PREDICTIVE EQUATIONS FOR DIMENSIONS AND LEAF AREA OF COASTAL SOUTHERN CALIFORNIA STREET TREES

by Paula J. Peper[1], E. Gregory McPherson[1], and Sylvia M. Mori[2]

Abstract. Tree height, crown height, crown width, diameter at breast height (dbh), and leaf area were measured for 16 species of commonly planted street trees in the coastal southern California city of Santa Monica, USA. The randomly sampled trees were planted from 1 to 44 years ago. Using number of years after planting or dbh as explanatory variables, mean values of dbh, tree height, crown width, and leaf area responses were modeled using two equations. There is strong correlation (adjusted $R^2 > 0.70$) between dbh as a function of number of years after planting, and total height, crown diameter, and leaf area as a function of dbh. Correlation is weaker between measures of crown height and dbh. This is probably due to crown pruning increasing the variability among measurements for trees having the same or similar dbh. Equations for less-intensively pruned species displayed adjusted R^2 greater than 0.70. Equations are presented for predicting dimensions and leaf area and applied to compare tree sizes and growth for all species 15 and 30 years after planting.

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

Equations to predict dimensions and leaf area of dominant municipal tree species 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). Modeling carbon sequestration, energy-use reduction, air pollution uptake, rainfall interception, and microclimate modification in cities 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; McPherson et al. 1998; Scott et al. 1998; Simpson 1998; Xiao et al. 1998). For instance, rainfall interception by open-growing trees depends on leaf area, which influences surface detention, and tree height because the rate at which stored rainfall is depleted from the crown of a tall tree via evaporation is greater than for a shorter tree (Xiao et al. 1998).

In the United States, much of the information available addressing dimensional relationships and leaf areas of common municipal tree species at particular ages of their life cycles is limited to personal observations or adapted, without validation, from traditional forestry literature. Several noteworthy exceptions include Nowak's (1994) estimation of urban tree growth from tree ring counts on sections cut from 543 trees (10 species) growing in the Chicago, Illinois, area. Since many of these trees were senescent or dead, dbh estimates were based on radial growth and tree cumulative radius for each ring developed between 1965 and 1985. In contrast, Frelich (1992) measured only healthy trees (221 trees representing 12 species) growing in the twin cities of St. Paul and Minneapolis, Minnesota, without root constraint or competition, not in soil pits, against buildings, or under utility lines to predict dimensional relationships. Similarly, Fleming (1988) measured only "normal" trees—those supporting a full green canopy with at least 50% of the major limbs present—to develop linear relationships between dbh, height, crown spread, and age. In each of these studies, trees sampled were of a particular health and condi-

tion. Sampling methods were neither random nor designed to address the broad range of tree conditions and locations existing in cities. In addition, the data were collected from USDA climate zones 3 to 6 (USDA 1990) having 150 to 180 frost-free days, representing significantly shorter growing seasons than those in many southern and western U.S. states.

The objective of this study was to develop regression equations to predict dbh, total height, crown height, crown diameter, and leaf area for 16 street tree species growing in the coastal southern California city of Santa Monica, California (USDA climate zone 10). This represents a continuation of work begun in 1998 when predictive models were fitted to data collected in the Central Valley community of Modesto, California (USDA zone 9) (Peper, forthcoming). Although both cities have similar rainfall averages, 315 mm (12.4 in.) for Modesto and 322 mm (12.7 in.) for Santa Monica, the latter has a more temperate climate, with the lowest and highest temperatures over the past 50 years of 0.5°C (33°F) and 40.0°C (104°F), respectively (Western Regional Climate Center).

METHODS
Field Data Collection Procedures
Computerized street tree inventories and hand-written documents containing planting records for trees were utilized to randomly sample the most common street tree species for Santa Monica, California. Trees ranged from approximately 1 to 4 years old at time of planting. The sample was designed to include 16 of the most abundant species growing in the city, representing 73.6% of its entire street tree population. To obtain dimensional information spanning the life cycle of each of the 16 species, tree samples were randomly selected after stratifying data into the following four planting date groups: 1949–1961, 1962–1974, 1975–1987, and 1988–1999. Thirty trees were selected for each species along with five alternates to be used if the sample tree was

dead, missing, or identified incorrectly. Ideally, eight trees were randomly selected for the first three age categories and six trees for the most recent age stratum. However, several species had not been planted regularly during the past 20 years (i.e., *Eucalyptus ficifolia*, *Melaleuca quinquenervia*, *Podocarpus macrophyllus*, *Schinus terebinthifolius*). In these cases, the entire sample was taken from earlier planting periods. In situations where planting dates appeared to be assigned incorrectly to city blocks of trees (trees appeared to be significantly older or younger than dates provided by city arborist), ages were verified or corrected by homeowners or the planting manager who had been with the planting program for 33 years. Permission could not be obtained for taking core samples from trees.

Many species have been planted in the city for nearly 100 years, but planting dates have been recorded only since 1952 when the city first became involved in street tree planting. Data were graphed and outliers were revisited, usually turning out to be "relics" from early plantings. These trees were dropped from the sample because ages were unknown and estimates of ages could not be verified by homeowners or the city; therefore, four species have less than 30 trees originally sampled.

Data collected for each tree during July and August 1999 included species, age, address, dbh (to nearest 0.1 cm by tape), and tree height (to nearest 0.5 m by clinometer or range pole), crown diameter in two directions (maximum and minimum axis, to nearest 0.5 m by tape), and leaf area. Observational data included a visual estimate of crown shape, pruning level, tree condition code, and planting location (i.e., front lawn, planting strip, sidewalk cutout).

Condition code (to nearest 5%) was calculated as 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= <10% of crown pruned, 2 = 10% to 39% pruned, and 3 = 40% or more, was based upon total percentage of

crown removed due to crown raising, reduction, thinning, and heading.

Two digital photos of each tree crown, taken at perpendicular angles (chosen to provide the most unobstructed view of the crown) were used to calculate leaf area using an image-processing method (Peper and McPherson 1998). Focal length of the camera (5.0 cm) and distance from camera to the tree were recorded (to nearest 0.1 m by sonar 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.

Data Analysis

The sample consisted of 481 trees. Since records did not report actual age of trees at planting, the term "age" as used here refers to number of years after planting. 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). Age was the dependent variable for dbh, and dbh the dependent variable for modeling tree height, crown diameter, and leaf area. 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, are available on the Western Center for Urban Forest Research web site (cufre.ucdavis.edu).

RESULTS AND DISCUSSION
The Sample

Sixty-eight percent of the trees sampled were in good to excellent condition, 22% fair, 9% poor, and 1% dead or dying. Fifty-five percent of the trees were located in restricted locations, either in sidewalk cutouts measuring 1.22 × 1.22 m or smaller (4 × 4 ft) or planting strips of less than 1.22 m width. Only 22% of Santa Monica's sampled trees were in front lawns, within 3.5 m of sidewalk and street, and 23 % were in planting strips that were wider than 1.22 m.

Santa Monica's pruning program appeared to have a direct effect on crown dimensions. The municipal trees in Santa Monica are placed in one of six different trim categories, depending upon growth rate and location. For example, large trees in residential zones or high public-use areas are pruned annually, and figs are pruned biannually. Trees with moderate growth habits are pruned every 3 to 5 years, and those with slow growth every 6 to 8 years; however, regardless of species or growth patterns, trees in commercial zones may be pruned annually to maintain sign clearance and leave storefronts visible. Trees of the same age and species are pruned differently according to location, thereby increasing variability in dimensional measurements.

Intensive crown pruning was reflected in the sample, with 46% of the trees sampled having more than 40% of their crowns removed. Indian laurel fig (*Ficus microcarpa* 'Nidita'), cajeput (*Melaleuca quinquenervia*), and sweetgum (*Liquid-ambar styraciflua*) were the most heavily pruned species. Their crowns were headed, reduced, and raised anywhere from 40% to 80% of natural crown size, partially in an effort to reduce root growth. Crowns were raised an average 4.8 m (15.8 ft), 4.6 m (15.0 ft), and 4.5 m (14.6 ft) for figs, sweetgum, and cajeput, respectively. Other mature medium to large
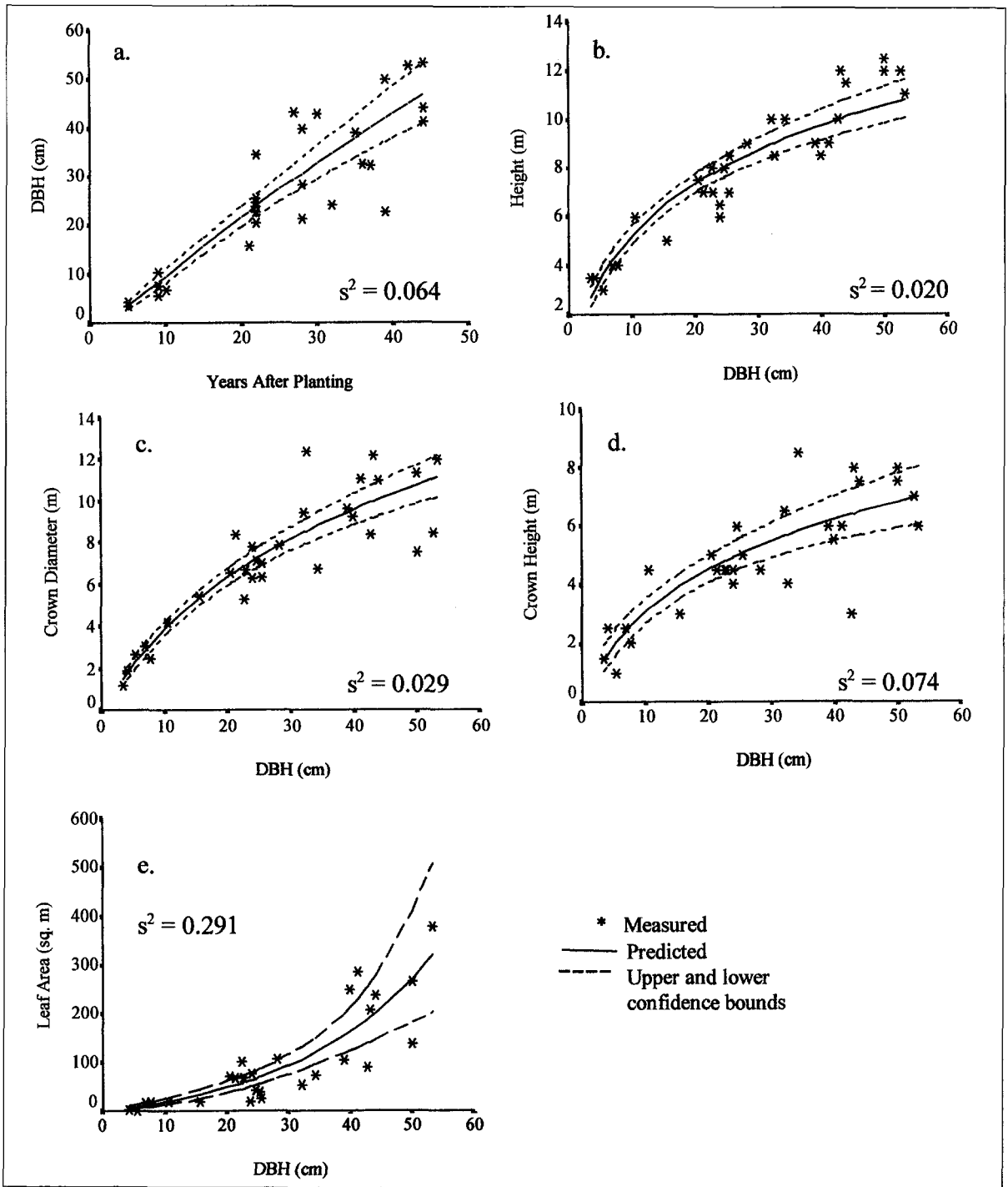
Figure 1. Actual measurements, predicted responses, and confidence intervals for southern magnolia (*Magnolia grandiflora*) growing in Santa Monica, California. Equation (2) was used to model leaf area for this and all other species. Equation (1) was used to predict all other dimensions for the species.

species had crowns raised an average 3 to 4 m (~9.5 to 13 ft) to provide clearance for buildings, vehicles, pedestrians, or vistas. Red-flowering gum, sweetgum, and cajeput crowns were extensively thinned.

Dbh, Height, and Crown Diameter

The regression coefficients for predicting dbh by age, and height, crown height, and crown diameter by dbh are presented in Table 1 along with the adjusted coefficients of determination (R^2). Of the four tree dimensions analyzed, dbh, height, and crown diameter displayed models with good fit ($R^2 \geq 0.70$) for 14, 12, and 13 of the 16 species, respectively (Table 1). Species with the highest coefficients of determination were carrotwood, Canary Island pine, and southern magnolia. The samples for these species contained trees with ages spanning over 35 years. An example of the fitted models for each tree dimension for southern magnolia (*Magnolia grandifolia*) is shown in Figure 1. Note that confidence bounds expand with increasing tree age and size. This trend was evident for all species and expresses increasing variability within species due to the cumulative effects of differences in genotype, culture, site condition, and biotic and abiotic factors that influence tree health.

Species with the lowest coefficients of determination were red-flowering gum, Brazilian pepper, and cajeput. Part of their relatively high variability can be explained by the fact that the sample was limited to about a 20-year age range and contained relatively few trees planted within the past 20 years. Historically, variable pruning of the large gum trees and heavy pruning of many cajeputs just prior to sampling influenced the variability of measured crown dimensions. The Brazilian pepper is a small-statured species subject to crown disfiguration from storm damage and crown pruning by residents.

Crown Height and Leaf Area

The predictive model for crown height showed good fit ($R^2 > 0.70$) for only four species (Table 1). This may be related to pruning methods since crown height measurements were a function of how high the crown was raised as well as crown reduction through heading and pruning back to laterals.

Unfortunately, the method used in this study to classify pruning levels was too coarse to be useful as an explanatory variable to illustrate these differences in crown height. The classification method did not differentiate between trees with 40% of their crowns removed and those with 75% removed, nor did it account for the effects of same species having different pruning cycles depending upon their locations. However, analysis for species receiving less intensive pruning (<40%) displayed models with higher adjusted R^2 (*Pinus canariensis, Jacaranda mimosifolia,* and *Magnolia grandifolia*).

Regressions coefficients, *mse*, adjusted R^2, leaf area sample mean, and the 95% confidence interval for leaf area for each species are shown in Table 2. For several species, the sample size for leaf area (*n*) was smaller than for other measured parameters. This was because photographs could not be taken of some tree crowns due to their locations (e.g., behind billboards or other trees).

The model showed good fit ($R^2 > 0.70$) for 8 of the 16 species, with R^2 greater than 0.65 for 3 additional species. Examples of the confidence bounds for expected leaf area (Table 2) illustrate the variability within each species, particularly for bottlebrush, jacaranda, sweetgum, cajeput, Victorian box, Brazilian pepper, and Brisbane box. Again, pruning probably contributes to the variability. For example, sweetgum and cajeput have low adjusted R^2 values. The sweetgums in Figure 2a and 2b measured 27 cm and 29 cm dbh, respectively, with corresponding leaf areas of 159 m² and 51 m². The cajeput trees in Figure 2c and 2d measured 60 cm and 66 cm dbh, respectively, with leaf areas of 314 m² and 54 m². In both cases, trees with similar dbh measurements have disparate quantities of foliage due to pruning.

Table 1. Sample size, estimated regression coefficients, and mean standard error values for predicting tree dimensions along with adjusted coefficients of determination for the modeling data set. To predict dimensions use: $\hat{y}_i = EXP\left[mse/2\left(\hat{A}+\hat{b}\log(\log(x_i+1))\right)\right]$, **where** $\hat{y}_i$ = **the tree dimension to be estimated and** x_i = **age or dbh.**

Species	Common name	n	Diameter at breast height (cm)				Height (m)				Crown height (m)				Crown diameter (m)			
			$\hat{A}$	$\hat{b}$	mse	R^2	$\hat{A}$	$\hat{b}$	mse	R^2	$\hat{A}$	$\hat{b}$	mse	R^2	$\hat{A}$	$\hat{b}$	mse	R^2
Callistemon citrinus	lemon bottlebrush	30	0.496	2.038	0.02646	0.71	-0.238	1.768	0.01667	0.64	-0.880	1.805	0.09283	0.23	-0.453	1.805	0.01253	0.71
Cedrus deodara	deodar cedar	28	0.895	2.461	0.16457	0.81	0.420	1.658	0.05827	0.82	0.476	1.417	0.08533	0.69	-0.356	1.986	0.05075	0.88
Ceratonia siliqua	carob	30	-1.43	4.042	0.07426	0.70	-0.239	1.747	0.02387	0.72	-0.848	1.767	0.10916	0.36	-0.803	2.229	0.02503	0.80
Cinnamomum camphora	camphor	28	0.147	2.931	0.08538	0.80	0.293	1.491	0.02189	0.78	0.248	1.109	0.07657	0.35	-1.003	2.486	0.02309	0.90
Cupaniopsis anacardioides	carrotwood	30	1.347	1.694	0.09648	0.91	0.742	1.077	0.02694	0.87	-0.256	1.399	0.08580	0.78	-0.349	1.932	0.02931	0.95
Eucalyptus ficifolia	red–flowering gum	31	-3.538	5.888	0.04513	0.61	-0.407	1.906	0.04145	0.37	-2.427	2.939	0.11720	0.33	-1.538	2.683	0.02238	0.69
Ficus microcarpa	laurel fig	33	1.718	1.724	0.02584	0.79	-1.517	2.730	0.01649	0.80	-1.491	2.161	0.08101	0.33	-3.126	3.896	0.02407	0.85
Jacaranda mimosifolia	jacaranda	31	1.544	1.354	0.11433	0.85	0.675	1.070	0.03395	0.78	-0.639	1.671	0.11998	0.71	-0.451	2.094	0.03610	0.93
Liquidambar styraciflua	sweetgum	33	1.123	1.754	0.05854	0.88	0.551	1.515	0.02049	0.89	0.383	1.188	0.06989	0.59	-0.232	1.726	0.02555	0.89
Magnolia grandiflora	southern magnolia	30	-0.781	3.436	0.06375	0.89	0.409	1.417	0.01988	0.88	-0.327	1.613	0.07373	0.71	-0.460	2.060	0.02918	0.91
Melaleuca quinquenervia	cajeput tree	30	-1.422	4.249	0.03020	0.69	-0.003	1.736	0.01284	0.61	-4.484	4.677	0.14139	0.50	-1.571	2.616	0.02242	0.67
Metrosideros excelsus	New Zealand Christmas tree	30	0.731	2.307	0.06686	0.76	-0.162	1.815	0.02884	0.73	-1.845	2.680	0.07627	0.69	-1.655	2.924	0.02411	0.89
Pinus canariensis	Canary Island pine	30	1.721	1.808	0.05344	0.91	0.556	1.721	0.03276	0.88	0.411	1.653	0.04567	0.82	-0.410	1.801	0.04928	0.84
Podocarpus macrophyllus	yew pine	30	1.268	1.441	0.04087	0.82	0.004	1.667	0.02774	0.76	-0.779	1.991	0.09776	0.56	-0.516	1.849	0.03870	0.74
Schinus terebinthifolius	Brazilian pepper	29	1.464	1.749	0.05810	0.53	-0.473	1.910	0.02750	0.56	-0.330	1.365	0.11763	0.11	-0.592	2.048	0.03019	0.57
Tristania conferta	Brisbane box	28	1.571	1.313	0.05347	0.88	0.791	1.074	0.02216	0.76	-0.869	1.940	0.17658	0.56	-0.917	2.308	0.04145	0.89

Table 2. The coefficient and mean standard error values for predicting tree leaf area using Equation (2) for the modeling data set. To predict leaf area as a function of dbh, use $LA = EXP(\hat{A}) * EXP((\hat{b}\,dbh) - 1) * EXP(mse/2)$**, where** LA **= estimated leaf area and** EXP **= the inverse of the natural logarithm. An example of the 95% confidence bounds for each species is presented by showing the predicted leaf area for the mean dbh for each species sampled and the associated confidence interval.**

Species	n	$\hat{A}$	$\hat{b}$	mse	R^2	Leaf area (m²) Mean	Lower	Upper
Callistemon citrinus	29	3.398	0.034	0.33762	0.31	34.37	27.47	43.01
Cedrus deodara	23	4.849	0.022	0.23969	0.87	236.99	192.31	292.06
Ceratonia siliqua	30	4.400	0.020	0.24623	0.68	115.61	95.57	139.71
Cinnamomum camphora	28	4.748	0.018	0.28622	0.74	132.44	107.80	162.71
Cupaniopsis anacardioides	29	2.941	0.053	0.28791	0.87	53.13	42.86	65.86
Eucalyptus ficifolia	31	4.077	0.022	0.23168	0.61	192.78	161.19	230.56
Ficus microcarpa	32	2.481	0.047	0.28770	0.68	116.02	95.40	141.09
Jacaranda mimosifolia	31	2.294	0.080	0.74336	0.75	60.59	44.07	83.29
Liquidambar styraciflua	33	3.544	0.042	0.79971	0.49	87.79	63.97	120.48
Magnolia grandiflora	27	3.337	0.045	0.29087	0.78	82.10	66.13	101.92
Melaleuca quinquenervia	30	2.695	0.042	0.99873	0.31	106.87	87.57	130.42
Metrosideros excelsus	30	2.732	0.053	0.27810	0.82	64.76	43.26	96.93
Pinus canariensis	28	3.793	0.039	0.24881	0.87	290.44	239.88	351.66
Podocarpos macrophyllus	28	2.763	0.060	0.26557	0.68	49.8	40.81	60.76
Schinus terebinthifolius	28	3.634	0.030	0.46873	0.43	116.20	90.20	149.69
Tristania conferta	27	0.529	0.134	0.79614	0.71	35.03	24.37	50.34

Growth Comparison

At 15 years after planting, estimated dbh ranged from 12 to 36 cm (4.7 to 14.2 in.), and tree height ranged from 4 to 16 m (13.1 to 52.5 ft) (Table 3). Fastest-growing trees by dbh are Canary Island pine, laurel fig, deodar cedar, and Brazilian pepper, while the slowest-growing ones are red-flowering gum, lemon bottlebrush, carob, and southern magnolia. These findings are surprising in that the two slowest-growing species are described as fast growing in the *Sunset Western Garden Book* (Brenzel 1997), and two of the fastest growing (laurel fig and Brazilian pepper) are listed as moderate.

Dbh growth tended to slow during the second 15 years for the species studied. The median rate of annual growth dropped from 1.29 cm

(0.5 in.) during the first 15 years to 0.97 cm (0.38 in.). Exceptions were red-flowering gum, which went from the slowest to the fastest-growing species, as well as the cajeput, carob, and southern magnolia. Our data suggest that these species are relatively slow starters.

Tree height and crown diameter showed similar growth patterns. Large-growing species such as Canary Island pine, deodar cedar, and camphor were among the tallest and widest after 15 years and continued growing at relatively fast rates. The median annual rates of height and diameter growth dropped from 0.44 m (1.4 ft) to 0.14 m (0.5 ft) and from 0.36 m (1.2 ft) to 0.13 m (0.4 ft), respectively, for the first and second 15-year periods. Only two species grew faster after the first 15 years. Average annual height and diam-
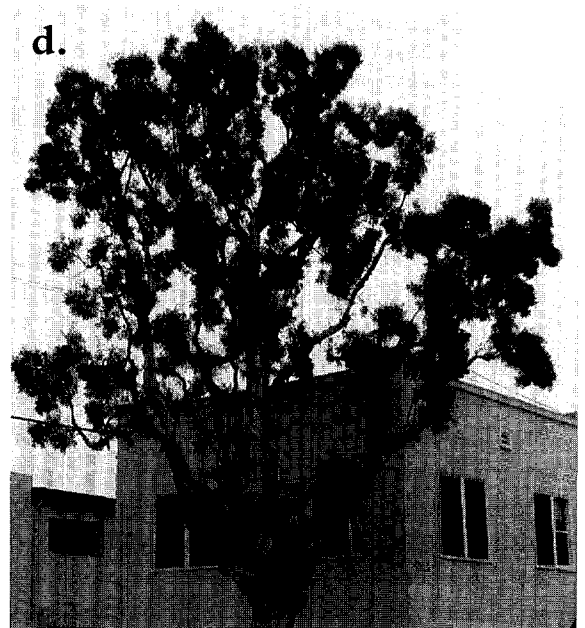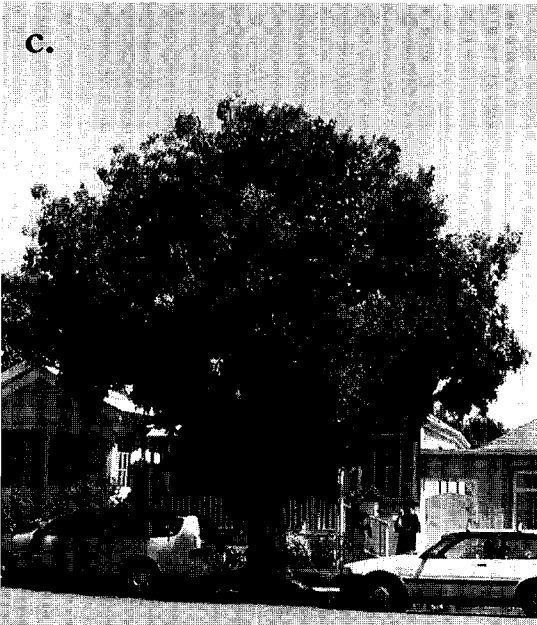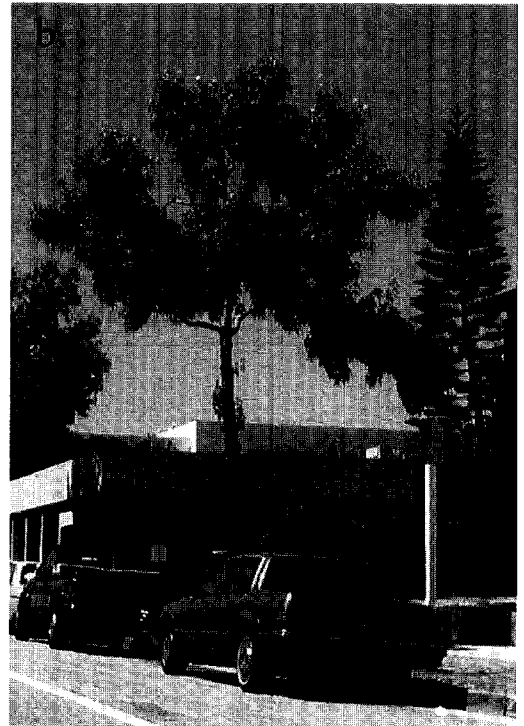
Figure 2. The municipal trees in Santa Monica are placed into one of six pruning classifications depending upon location and/or growth rates. Photos of sweetgum (top) and cajeput trees (bottom) illustrate the variability in crown height and leaf area. Each pair of trees has similar dbh measurements.

Table 3. Predicted sizes for all 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 (m²)	
	15	30	15	30	15	30	15	30
Pinus canariensis	36.29	53.43	16.21	19.24	6.90	8.25	154.42	347.02
Ficus macrocarpa	32.74	47.33	6.86	8.95	5.97	8.73	50.58	114.13
Cedrus deodara	32.69	57.85	11.77	16.09	8.04	11.70	126.62	380.86
Schinus terebinthifolius	26.50	38.52	6.23	7.59	6.53	8.08	59.10	106.23
Cinnamomum camphora	24.00	44.93	7.74	10.02	6.79	10.44	71.19	163.72
Cupaniopsis anacardioides	22.70	32.61	7.36	8.24	6.63	8.12	50.66	100.55
Metrosideros excelsus	22.58	36.99	6.26	10.00	4.70	10.01	30.07	190.71
Jacaranda mimosifolia	19.72	26.35	5.95	7.23	5.49	8.04	33.10	108.00
Liquidambar styraciflua	18.93	27.55	9.57	11.37	5.33	6.48	80.86	205.17
Melaleuca quinquenervia	18.65	46.30	6.90	10.43	4.27	6.16	38.07	89.44
Tristania conferta	18.45	24.96	7.22	7.92	5.10	6.22	28.88	68.56
Podocarpus macrophyllus	15.76	21.45	5.73	6.75	6.58	7.90	28.51	47.48
Magnolia grandiflora	15.72	32.78	6.59	9.04	5.41	8.56	33.23	108.64
Ceratonia siliqua	15.32	36.39	4.79	7.55	4.47	7.98	32.48	96.10
Callistemon citrinus	13.29	20.56	4.48	5.78	3.74	4.85	20.35	40.74
Eucalyptus ficifolia	12.05	42.48	4.11	8.54	2.73	7.66	20.52	105.27

eter growth accelerated slightly during the second 15 years for red-flowering gum, while only crown diameter growth accelerated during the later period for New Zealand Christmas tree.

Although large trees had the most leaf area, trees of all sizes tended to add more leaf area during the second 15-year period than during the first. The median annual rate of leaf area growth increased from 2.2 m² (78 ft²) for the first 15 years to 4.2 m² (150 ft²) for the next 15 years. Only three species exhibited a decreased rate of leaf area growth during the second 15 years (Brazilian pepper, carrotwood, and yew pine).

This finding indicates that the foliar biomass in tree crowns may be relatively sparse initially, when height and diameter are increasing at a rapid rate. As height and diameter growth slow, the foliage becomes more dense. Benefits associated with leaf area will increase as foliage thickens within the crowns of older trees. Unfortunately, as trees grow larger, an increasing number are removed due to conflicts with infrastructure (Bernhardt and Swiecki 1989). Maximizing benefits associated with densely crowned older trees will require more strategies to reduce these conflicts.

CONCLUSIONS

Our equations modeling the change in dbh, as a function of age, and the changes in tree height, crown diameter, and leaf area as functions of dbh produced strong correlations, particularly for those species planted over a long period of time. Although models based on measurements of tree dimensions are not ideal for predicting tree growth as a function of number of years after planting or dbh, they are currently the only available method for predicting tree dimensions and leaf area in urban forests. Application of the models to compare tree sizes across species at 15 and 30 years after planting showed that several species grow in Santa Monica at different rates than indicated in regional planting guides. Also, the finding that leaf area is greater for larger trees, and that it nearly doubles for all species during the second 15 years after planting, indicates the importance of managing urban forests for long-term health and sustainability while minimizing associated costs.

The method we used to develop the prediction equations differs from prior methods by incorporating a random sample of trees representing

a range of ages, planting locations, and conditions. The 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 any city to better understand the changing architecture of its street trees. Predictions derived from data collected in these cities can assist with urban forest planning by allowing tree managers to "grow" and match trees spatially to potential planting sites. Other applications include estimating pruning costs associated with different pruning cycles or the production of waste wood and leaf litter.

On a larger scale, the continued collection of data and development of predictive equations for additional tree species eventually 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. This will assist researchers and managers alike in determining the best urban forest management practices for increasing benefits and reducing costs associated with urban forests.

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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:

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

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.

Visual observation of the data suggested that the errors were of a multiplicative nature (Figure 1), increasing with age or dbh; therefore, the error was assumed to be multiplicative, and the responses were transformed via logarithm to equalize the variance along the line for the appropriate use of standard least-squares estimation procedures (LSE). The following regression model was used for the transformed response:

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

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

Parameter estimation was conducted using SAS (ver. 6.12) linear regression routines and 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

$$\hat{z}_i = \hat{A} + \hat{b}v_i \text{ and}$$

mse = mean sum of squares from LSE. Therefore, the fitted value of y_i is given by

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

where

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

Estimates $\hat{A}$ and $\hat{b}$, and mse are used to predict dimensions for each species listed in Table 1.

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.

[1*]*USDA Forest Service*
Pacific Southwest Research Station
c/o Department of Environmental Horticulture
One Shields Avenue
University of California
Davis, CA, USA 95616-8587

[2]*USDA Forest Service*
Pacific Southwest Research Station
Berkeley, CA, USA

Corresponding author

Résumé. La hauteur de l'arbre, la hauteur et la largeur de la cime, le DHP (diamètre à hauteur de poitrine) du tronc, et la surface foliaire ont été mesurés pour 16 espèces d'arbres couramment plantées le long des rues au sein de la ville de Santa Monica, ville située dans la zone côtière de la Californie méridionale. Les arbres échantillonnés aléatoirement ont été plantés il y a de 1 à 44 ans auparavant. En utilisant le nombre d'années après la plantation ou encore le DHP comme variable explicative, des valeurs moyennes de DHP, de hauteur de l'arbre, de largeur de la cime et de surface foliaire ont été modélisées au moyen de deux équations. Il y a une corrélation forte (valeur ajustée de $R^2 > 0,70$) entre le DHP–comme fonction du nombre d'années après la plantation–et la hauteur totale, ainsi qu'entre le diamètre de la cime et la surface foliaire en fonction aussi du DHP. La corrélation est plus faible entre les mesures de la hauteur de cime et le DHP. Ceci est probablement dû à l'élagage passé de la cime qui a fait augmenter la variabilité entre ces mesures pour des arbres ayant des DHP identiques ou similaires. Les équations pour les espèces élaguées moins intensivement ont donné des valeurs ajustées de R^2 plus grandes que 0,70. Des équations pour prédire les dimensions et la surface foliaire sont présentées et appliquées pour comparer les dimensions et la croissance de toutes les espèces d'arbres, et ce 15 et 30 ans après leur plantation.

Zusammenfassung. In der südkalifornischen Küstenstadt Santa Monica wurde die Baumhöhe, Kronenhöhe, Kronebreite, BHD und die Blattfläche von 16 häufig gepflanzten Straßenbäumen gemessen. Die zufällig ausgewählten Bäume wurden vor 1–44 Jahren gepflanzt. Wenn die Anzahl der Jahre nach der Pflanzung oder der BHD als erläuternde Variablen angenommen werden, können die Ergebnisse der Baumhöhe, Kronebreite und Blattfläche durch zwei Gleichungen dargestellt werden. Es gibt eine starke Korrelation (korrigiert $R^2>0.70$) zwischen dem BHD als eine Funktion der Anzahl der Jahre nach der Pflanzung und totaler Höhe, Kronendurchmesser und Blattfläche als eine Funktion des BHD. Die Korrelation ist schwächer zwischen Messungen der Kronenhöhe und des BHD. Dies ist wahrscheinlich auf den Kronenrückschnitt zurückzuführen, welcher die Variabilität zwischen den Messungen an Bäumen mit ähnlichem oder gleichem BHD darstellt. Gleichungen für weniger geschnittene Arten zeigten korrigiert $R2>0,70$. Es werden Gleichungen präsentiert, die die Blattfläche und deren Ausmaß vorhersagen und die angewendet werden können, um Baumgrößen und Wachstum aller Spezies 15 bis 30 Jahre nach der Pflanzung zu vergleichen.

Resumen. Se midió la altura del árbol, la altura de la copa, el diámetro de la copa, el diámetro a la altura del pecho (d.b.h.) y el área foliar, de 16 especies de los árboles urbanos más comunes en la ciudad de Santa Mónica en la costa sur de California. Los árboles seleccionados al azar fueron plantados desde hace uno a 44 años. Utilizando el número de años después de la plantación o el d.b.h como variables de respuesta, se modelaron, usando dos ecuaciones, los valores medios de d.b.h., la altura del árbol, el diámetro de la copa y el área foliar. Existe una fuerte correlación ($R^2>0.70$) entre d.b.h., como función del número de años después de la plantación, y la altura total, diámetro de copa y área foliar, como una función de d.b.h. La correlación es más débil entre las mediciones de la altura de la copa y d.b.h. Esto es probablemente debido a que las podas de la copa incrementan la variabilidad entre las mediciones para los árboles que tienen el mismo o similar d.b.h. Las ecuaciones para árboles podados menos intensivamente desplegaron R^2 ajustados mayores que 0.70. Se presentan las ecuaciones para predecir las dimensiones y el área foliar, y se aplican para comparar las dimensiones de los árboles y el crecimiento para todas las especies, 15 y 30 años después de la plantación.