	10.44	16.24	4.79	5.50	3.77	4.68	23.41	41.76

growing were crapemyrtle, ginkgo, southern magnolia, and goldenrain trees. These findings are compatible with the species descriptions in the *Sunset Western Garden Book* (Brenzel 1997).

Dbh growth tended to slow during the second 15 years for the species studied. The median rate of annual growth dropped from 1.67 cm (0.66 in.) during the first 15 years to 1.06 cm (0.42 in.). Exceptions were ginkgo, with a growth rate that doubled during the second 15 years, and silver maple with a growth rate about 11% higher than in the first 15 years. Ginkgo went from the second slowest- to the second fastest-growing species, supporting anecdotal accounts of it having a longer establishment period compared to other medium- to large-growing trees.

Like dbh growth, tree height and crown diameter growth also slowed during the second 15 years. The median annual rates of height growth dropped from 0.66 m (2.16 ft) to 0.16 (0.52 ft) between the first and second 15-year periods. Larger-growing species such as London plane, silver maple, zelkova, and sweetgum were among the tallest after 15 years. Sweetgum and silver maple continued growing at relatively fast rates, but London plane and zelkova were replaced by ginkgo and camphor tree as the fastest growers during the second fifteen years. Zelkova and camphor tree, listed in regional tree guides (Brenzel 1997; Reimer and Mark 2001) as large trees, were medium-sized after 30 years in Modesto, measuring 12.8 and 13.4 m (41.9 and 43.9 ft), respectively.

Although crown diameters for two small- to medium-sized trees, Bradford pear and Chinese pistache *(Pistacia chinensis)*, were among the fastest growing in the first 15 years, they slowed significantly during the second. Average annual crown diameter growth generally decreased during the second 15 years for all species.

The median annual estimated rate of leaf area growth increased from 8.2 m^2 (88.3 ft^2) for the first 15 years to 10.1 m^2 (108.7 ft^2) for the next 15 years. Only four species exhibited a decreased rate of leaf area growth during the second 15 years (London plane, Bradford pear, southern magnolia, and ginkgo). Silver maple is considered a large tree in regional planting guides, and its height in Modesto classified it as large, but zelkova, a medium-sized tree in Modesto, had more leaf area. Although not as tall as silver maple, zelkova's crown at 15 and 30 years was wider and more dense. Bradford pear and Chinese pistache, described by Benzel (1997) as small-to-medium and medium trees, respectively, were among the four species adding the most leaf area to their crowns during the first 15 years of growth. Although Bradford pear rank changed from the top four in the first 15 years to the bottom three in the second 15 years, Chinese pistache remained ranked in the top four species adding the most leaf area along with zelkova, silver maple, and sweetgum. Like zelkova, the higher leaf area for Chinese pistache when compared with Bradford pear was related to its wider crown diameter.

Customarily, regional planting guides use measurements of tree height alone to classify trees as small, medium, or large. However, our findings show that the "medium-sized" zelkova is wider, with more leaf area than the "large" London plane tree. Similarly the "medium-sized" Chinese pistache is wider, with more leaf area than the "large" camphor tree. This suggests that using height alone to indicate mature tree "size" provides an inaccurate picture, particularly when the majority of benefits (hydrologic, air quality, energy savings) are usually linked to crown volume, leaf area and crown area, as well as tree height.

Modesto and Santa Monica Comparison

Camphor tree, sweetgum, and southern magnolia were common to Modesto and Santa Monica, allowing comparison of predicted tree sizes in the two cities. Predicted tree sizes at years 15 and 30 were compared using equations reported here and equations developed for Santa Monica species. All dimensions and leaf area were larger for camphor tree and sweetgum growing in Modesto than in Santa Monica. Camphor trees in Modesto were 1.38 and 2.19 m (4.53 and 7.18 ft) taller than Santa Monica camphor trees at 15 and 30 years after planting. Crown diameters were closer in size, with Modesto trees being 0.59 and 0.46 m (1.94 and 1.51 ft) wider 15 and 30 years after planting. However, at year 30, Modesto camphor trees had over 100 m^2 (1076 ft^2) more leaf area than their Santa Monica counterparts. These differences were more dramatic for sweetgum. By year 30, Modesto sweetgums were more than 4.5 m (14.76 ft) taller and 3.2 m (10.5 ft) wider, with 181 m^2 (1948 ft^2) more leaf area, than Santa Monica sweetgums. At maturity, sweetgums in Modesto were large trees [>17 m (55 ft)], but Santa Monica sweetgums were pruned to a medium height [12 m (40 ft)] and leaf area. Santa Monica sweetgums were pruned heavily in an effort to reduce root size and associated sidewalk damage. Camphor trees were also pruned but not to the extent of sweetgums. In contrast, southern magnolias in Santa Monica were 0.16 m (0.52 ft) taller, 1.82 m (5.97 ft) wider, and had 17 m^2 (183 ft^2) more leaf area than Modesto southern magnolias. The majority of southern magnolias were planted in front lawns in Santa Monica and received little pruning beyond crown raising for vehicle and pedestrian traffic. Size differences were cultural.

The equations for modeling dbh as a function of age, and tree height, crown diameter, and leaf area as functions of dbh, produced strong correlations, particularly for those species planted over a longer period of time. Application of these equations should be limited to populations of trees falling within the same climate zone, maintenance category, and dbh (or planting age). However, the approach used to develop the models is transferable, providing a basis for city urban forest managers to better understand the changing architecture of their street trees. Other applications include estimating pruning costs associated with different pruning cycles or the production of waste wood and leaf litter.

CONCLUSIONS

The application of the models to compare tree sizes at 15 and 30 years after planting showed that several Modesto species grow to different sizes than indicated in regional planting guides. The finding that shorter trees with wide crowns had more surface leaf area than taller trees with narrow crowns indicates that classifying trees on the basis of one or two dimensions (e.g., dbh or height) is inadequate. The Modesto data suggest the need to develop a four-dimensional approach for classifying and visualizing tree growth, an approach that better describes the three-dimensional tree and how those dimensions change and grow over time. Predictive equations provide the essential data required to develop computerized visualization programs capable of "growing" trees in a variety of urban locations. This information will assist arborists, landscape architects, and municipal tree managers to better match trees to planting sites.

The continued collection of data and development of predictive equations for additional tree species can provide a basis for comparing the effects of climate and alternative management scenarios on like species of trees throughout different regions of the world. However, comparisons of predicted sizes for Modesto and Santa Monica trees suggest that cultural practices, especially pruning, have a significant impact on tree size and leaf area, potentially more than climate and soil characteristics. Essentially, pruning is a highly variable social factor involving multiple managers and multiple pruning practices. This makes the application of the predictive equations to other populations in similar climate zones difficult unless a pruning index is developed to adequately and consistently describe reductions to crown dimensions and density.

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APPENDIX

Models for Predicting Dbh, Tree Height, and Crown Diameter

Using age (years after planting) or dbh as explanatory (dependent) variables, mean values of dbh, tree height, and crown diameter responses were modeled using the following regression equation:

$$E(y_i) = a*[\log(x_i + 1)]^b \qquad (1)$$

where

y_i = observed response i, $i = 1, 2, \ldots, n$;
n = number of observations
x_i = age or dbh
a, b = parameters to be estimated
$E(\ )$ = expected value.

The following regression model was used for the transformed response:

$$\log(y_i) = A + b\log(\log(x_i + 1)) + \varepsilon_i \qquad (1')$$

This model can be rewritten as

$$z_i = A + bv_i + \varepsilon_i$$

where

A, b = parameters to be estimated
$z_i = \log(y_i)$
$v_i = \log(\log(x_i + 1))$
ε_i = error term

The estimated parameters, A and b, are denoted by $\hat{A}$ and $\hat{b}$. The Baskerville (1972) bias correction, $e^{MSE/2}$, was applied to the back-transformed fitted, e^{z_i}, $e^{\hat{z}_i}$:

$$\hat{y}_i = e^{\hat{z}_i} * e^{MSE/2},$$

where

$\hat{z}_i = \hat{A} + \hat{b}v_i$ and
MSE = mean sum of squares from least squares estimation (LSE) procedure. Therefore, the fitted value of y_i is given by

$$\hat{y}_i = \hat{a}[\log(x_i + 1)]^{\hat{b}}$$

where

$\hat{a} = e^{\hat{A} + MSE/2}$.

Estimates $\hat{A}$ and $\hat{b}$, and MSE are used to predict dimensions for each species listed in Table 2.

Model for Predicting Leaf Area

The expected value of leaf area was modeled as follows:

$$E(\text{leaf area}_i) = a*\left(e^{b*\text{dbh}_i} - 1\right) \qquad (2)$$

Again, we assumed the errors to be multiplicative and log transformed the leaf area response:

$$z_i = \log(\text{leaf area}_i) = A + \log\left(e^{b*\text{dbh}_i} - 1\right) + \varepsilon_i \qquad (2')$$

The A and b coefficients were estimated using a nonlinear regression estimation (NLE) technique. As before, the back-transformed estimated $e^{\hat{z}_i}$ was bias corrected with $e^{MSE/2}$, where MSE is the mean sum of squares from NLE.

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Résumé. Même si la modélisation de la réduction d'énergie utilisée, du captage des polluants, de l'interception de pluie et de la modification du microclimat associés aux arbres urbains dépend des données reliant DHP (diamètre à hauteur de poitrine), hauteur de cime, largeur de cime et surface foliaire à celles de l'âge de l'arbre ou du DHP, des informations partielles sont disponibles pour les espèces les plus communes d'arbres de villes. Dans cette étude, la hauteur de l'arbre, la largeur de cime, la hauteur de cime, le DHP et la surface foliaire ont été mesurés pour 12 espèces communes d'arbres de rues dans la vallée de San Joaquin de la ville de Modesto en Californie. Les arbres échantillonnés aléatoirement ont été plantés de 2 à 89 ans auparavant. En utilisant l'âge ou le DHP comme variables explicatives, des paramètres comme le DHP, la hauteur de l'arbre, la largeur de cime, la hauteur de cime et la surface foliaire ont été modélisés au moyen de deux équations. Il y avait une corrélation forte ($R^2 > 0,70$) pour la hauteur totale, la largeur de cime et la surface foliaire avec le DHP. Les corrélations du DHP avec l'âge et la hauteur de cime étaient plus faibles pour plusieurs espèces. Les équations pour prédire les dimensions de l'arbre et la surface foliaire sont présentées et appliquées pour comparer la dimension et le taux de croissance de chaque espèce 15 et 30 ans après leur plantation. Les taux de croissance en hauteur de l'arbre, en largeur de cime et en DHP tendent à ralentir durant la seconde période de 15 ans, mais le taux de croissance de la surface foliaire de la plupart des espèces s'accroît. Des comparaisons de prédiction de dimensions pour trois espèces communes d'arbres à Modesto et Santa Monica suggèrent que l'élagage a un impact significatif sur la dimension des arbres et la surface foliaire, potentiellement plus que le climat et les caractéristiques du sol.

Zusammenfassung. Obwohl die Simulation von vermindertem Energieverbrauch, Luftverschmutzungszunahme, Regenfallaufnahme und Modifikation vom Mikroklima in Verbindung mit Stadtbäumen auf den Daten bezüglich Brusthöhendurchmesser (BHD), Kronenhöhe, Kronendurchmesser und Blattfläche zur Baumhöhe und BHD basiert, ist nur spärliche Information über öffentlich verwendete Baumarten erhältlich. In dieser Studie wurde die Höhe, Kronenhöhe und –breite, BHD und Blattfläche an 12 gewöhnlichen Straßenbaumarten in San Joaquin Valley, City of Modesto, Cal. gemessen. Die zufällig ausgewählten Bäume wurden vor 2 bis 89 Jahren gepflanzt. Unter Verwendung von zwei Gleichungen wurden die Antworten, bestehend aus Angaben über Alter oder BHD als Bezugsgrößen, Parameter wie BHD, Höhe und Breite der Krone und Blattfläche, in ein Modell einbezogen. Es gab eine starke Korrelation (angepasst $R^2 > 0.70$) für die totale Kronenhöhe, -durchmesser und Blattfläche mit BHD. Die Korrelationen für BHD mit Alter und Kronenhöhe war für einige Arten schwächer. Die Gleichungen zum Bestimmen von Baumgröße du Blattfläche wurden dargestellt und angewendet, um die Größe und Wachstum aller Arten 15 und 30 Jahre nach dem Pflanzen zu vergleichen. Baumhöhe, Kronendurchmesser und BHD Wachstumsraten tendierten während der zweiten 15 Jahre zum Verlangsamen, aber die Blattflächenwachstumsrate stieg bei den meisten Baumarten. Vergleiche zwischen den vorhergesagten Größen dreier Baumarten in Modesto und Santa Monica wiesen daraufhin, dass Rückschnitt einen deutlichen Einfluss auf die Baumgröße und Blattfläche hat, insbesondere mehr als klimatische oder Bodenfaktoren.

Resumen. A pesar de que el modelamiento de la reducción de energía, control de la contaminación del aire, intercepción de la lluvia y modificación microclimática asociada con los árboles urbanos depende de los datos relacionados con el diámetro a la altura del pecho (dap), altura de la copa, diámetro de la copa y área foliar, la información no es suficiente para el común de los árboles urbanos. En este estudio, la altura del árbol, el diámetro de la copa, la altura de la copa, el dap y el área foliar fueron medidos para 12 especies de árboles comunes en la ciudad de Modesto en el Valle San Joaquín, California. Los árboles muestreados al azar fueron plantados desde hace 2 a 89 años. Con el uso de la edad o diámetro como variables explicatorios se modelaron los parámetros tales como dap, altura del árbol, anchura de la copa, altura de la copa y área foliar usando dos ecuaciones. Existe una fuerte correlación ($R^2 > 0.70$) para altura total, diámetro de la copa y área foliar, con dap. Las correlaciones para dap con edad y altura de la copa para varias especies fueron débiles. Las ecuaciones para predecir los tamaños de los árboles y área foliar son presentadas y aplicadas para comparar tamaño y crecimiento para todas las especies, 15 y 30 años después de la plantación. Las tasas de crecimiento en altura del árbol, diámetro de la copa y dap tienden a bajar durante los segundos 15 años, pero la tasa de crecimiento del área foliar incrementa para la mayoría de las especies. Las comparaciones de los tamaños predichos para tres especies comunes sugieren que las podas tienen un impacto significativo sobre el tamaño de los árboles y el área foliar, potencialmente más que el clima y las características del suelo.