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Structure, function and value of street trees in California, USA

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ABSTRACT

This study compiled recent inventory data from 929,823 street trees in 50 cities to determine trends in tree number and density, identify priority investments and create baseline data against which the efficacy of future practices can be evaluated. The number of street trees increased from 5.9 million in 1988 to 9.1 million in 2014, about one for every four residents. Street tree density declined from 65.6 to 46.6 trees per km, nearly a 30% drop. City streets are at 36.3% of full stocking. State-wide, only London planetree (*Platanus* × *hispanica*) comprises over 10% of the total, suggesting good state-wide species diversity. However, at the city scale, 39 communities were overly reliant on a single species. The state's street trees remove 567,748 t CO_2 (92,253 t se) annually, equivalent to taking 120,000 cars off the road. Their asset value is $2.49 billion ($75.1 million se). The annual value (USD) of all ecosystem services is $1.0 billion ($58.3 million se), or $110.63 per tree ($29.17 per capita). Given an average annual per tree management cost of $19.00, $5.82 in benefit is returned for every $1 spent. Management implications could include establishing an aggressive program to plant the 16 million vacant sites and replace removed trees, while restricting planting of overabundant species. Given the tree population's youth there is likely need to invest in pruning young trees for structure and form, which can reduce subsequent costs for treating defects in mature trees.

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1. Introduction

Street trees, defined as trees growing along public street right-of-way and managed by the city, account for a relatively small fraction of the entire urban forest, but are prominent because of their visual and physical impacts on the quality of urban life. For example, although street trees in the City of Chicago accounted for only 10% of the city's tree population, they comprised 24% of total leaf surface area (McPherson et al., 1997). This study examines the structure, function and value of California's current street tree population. Several studies indicate that street tree density in California is declining. One goal of this study is to determine if this remains cause for concern. A second goal is to prioritize management challenges at the state and regional levels. For the first time, this study quantifies the value of ecosystem services produced by California's street tree population. This assessment provides a baseline for California and it is among the first to present a comprehensive view of a state's street tree resource.

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Municipal forests consist of street and park trees managed for the public good. Street tree populations have their own unique structure, tending to be less diverse, containing more large-stature species and exhibiting higher levels of spatial continuity than other components of the urban forest (Jim and Liu, 2001).

The following review begins with a description of street tree assessments conducted at large scale, for the entire United States and for several states within the U.S. It then narrows its focus to studies concerned with municipal forests in the state of California.

1.1. United States and state-wide assessments

In 1989, an assessment of street trees in 320 U.S. cities was conducted (Kielbaso and Cotrone, 1990). There were identified approximately 61.6 million street trees averaging 63.4 trees per street km (102/mile) and 0.4 per person. Assuming trees were planted 15.2 m (50 ft) apart, there was room for planting another 66 million street trees. The ratio of trees planted to removed each year was 0.99, a decrease from 1.2 found several years earlier. The authors reported that this ratio dropped in larger cities, as did the condition rating of trees. The asset value of the nation's street trees was an estimated $30 billion, assuming $500 per tree.

A more recent U.S. survey focused on public tree management (Tschantz and Sacamano, 1994). In 1994, the average number of publically-owned street and park trees was 0.63 per capita. The average municipal tree management budget was $2.49 per capita, down from $4.14 in 1986.

State-wide assessments in the U.S. have varied in their methods and scope. A 1994 survey of public trees in 20 Michigan communities estimated 1.67 million street trees state-wide with 49% full stocking (Wildenthal and Keilbaso, 1994). Between 2001 and 2003 the US Forest Service Forest Health Monitoring (FHM) team partnered with Urban & Community Forestry staff in Wisconsin (Cumming et al., 2008), Maryland and Massachusetts (Cumming et al., 2006) to survey street trees state-wide. The most serious management issue noted was lack of species diversity. The top five species accounted for 45% to 60% of the total street tree populations, indicating overreliance on a small number of species. The susceptibility of black walnut (*Juglans nigra*) street trees to Thousands Cankers Disease (resulting from the fungus *Geosmithia morbida*) in Kansas (Treiman et al., 2010) and ash trees to emerald ash borer (*Agrilus planipennis*) in South Dakota (Ball et al., 2007) were the subjects of state-wide analyses of tree inventories. A region-wide-assessment used street tree inventory data to examine threats posed by exotic borers in eastern North America (Raupp et al., 2006).

A 2008 study of street trees in 23 Indiana communities applied i-Tree Streets (formerly STRATUM) software to calculate the economic value of ecosystem services produced annually by the state's 1.42 million street trees (Davey Resource Group, 2010a,b). Annual services were valued at $78.7 million or $55.51 per tree.

In 2010 street trees on 284 plots in 44 Missouri communities were resurveyed after previous inventories in 1989 and 1999 (Treiman et al., 2011a,b). This 20-year longitudinal assessment is unique. Street tree density increased from 28.7 trees per km (46.2/mile) in 1989 to 40 (64.3/mi) in 2010. During the same period the percentage of total street tree sites filled with trees, or percentage of full stocking, increased from 33% to 56%. State-wide, 33.9% of all trees were juvenile (<15 cm dbh), 22.5% were maturing (15–30 cm dbh), 30.6% were semi-mature (30–61 cm dbh) and 13.0% were mature (>61 cm dbh). The most frequent condition class was Fair (62.1%), followed by Good (19.2%), Poor (16.2%) and Dead/Dying (2.5%). Sidewalk conflicts occurred with 30.2% of the trees. Annual ecosystem benefits totaled $147.9 million ($90.55 per tree).

A state-wide assessment for New York used 142 inventory datasets (Cowett and Bassuk, 2014). Total street trees were estimated by weighting the sample using the relative percentages of summed street length for each climate zone. Statistical analyses found that average minimum winter temperature was the best predictor of species composition. Therefore, data were presented for each USDA Hardiness Zone, as well as for the entire state. There were an estimated 4.2 million street trees and the weighted mean street tree density was 50 trees per km (80.5/mile). Trees in the genus *Acer* (maple) accounted for 44.1% of the total, a cause for concern because of their vulnerability to Asian longhorned borer (*Anoplophora glabripennis*).

1.2. California's municipal forests

Several studies have assessed the structure and function of municipal forests in California. Computerized street and park tree inventories from 29California communities were analyzed to score their relative stability (McPherson and Kotow, 2013). Grades were assigned to four aspects of a stable and resilient municipal forest: species dominance (based on numbers and size), age structure (based on dbh distribution), pest threat (based on pest count and severity) and potential asset loss (based on percentage of total asset value at high and very high risk of loss from pests). Thirteen inventories received their lowest grade for age structure, largely because juvenile trees were underrepresented. Data were not compiled to estimate tree numbers state-wide.

Muller and Bornstein (2010) reviewed trends in species diversity using policies and planting lists from 49California communities and inventories from 18 cities. They reported that species richness was high (mean of 185 taxa per community) but recent plantings lacked diversity. This trend towards planting of a few preferred species was previously noted by Lesser (1996) as well.

Comprehensive questionnaires were administered to municipal forest managers in California communities in 1988, 1992, 1998 and 2003 to identify trends (Bernhardt and Swiecki, 1989, 1993; Thompson, 2006; Thompson and Ahern, 2000). Over the 15-year period the state's street tree population and street trees per capita were estimated to have increased from 5.9 to 7.2 million and 0.24–0.29, respectively. However, the California surveys identified several troubling trends:

- increased planting of small, short-lived species due to lack of space for street trees
- declining species diversity
- average city tree budget has declined in real dollars from about $3 per capita in 1988 to $2 in 2003
- higher percentages of programs report removing more trees than they plant (18% in 1988–22% in 2003)
- reduction in the average number of trees per km street length, from 65.6 in 1988 to 64.3 in 1993 (105.5–103.5/mile).

If street tree stocking levels are decreasing so might the ecosystem services they provide, such as energy savings, carbon storage, air pollutant uptake and rainfall interception. One goal of this study is to determine if trends in street tree stocking levels are increasing or decreasing. Although previous studies have calculated tree numbers, density and stocking levels, their estimates were derived from questionnaires, not tree inventories. Estimates were not well substantiated, lacking standard errors or other measures of variance. This study improves the quality of the assessment of the state's municipal forest structure by using tree inventories, allowing measures of variance to be presented. A second goal of this study is to identify planning and management priorities based on the assessment of structure, function and value. The third goal is to generate new information on street tree function and value scaled to the state-wide level. Hence, this assessment serves as a comprehensive baseline against which the efficacy of future planning and management practices can be evaluated.

2. Methods

2.1. Climate zones

For purposes of i-Tree modeling (McPherson, 2010) California was subdivided into six climate zones based largely on aggregation of Sunset National Garden Book's 45 climate zones (Brenzel, 1997) and ecoregion boundaries delineated by Bailey (2002) and Breckle (1999) (Fig. 1). Extensive tree size measurements were made in a reference city in each climate zone, with growth equations used for benefit modeling in the i-Tree Streets application (McPherson and Peper, 2012; Peper et al., 2001).

2.2. Street tree inventories

Fifty-six tree inventories were obtained from CAL FIRE, who has funded inventories and management plans in many California communities. To be included in this study the inventory had to:

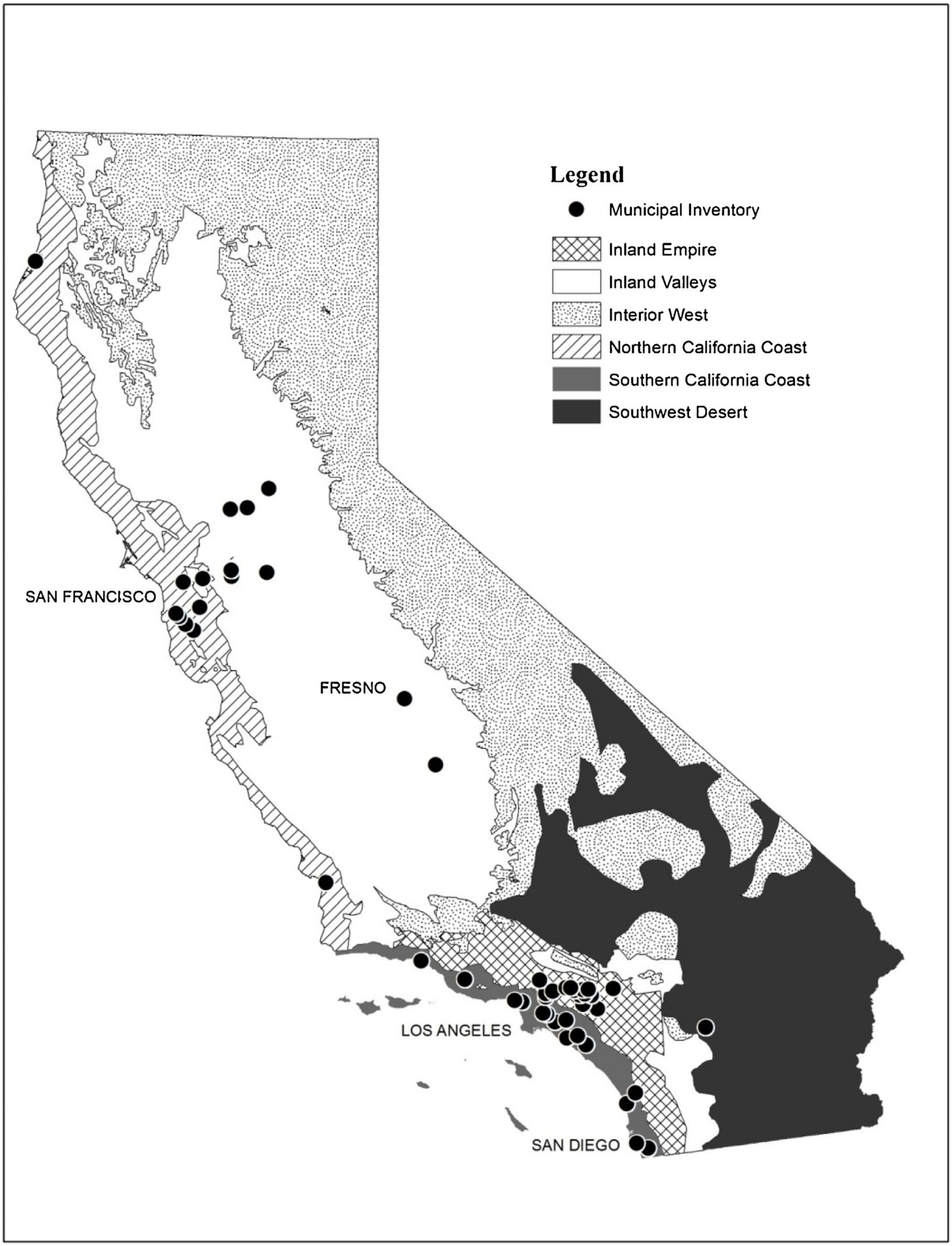

Fig. 1. Locations of climate zones and cities with street tree inventories used in this study.

- include all publicly managed trees
- contain data for each tree on species and diameter at breast height (dbh)
- be conducted after 2005

Data from 49 municipal inventories met these criteria. Each inventory was pre-processed to eliminate park trees and other trees that were not street trees. Any tree labeled as stump, planting site, vacant or unsuitable site was removed from the database. In total, the final 49California inventories comprised 908,304 trees. Lacking a street tree inventory for a California city in the Interior West (IW) zone, street tree data for the IW climate zone's reference city, Albuquerque, NM, were used. Albuquerque was selected to represent the IW instead of a California city from another climate zone because Albuquerque's high desert climate is most similar to those of cities like Bishop, Bridgeport and South Lake Tahoe. As a result, the function and value of ecosystem services are likely to be more accurately modeled (McPherson, 2010). Adding this city increased the number of inventoried trees used in the analysis to 929,823 (Table S1 in the supplementary on-line information).

Tree data were prepared for entry into i-Tree Streets by matching species to those in the i-Tree database. If species did not match directly, they were assigned using a species in the same genus with similar growth characteristics. Because different tree inventory software were originally used it was necessary to standardize data for comparison purposes. Six dbh size classes were established: 0–15.1 cm, 15.2–30.4 cm, 30.5–45.6 cm, 45.7–60.9 cm, 61–76.1 cm, >76.2 cm. Maintenance recommendations were: none, prune, remove and other.

2.3. i-Tree streets modeling

i-Tree is a suite of urban and community forestry computer tools designed to help communities of all size strengthen their urban forest management and advocacy efforts by quantifying the structure of community trees and the value of ecosystem services that trees provide (www.itreetools.org). Within i-Tree, street tree populations are assessed using Streets. i-Tree Streets uses tree inventory data to quantify structure, function and value of annual benefits. Descriptions of the numerical models used to calculate effects of trees on energy use, carbon storage, air pollutant uptake, rainfall interception and residential property values are found in Maco and McPherson (2003) and (McPherson et al., 2005). This study used i-Tree Streets (v.5.1.5) and existing inventories of street trees to evaluate current ecosystem services and management needs.

A database was created for each street tree inventory in Microsoft Access and imported into i-Tree Streets. Information regarding default and user-defined input values for each city such as name, climate zone, population, and area, as well as electricity emission factors and prices used to monetize ecosystem services are included in the online supplementary data tables. Additional information on the assumptions and calculations used in i-Tree Streets to compute structure, function and value can be found in six Tree Guidelines documents, one for each climate zone (McPherson et al., 2010; McPherson et al., 2004; McPherson et al., 2000a; McPherson et al., 1999; McPherson et al., 2000b; Vargas et al., 2007).

2.4. Street tree structure

2.4.1. Tree numbers and stocking

Following the method applied in New York State to calculate street tree numbers, the mean street tree density was multiplied by the total street length for all cities in each climate zone (Cowett and Bassuk, 2014). The number of street miles were obtained for each city from the U.S. Census Tiger Line dataset (U.S. Census Bureau, 2010). Highways, private streets, trails and other thoroughfares unlikely to contain trees managed by the city were eliminated. Following the approach of Cowett and Bassuk (2014) to calculate weighted state-wide means for street tree density and species composition, the relative percentages of summed street lengths were calculated for each climate zone as:

$$\bar{m} = \frac{\sum_{i=1}^{6} w_i m_i}{\sum_{i=1}^{6} w_i} \quad (1)$$

where m_i is the mean value for climate zone i and w_i is the weight defined as the percentage of street lengths in all inventoried cities represented in climate zone i (total across all six climate zones = 100%). Weighting by the percentage of street lengths accounts for differences among the non-random sample inventories. Standard errors for the state-wide means were calculated similarly:

$$se_{\bar{m}} = \frac{\sqrt{\sum_{i=1}^{6} se_i^2 w_i}}{\sum_{i=1}^{6} w_i} \quad (2)$$

where se_1 is the standard error of the mean for climate zone i.

Wray and Prestemon (1983) defined full stocking as having a spacing of 15.2 m (50 ft) between stems of street trees. This distance includes street length occupied by driveways and intersections. We used this spacing with street lengths and tree numbers to calculate "stocking levels" as the percentages of full stocking. These values are an index for comparing density of trees along city streets and the opportunities for plantings.

2.4.2. Species abundance

Street tree relative species abundance was scaled up from the municipal inventory level (49 inventories) to the climate zone level (6 zones) and eventually to a state-wide level. Relative species abundance was calculated as the percentage of species occurring in the city (or climate zone) divided by the total number of street trees in the city (or climate zone). At each level, a weighted mean (as in Eq. (1)) was applied to account for the unequal street tree population sizes in each city or climate zone.

As part of the data processing to summarize relative species abundance, all cultivars and subspecies were lumped to the species level since most management issues (i.e., pest/disease threats, pruning requirements, longevity and growth rates, etc.) do not differ substantially among cultivars and subspecies. For example, although the many cultivars of *Pyrus calleryana* have different flowering traits and form, similar management requirements warrant treating them as one lumped species.

2.4.3. Size diversity

In this study we use size diversity (measured dbh) as a proxy for age diversity recognizing that the relationship between the dbh and age is not linear and, thus, the relationship can only be approximate. Good age diversity is essential for population stability because an uneven-aged population allows managers to allocate maintenance costs uniformly over many years, and assures a consistent stream of benefits from stable tree canopy cover (Richards, 1983). McPherson and Rowntree (1989) identified three patterns of age structure in street tree populations. Youthful populations had over 40 percent of the trees in the smallest diameter at breast height (dbh) class. Maturing populations had more individuals in the 16–45 cm dbh classes than in the 0–15 cm class, indicating that most trees were planted approximately 20–50 years ago. Mature populations had a relatively even distribution of trees among all diameter classes, with many mature or senescent trees planted over 50 years ago. Benefits associated with the biomass of these large, old trees may be partially negated by their potential for failure, as well as their high maintenance and removal costs. A target age distribution for population stability would be 40 percent of all trees under 20-cm dbh, 30 percent 20- to 40-cm, 20 percent 40- to 60-cm and 10 percent >60-cm (Richards, 1983). The high proportion in the small dbh class is needed to offset establishment-related mortality. Characteristic patterns of size structure were identified for the inventories in each climate zone as the mean percentage of trees at each dbh size class.

2.5. Function and value calculations

i-Tree Streets default values were used to calculate function and value except for cases where more current environmental, economic and demographic data were collected for the analysis (Table

S1). To scale-up results from each inventory, mean values per tree (e.g., kWh cooling savings per tree) were calculated for each climate zone. The mean values were multiplied by the estimated total number of trees and associated measures of variance in each climate zone. Climate zones totals were summed to derive state-wide grand totals. Standard errors reflect variance associated with estimates of tree numbers, and do not include uncertainties related to tree measurements and numerical modeling.

Calculations of energy effects of trees on residential buildings incorporated tree species and size data from the inventories. Shading effects were based on the distribution of street trees with respect to buildings recorded from aerial photographs for each reference city (McPherson and Simpson, 2002). Because these distributions are unique to each city the values are first-order approximations. Energy savings result in reduced emissions of criteria air pollutants (volatile organic hydrocarbons [VOCs], NO_2, SO_2, PM_{10}) from power plants and space-heating equipment. These avoided emissions were calculated using updated emission factors for electricity (Table S2) and i-Tree Streets default values for natural gas heating fuel. The updated value of avoided CO_2 emissions assumed a price of $16.53 per t CO_2, based on the California Carbon Allowance Futures for June 2012 (Climate Policy Initiative, 2014) (Table S3).

The uptake of air pollutants by municipal forests can affect human health (Nowak et al., 2014). Hourly pollutant dry deposition per tree was calculated using i-Tree Streets default deposition velocities and hourly meteorological data and pollutant concentrations (Scott et al., 1998). Air quality effects were monetized as the mean cost of pollution offset transactions (Table S3). California requires air quality management districts that are not in attainment of ambient air quality standards to adopt emission reduction programs. These programs allow polluters to reduce their own emissions to target levels or purchase offsets from polluters who have already cut their emissions. The California Air Resources Board's (2011) most recent report found that 666 transactions took place in California in 2008. Mean values that represent the state-wide average cost of a transaction were used in this study.

Intercepted rainfall can evaporate from the tree crown, thereby reducing stormwater runoff. A numerical interception model accounted for the amount of annual rainfall intercepted by trees, as well as throughfall and stem flow (Xiao et al., 2000). The rainfall interception benefit was priced by estimating costs of controlling stormwater runoff, and i-Tree Streets default values were used (Table S3).

Many benefits attributed to urban trees are difficult to price (e.g., increased property values, beautification, privacy, wildlife habitat, sense of place, well-being). However, the value of some of these benefits can be captured in the differences in sales prices of properties that are associated with trees (Anderson and Cordell, 1988). Previous analyses showed that differences in residential property values among cities and associated tree benefits were best modeled by applying the 0.88% sales price increase to the city's median home sales price. Hence, in the i-Tree Streets analysis, property value benefits ($/tree/year) reflect differences in the contribution to residential sales prices of a large front yard tree, and annual changes in leaf area as trees grow in each city. Median home sales prices were gathered for January to April 2014 (Trulia.com, 2015) (Table S1). Values for ecosystem services are expressed in annual terms, but trees provide benefits across many generations. To enable tree planting and stewardship to be seen as a capital investment, the replacement value of all street trees was calculated by i-Tree Streets following trunk formula procedures outlined by the Council of Tree and Landscape Appraisers (2000) .

3. Results

3.1. Sample

The total population of inventoried cities (4.5 million) is 14.8% of California's 30.8 million people living in cities (Table 1). Another 6.4 million Californians live in unincorporated areas, but there were no tree inventory data for counties. There are differences in percentages of population, street length, city area and street tree inventory numbers across climate zones. For example, 13.3 million people living in cities in the Southern California Coast (SC) climate zone account for 38.5% of the state's inhabitants. However, because population density is relatively high, the percentages of street length (27.6%) and land area (21.2%) are substantially less than population. Conversely, population densities are lowest in the Southwest Desert (SW) and Interior West (IW) zones, where percentages of street length and land area are several times greater than their respective population percentages.

3.2. Structure

3.2.1. Tree numbers and stocking

The weighted mean street tree density is 46.6 (3.5 standard error [se]) trees per km street length (75.0/mile, 5.7 se) and ranges from 6.6 (IW, 10.6/mile) to 56.8 per km (Northern California Coast [NC], 91.3/mile). There are approximately 9.1 million street trees in California cities (Table 1) and 0.26 street trees per capita, about one street tree for every four persons. State-wide, city streets are at 36.3% of full stocking and there are approximately 16 million vacant tree sites.

The SC zone has 30.3% of all California street trees, but the number of trees per capita, 0.21 (about 1 street tree for every 5 people), is relatively low. Cities in the Inland Valley (IV) and NC zones contain 22.4% and 21.8% of all trees, respectively. The numbers of trees per capita are similar, 0.28 and 0.30. Street trees in the IE account for 18.3% of the state-wide total and there are 0.29 trees per capita. The estimated 631,146 street trees in the SW zone account for 6.8% of the state-wide total and there are 0.5 trees per capita. Cities in the IW zone had an estimated 25,516 trees (0.3%) and 0.13 trees per capita.

Table 1
Summary statistics for each climate zone in California (standard error).

	Inland Empire	Inland Valleys	North. Calif. Coast	South. Calif. Coast	Southwest Desert	Interior West	Total
Street Length (km)	32,940	52,872	35,150	33,607	16,766	4032	195,845
Population	5,818,216	7,263,710	6,738,763	13,339,610	1,250,997	211,054	34,622,350
Area (km^2)	5074	8275	4431	6028	3643	1049	28,499
Trees Sampled	273,351	261,371	147,659	215,624	10,299	21,519	929,823
Mean Density (trees/km)	50.74 (6.65)	38.64 (8.02)	56.75 (10.20)	51.09 (6.11)	37.64 (6)	6.58 (1.04)	46.62 (3.52)
Total Street Trees (1,000s)	1,671.4 (219.0)	2,042.7 (424.1)	1,994.8 (358.4)	2,763.3 (330.4)	631.1 (100.7)	26.5 (4.2)	9,129.8 (689.7)
Total Sites (1,000s)	4,322.9	6,938.6	4,612.9	7,097.8	2,200.3	529.1	25,172.4
Vacant Sites (1,000s)	2,651.5	4,895.9	2,618.1	4,334.5	1,569.1	502.6	16,042.6
Full Stocking (%)	38.7	29.4	43.2	38.9	28.7	5.0	36.3
Trees per Capita	0.29 (0.04)	0.28 (0.06)	0.30 (0.05)	0.21 (0.02)	0.50 (0.08)	0.13 (0.02)	0.26 (0.02)

Table 2
Relative species abundance (%) by climate zone and statewide. Species are listed in descending order of relative abundance.

Inland Empire	%	Inland Valleys	%	North. Calif. Coast	%	South. Calif. Coast	%	Southwest Desert	%	California	%
Lagerstroemia indica	9.4	*Platanus x hispanica*	11.3	*Platanus x hispanica*	10.5	*Pinus canariensis*	6.3	*Washingtonia robusta*	18.0	*Platanus x hispanica*	10.5
Liquidambar styraciflua	9.3	*Pistacia chinensis*	8.9	*Magnolia grandiflora*	7.0	*Lophostemon confertus*	4.8	*Washingtonia filifera*	9.3	*Pistacia chinensis*	7.0
Cinnamomum camphora	4.5	*Lagerstroemia indica*	6.9	*Liquidambar styraciflua*	6.6	*Washingtonia robusta*	4.4	*Phoenix dactylifera*	6.8	*Lagerstroemia indica*	6.6
Pinus canariensis	4.2	*Pyrus calleryana*	5.2	*Pyrus calleryana*	3.7	*Lagerstroemia indica*	4.2	*Dalea spinosa*	4.9	*Pyrus calleryana*	3.7
Platanus x hispanica	4.2	*Celtis sinensis*	4.5	*Pistacia chinensis*	3.4	*Liquidambar styraciflua*	4.0	*Acacia aneura*	4.5	*Liquidambar styraciflua*	3.4
Syagrus romanzoffiana	3.5	*Fraxinus velutina*	3.6	*Lagerstroemia indica*	3.2	*Jacaranda mimosifolia*	3.7	*Parkinsonia florida*	3.8	*Celtis sinensis*	3.2
Pyrus calleryana	2.8	*Zelkova serrata*	3.6	*Prunus cerasifera*	3.1	*Eucalyptus globulus*	3.5	*Acacia stenophylla*	3.6	*Fraxinus velutina*	3.1
Washingtonia robusta	2.8	*Liquidambar styraciflua*	3.0	*Quercus agrifolia*	3.1	*Magnolia grandiflora*	3.1	*Acacia farnesiana*	3.6	*Magnolia grandiflora*	3.1
Magnolia grandiflora	2.7	*Sequoia sempervirens*	2.9	*Cinnamomum camphora*	2.9	*Syagrus romanzoffiana*	2.8	*Brachychiton populneus*	3.3	*Zelkova serrata*	2.9
Ulmus parvifolia	2.7	*Magnolia grandiflora*	2.6	*Fraxinus velutina*	2.7	*Cupaniopsis anacardioides*	2.8	*Chilopsis linearis*	2.7	*Sequoia sempervirens*	2.7
Mean # taxa	174		157		214		171		105		175

3.2.2. Species abundance

The relative abundance of the top species is listed for each climate zone, as well as the mean number of taxa in the inventories (Table 2). The mean number of taxa for California is 175 and the means range from 105 (SW) to 214 (NC) among climate zones.

In the SW climate zone California fan palm (*Washingtonia robusta*) is by far the most abundant species (18%), followed by two other palm species: Mexican fan palm (*Washingtonia filifera*) at 9.3% and date palm (*Phoenix dactylifera*) at 6.8%. The climate zones with the next highest single species abundance are the IV and the NC, where London planetree (*Platanus x hispanica*) accounts for 10.5% of all trees. Of all the climate zones, SC has the lowest relative abundance of a top species, with Canary Island pine (*Pinus canariensis*) comprising 6.3% of the street tree population.

On the state-wide scale, London planetree (10.5%) is the sole species that claimed more than 10% relative abundance (Table 2). The next most abundant species are Chinese pistache (*Pistacia chinensis,* 7.0%), crape myrtle (*Lagerstroemia indica*, 6.6%), Callery pear (*Pyrus calleryana*, 3.7%) and sweetgum (*Liquidambar styraciflua*, 3.4%). Chinese hackberry (*Celtis sinensis*), velvet ash (*Fraxinus velutina*), Southern magnolia (*Magnolia grandiflora*), Japanese zelkova (*Zelkova serrata*) and redwood (*Sequoia sempervirens*) each comprise about 3% of the state's street tree population.

Besides Canary Island pine, which is present in substantial numbers in the SC and IE, the only other coniferous species in the top ten most abundant species is redwood (2.7% in the IV). State-wide, these two conifers make up nearly 4% of the street tree population's relative abundance.

3.2.3. Size diversity

The IV inventories are characterized as young populations, with relatively high percentages of young trees (55%) and lower than ideal percentages of mature (18%) and old (5%) trees (Fig. 2). The IE and SW populations are mature, with above ideal percentages of mature trees (37%) and relatively few young trees (26%). The SC and NC have nearly ideal percentages of young trees (35%), but the SC has above ideal percentages of mature trees (33%) and relatively few old trees (5%). The mean percentages for the NC come closest to matching the ideal distribution of age diversity.

3.2.4. Life form

In the IW, IV and NC over 60% of inventoried trees are deciduous (Fig. 3). In the IE inventories, deciduous (44%) and broadleaf evergreens (39%) account for 83% of their populations. In the SC inventories, 50% of all trees are broadleaf evergreens. Palms (35%) are the most abundant life form in the SW inventory, followed closely by broadleaf evergreens (31%) and deciduous (30%).

3.2.5. Maintenance

Tree maintenance recommendations were reported in 44 of the 49California inventories. The mean percentage of trees requiring pruning range from 63.4% in the IV to 94.8% in the NC. In the IE and SC the mean values are 89.1% and 90.9%, respectively. The mean percentage of trees requiring removal range from 1.2% (IV) to 3.3% (IE). Mean values are 1.5% and 2.0% for the SC and NC zones, respectively.

3.3. Function and value

3.3.1. Energy

State-wide annual electricity savings from air conditioning reductions total 684 GWh year^{-1} (114 GWh year^{-1} se), or 74.9 kWh year^{-1} per tree (12.5 se) on average (Table 3). Cooling savings average 90–100 kWh year^{-1} per tree in the NC, IV, and IE climate zones, and total 200, 186 and153 GWh year^{-1}, respectively.

State-wide, street trees reduce annual natural gas used for heating by 580,152 GJ year^{-1} (100,049 GJ year^{-1} se), or 60.2 kBtu year^{-1} per tree on average (Table 3). Trees slightly increase heating in the IE zone by −35,921 GJ year^{-1} (−20 kBtu year^{-1} per tree). Heating savings are greatest in the NC zone (427,326 GJ year^{-1}, 203 kBtu year^{-1} per tree).

The total annual monetary value of energy savings from the state's 9.1 million street trees is $101.15 million ($16.8 million se) (Table 4). The average annual benefit per tree is $11.08 ($1.84 se) and ranges from $5.77 in the SC to $15.68 in the NC.

3.3.2. Carbon dioxide

California's 9.1 million street trees are estimated to store 7.78 million metric tonnes (MMt) (1.3 MMt se) CO_2 (Table 3). Climate zones wherein the most CO_2 is stored in street tree biomass are the NC (2.51 MMt) and IV (2.17MMt). On average, 852.4 kg (142.1 kg) CO_2 is stored per tree. The average amount stored per tree is nearly four times greater in the NC (1,256.3 kg) than the SW (327.6 kg).

The amount of CO_2 sequestered each year by street trees is 375,704 t year^{-1} (59,530 t year^{-1} se) (Table 3). Municipal forests in the NC (133,772 t year^{-1}) and SC (94,961 t year^{-1}) zones sequester the most CO_2. Sequestration rates per tree

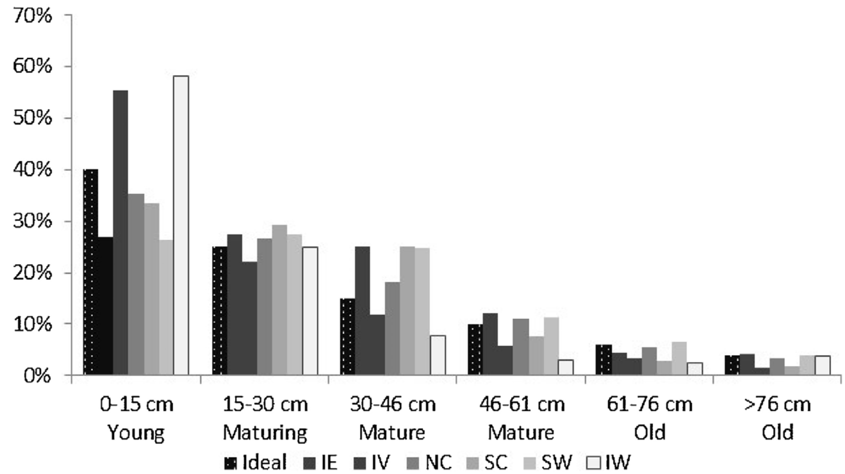

Fig. 2. Patterns of street tree age structure from inventories in each climate zone and the "ideal" (IE is Inland Empire, IV is Inland Valleys, NC is Northern California Coast, SC is Southern California Coast, SW is Desert Southwest, IW is Interior West).

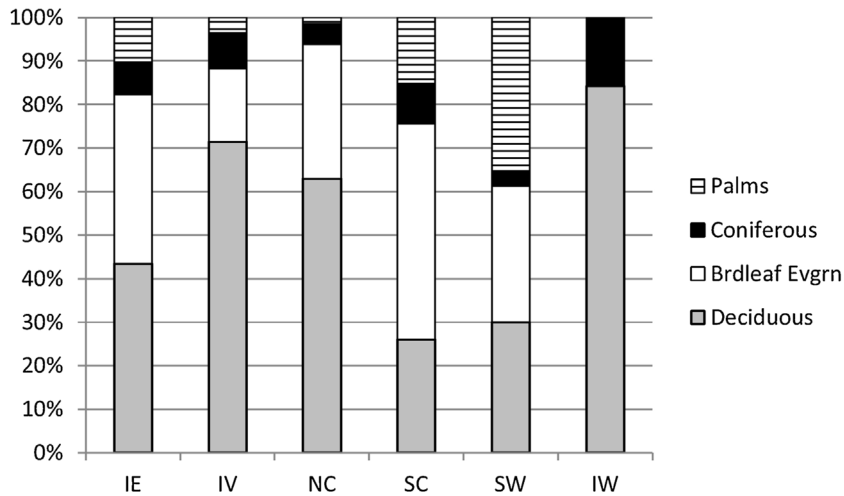

Fig. 3. Percentage of street tree populations in each climate zone by growth form (IE is Inland Empire, IV is Inland Valleys, NC is Northern California Coast, SC is Southern California Coast, SW is Desert Southwest, IW is Interior West).

range from 22.9 kg year^{-1} (IW) to 67.1 kg year^{-1} (NC) and average 41.2 kg year^{-1} (6.5 kg year^{-1} se).

Annual avoided CO_2 emissions from building energy savings total 257,013 t year^{-1} (43,535 t year^{-1} se) (Table 3). Total annual avoided emissions are greatest in the IV (79,188 t year^{-1}) and NC (76,413 t year^{-1}). Annual avoided emissions per tree range from 16.3 kg year^{-1} (SC) to 64.3 kg year^{-1} (IW), and average 28.2 kg year^{-1} (4.8 kg year^{-1} se).

Annual emissions of CO_2 from decomposition of pruned wood and removed trees (57,567 t year^{-1}), as well as by equipment and vehicles used to maintain trees (7403 t year^{-1}) is 64,970 t year^{-1} (10,812 t year^{-1} se) (Table 3). Decomposition emissions average 6.3 kg year^{-1} per tree (1.1 kg year^{-1} se) and are 9.1% of sequestered plus avoided emissions. Maintenance emissions average 0.8 kg year^{-1} per tree (0.12 kg year^{-1} se) and are 1.2% of sequestered plus avoided emissions.

Net annual CO_2 removed from the atmosphere totals 567,748 t year^{-1} (92,253 t year^{-1} se) state-wide, and is greatest in the NC (186,020 t year^{-1}) and SC (126,167 t year^{-1}) (Table 3). Annual reductions per tree range from 50.6 kg year^{-1} (SW) to 93.3 kg year^{-1} (NC) and average 62.2 kg year^{-1}. The associated monetary value is $10.32 million ($1.67 million se) per year or $1.13 per tree on average (Table 4).

3.3.3. *Air quality*

Annual air pollutant uptake by the state's 9.1 million street trees totals 2658 t year^{-1} (421 t year^{-1} se) per year (Table 3). Uptake is greatest in the IV (805 t year^{-1}), IE (740 t year^{-1}) and SC (692 t year^{-1}) zones. Trees remove ozone (1358 t year^{-1}) and particulate matter (772 t year^{-1}) in greater quantities than other pollutants.

Energy savings resulted in avoided emissions of air pollutants that amount to 727 t year^{-1} (113 t year^{-1} se) per year (Table 3). Avoided emissions are greatest in the IE (295 t year^{-1}).

BVOCs released by trees total 3400 t year^{-1} (541 t year^{-1} se) and are greatest in the IE (1223 t year^{-1}) and NC (1145 t year^{-1}) (Table 3). The mix of species and numbers of trees contribute to this result.

The net annual value of trees' effects on air quality is $18.15 million ($2.45 million se) (Table 4). The average annual benefit per tree is $1.59 ($0.27 se), and values range from −$16.09 ($2.89 se) in the NC to $23.84 ($3.78) in the IW.

3.3.4. *Rainfall interception*

California's 9.1 million street trees intercept 26.19 million m^3 year^{-1} (4.15 year^{-1} se) of rainfall annually (Table 3). Trees in the NC (8.8 million m^3 year^{-1}) and IE (7.5 million m^3 year^{-1}) zones intercept the most rainfall. Annual interception averages

Table 3
Functional services produced by the street tree population in each climate zone and statewide.

Resource Units	Inl. Empire	Inl. Valleys	North. Coast	South. Coast	SW Desert	Int. West	Total
Energy							
Cooling	153 (20)	186 (39)	200 (36)	101 (12)	42 (7)	2 (0)	684 (114)
Heating	−35.9 (4.7)	44.6 (9.3)	427.3 (76.8)	106.9 (12.8)	31.4 (5.0)	5.8 (0.9)	580.2 (100.0)
CO2							
Stored	1361 (178)	2174 (451)	2506 (450)	1517 (181)	207 (33)	18 (3)	7782 (1297)
Sequestered	73.6 (9.6)	58.0 (12.0)	133.7 (24.0)	95.0 (11.4)	14.8 (2.4)	0.6 (0.1)	375.7 (59.5)
Avoided	35.8 (4.7)	79.2 (16.4)	76.4 (13.7)	44.9 (5.4)	19.0 (3.0)	1.7 (0.3)	257.0 (43.5)
Released Decomp.	−1.3 (0.2)	−15.3 (3.2)	−24.1 (4.3)	−15.2 (1.8)	−1.7 (0.3)	−0.1 (0.02)	−57.6 (9.8)
Released Maint.	−4.4 (0.6)	−1.1 (0.2)	−0.1 (0.02)	−1.5 (0.2)	−0.2 (0.03)	−0.01 (0.00)	−7.4 (1.1)
Net Total	103.7 (13.6)	120.8 (25.1)	186.0 (33.4)	123.2 (14.7)	31.9 (5.1)	2.2 (0.3)	567.8 (92.3)
Air Quality							
Deposition O3	378 (49)	443 (92)	166 (30)	339 (41)	28 (4)	4 (1)	1358 (217)
Deposition NO2	141 (18)	112 (23)	68 (12)	149 (18)	14 (2)	1 (0)	485 (74)
Deposition PM10	207 (27)	250 (52)	96 (17)	191 (23)	27 (4)	1 (0)	772 (124)
Deposition SO2	15 (2)	0 (0)	13 (2)	12 (1)	3 (0)	0 (0)	43 (6)
Total Deposition	740 (97)	805 (167)	343 (62)	692 (83)	72 (11)	6 (1)	2658 (421)
Avoided NO2	85 (11)	93 (19)	50 (9)	57 (7)	34 (5)	4 (1)	324 (52)
Avoided PM10	21 (3)	18 (4)	13 (2)	14 (2)	2 (0)	1 (0)	68 (11)
Avoided SO2	168 (22)	43 (9)	26 (5)	27 (3)	29 (5)	3 (1)	296 (44)
Avoided VOC	21 (3)	5 (1)	6 (1)	6 (1)	0 (0)	1 (0)	39 (6)
Total Avoided	295 (39)	159 (33)	96 (17)	104 (12)	65 (10)	9 (1)	727 (113)
Released BVOC	−1223 (160)	−531 (110)	−1145 (206)	−390 (47)	−108 (17)	−4 (1)	−3400 (541)
Net Total	−188 (25)	433 (90)	−707 (127)	397 (48)	29 (5)	11 (2)	−25 (8)
Stormwater							
Interception	7498	4144	8840	4674	985	45	26,186
(se)	(983)	(860)	(1588)	(559)	(157)	(7)	(4154)

Units: Cooling (GWh/yr), Heating (MJ/yr), Stored CO_2 (1,000 t), Units: Sequestered, Avoided, Released, Net CO_2 (1000 t/yr), Air Quality (1 metric tonne/yr), Interception (1000 m3/yr).

Table 4
Annual monetary value (in million $US) of street tree services by climate zone and statewide (se).

Service	Inland Empire	Inland Valleys	North. Calif. Coast	South. Calif. Coast	Southwest Desert	Interior West	Total
Energy	21.37 (2.80)	25.73 (5.34)	31.27 (5.62)	15.95 (1.91)	6.54 (1.04)	0.28 (0.04)	101.15 (16.76)
Carbon Dioxide	1.95 (0.26)	2.13 (0.44)	3.28 (0.59)	2.36 (0.28)	0.56 (0.09)	0.04 (0.01)	10.32 (1.67)
Air Quality	0.60 (0.08)	23.64 (4.91)	−32.09 (5.77)	23.01 (2.75)	2.37 (0.38)	0.63 (0.10)	18.15 (2.45)
Stormwater	14.26 (1.87)	8.32 (1.73)	9.34 (1.68)	8.27 (0.99)	1.25 (0.20)	0.06 (0.01)	41.50 (6.47)
Property Value/Other	150.48 (19.72)	108.36 (22.50)	299.42 (53.80)	246.56 (29.48)	33.70 (5.37)	0.43 (0.07)	838.94 (130.94)
Total	188.67 (24.73)	168.18 (34.92)	311.20 (55.92)	296.14 (35.41)	44.42 (7.08)	1.44 (0.23)	1,010.05 (158.29)

2.87 m^3 $year^{-1}$ per tree (0.46 se) and ranges from 1.56 m^3 $year^{-1}$ (SW) to 4.49 m^3 $year^{-1}$ (IE).

The monetary value of rainfall interception totals $41.5 million, with the greatest benefit in the IE ($14.26 million) (Table 4). The average annual benefit per tree is $4.55 ($0.71 se) and ranges from $1.98 (SW) to $8.53 (IE).

3.3.5. *Property values and other benefits*

Street trees contribute to the sales prices of homes and provide other benefits valued at $838.94 million ($130.9 se) per year (Table 4). Property values and other benefits are largest in the NC ($299.4 million) and SC ($246.6 million) zones. Average annual benefits per tree range from $16.19 (IW) to $150.09 (NC) and average $91.89 ($14.34 se).

3.3.6. *Total annual benefits*

The total annual value of street tree services is $1.0 billion ($58.3 million se), or $110.63 per tree ($17.34 se) (Table 4). Total annual benefits are $311.2 ($156.0 per tree) and $296.1 ($107.17 per tree) in the NC and SC zones, respectively.

3.3.7. *Replacement value*

The replacement value for all street trees is $2.49 billion ($7.96 million se) (Table 4). This amount is the asset value of the state's street trees when considered as a capital investment similar to other infrastructure. It averages to $2677 per tree ($108.90 se).

4. Discussion

California has approximately 9.1 million street trees, about one for every four city resident. To fill the vacant street tree sites would require planting 16 million trees. Assuming that 50% of these are readily plantable, it appears feasible to nearly double the state's street tree population through planting of another 8 million vacant street tree sites. State-wide, species diversity is good, with only London planetree accounting for over 10% of the population. The annual value of street tree services is $1.0 billion, or $110.63 per tree ($29.17 per capita). These findings contribute new knowledge on the structure, function and value of street trees in California.

4.1. *Structure*

McPherson and Simpson (2003) reported that there were 177.3 million trees in urban areas in California. Assuming this number is still valid, the state's 9.1 million street trees account for about 5% of the urban forest. This study's findings indicate that the trend of increasing street tree numbers reported by Thompson (2006) is continuing, although the use of different methodologies limits the conclusiveness of these comparisons. In 1988 there were approximately 5.9 million street trees (0.26 per capita) and the number increased to 7.2 million trees (0.29 per capita) in 2003. The 9.1 million street trees reported here continues the increasing trend in tree numbers, while the 0.26 trees per capita is a slight decrease from 2003. Thompson (2006) reported a rapid increase in planting

Table 5
For each climate zone, the number of cities in which the most dominant species account for a percentage of total zone-wide species and genus. Total number of inventories in parentheses.

	Species					Genus				
Climate zone	<10%	10–15%	15–20%	20–30%	>30%	<10%	10–15%	15–20%	20–30%	>30%
Inl. Empire (17)	3	7	5	2	0	1	6	7	3	0
Inl. Valleys (8)	1	4	2	1	0	1	3	3	1	0
North Coast (8)	2	5	1	0	0	1	6	1	0	0
South Coast (15)	4	7	3	1	0	2	7	3	2	1
SW Desert (1)	0	0	1	0	0	0	0	0	1	0
California (49)	1	0	0	0	0	1	0	0	0	0

in the late-1980s and early-1990s, but this trend began to erode in the mid-1990s. However, California had a number of tree planting initiatives during the past decade that were funded through voter-approved bond measures. The current ratio of 0.26 trees per capita matches the value reported for 1988, suggesting that the trend is stable. It should be noted that these ratios are less than the 0.38 reported for California in 1979 (Kielbaso et al., 1988) and the mean value of 0.37 reported for 22 U.S. cities (McPherson and Rowntree, 1989).

Average street tree density in California (46.6/km, 75.0/mile) is less than 50.0 per km (80.5/mile) reported for New York (Cowett and Bassuk, 2014), but greater than 28.6 (46/mi.), 36.0 (58/mi.), 37.3 (60/mi.) and 39.1 (63/mi) reported for Maryland, Massachusetts, Missouri and Wisconsin, respectively (Cumming et al., 2008; Cumming et al., 2006; Gartner et al., 2002). It is a substantial reduction from 65.6 (105.5/mi.) and 64.3 (103.5/mi.) trees per km reported for California in 1988 and 1992 (Bernhardt and Swiecki, 1989, 1993), respectively. One possible explanation for this downward trend is that street tree planting rates are lagging behind development of new streets. Another factor could be that relatively few removed trees are being replaced. In 1992, 15% of surveyed programs were removing more trees than they planted (Bernhardt and Swiecki, 1993). In 2003, this increased to 22% (Thompson, 2006).

The ideal urban forest is not dominated by a few species. Rather, tree numbers are distributed fairly evenly among dozens of well-adapted species. Species diversity protects a community's tree canopy cover by limiting the amount of damage from any one threat such as pests, drought or storms (McPherson and Kotow, 2013). A commonly accepted diversity goal is for no single species to account for more than 10% of the population, no genus more than 20% and no family more than 30% (Santamour, 1990).

The absence of diversity has been reported at state-wide and local scales (Ball et al., 2007; Raupp et al., 2006). For example, Norway maple (*Acer platanoides*) accounted for 34%, 31%, 21% and 20.7% of all street trees in the states of Massachusetts, Wisconsin, Michigan and New York, respectively. This lack of diversity was not the case for California. At the state-wide scale, London planetree was the most abundant species accounting for 10.5% of all trees (Table 2). The *Platanus* genus comprised only 10% of the population. Hence, no single genus accounted for more than 20% of the population (Table 5). However, the need for further diversification was evident at the city and climate zone scales. The metric of no single species accounting for more than 10% of the population was exceeded in 3 climate zones and 36 of the municipal inventories. The metric of no single genus accounting for more than 20% of the population was exceeded in 4 climate zones and 8 cities. Genera that exceeded the 20% target at the city scale were *Eucalyptus*, *Lagerstroemia*, *Quercus*, *Pistacia*, *Pinus* and *Washingtonia*.

Overreliance on the London planetree was identified as a serious concern in California because of its vulnerability to severe pests such as the granulate ambrosia beetle (*Xylosandrus crassiusculus*), Asian longhorned borer and Armillaria root rot (caused by members of the genus *Armillaria*) (McPherson and Kotow, 2013). Planting of this species and other overly abundant and highly vulnerable species such as sweetgum, Chinese pistache, velvet ash and Callery pear could be reduced. Ongoing evaluation of climate-ready species that are also compatible to street-side conditions is needed (McPherson and Berry, 2015).

The results from this study support the notion that growth forms reflect environmental conditions (McPherson and Rowntree, 1989). Deciduous trees prevail in the more temperate climate zones (IW, IV, NC), while broadleaf evergreens and palms predominate in the subtropical climate zones (SC, SW). Conifers are relatively unimportant along California streets, regardless of climate zone.

The age structure of street trees in California is younger than reported for Maryland, Massachusetts and Missouri. For example, in these states less than 20% of all trees are in the smallest dbh size class. In California climate zones this number ranges from 26% to 55%. The preponderance of small sized trees may reflect a relatively youthful state-wide population. Alternatively, it could reflect recent planting of many small-stature trees that may never grow out of the 0–15 cm dbh class. Further investigation is needed to identify the species composition and mature ages and sizes of recently planted tree species.

4.2. Function and value

Street tree population function has been reported for the California cities of Modesto, Santa Monica and Berkeley (McPherson and Simpson, 2002; McPherson et al., 2005). The annual monetary values of street tree services were reported for the states of Missouri (Treiman et al., 2011a), Indiana (Davey Resource Group, 2010a) and Wisconsin (Cumming et al., 2008). For comparison purposes, results were divided by total tree numbers and presented per tree except for Wisconsin, where data were missing for many services (Table 6). Because results are all from the same i-Tree Streets model they are comparable. Differences among states reflect the effects of different street tree structures, climate zones and model inputs such as local prices for ecosystem services.

The 684 GWH of electricity saved annually by California's street trees is equivalent to the amount required to air condition 530,000California households each year (4.4% of 12.2 million). The average per tree amount of 74.9 kWh falls within the range of values reported for other California cities (36–138 kWh). Average annual energy savings of $11.08 per street tree for California is more than $6.83 in Indiana and less than $32.71 in Missouri.

Approximately 7.78 million t CO_2 is stored in the state's 9.1 million street trees. They remove and avoid 567,748 t of CO_2 emissions annually, equivalent to removing 120,000 cars from the road. On an average annual per tree basis, street trees sequester and avoid 34.7 and 28.2 kg of CO_2, respectively. The amount sequestered is less than values previously reported for California cities (41–96 kg year^{-1}) and the amount avoided falls within the range reported in other states and cities (18–36 kg year^{-1}). The average annual value of CO_2 removal is $1.13 per tree, more than $0.20 and $0.82 in Wisconsin and Indiana, but less than $2.75 in Missouri.

Table 6
Annual monetary value ($US) per tree of services from street tree populations.

Service	Modesto (McPherson and Simpson, 2002)	Santa Monica (McPherson and Simpson, 2002)	Berkeley (McPherson et al., 2005)	Indiana (Davey Resource Group, 2010a)	Missouri (Treiman et al., 2011a)	California
Energy	10.89	4.82	15.16	6.83	32.71	11.08
Carbon Dioxide	3.42	1.67	1.28	0.82	2.75	1.13
Air Quality	5.90	6.01	−0.04	1.99	3.68	1.99
Stormwater	6.75	3.78	5.42	17.00	29.91	4.55
Property Value/Other	26.11	64.82	69.63	28.88	33.44	91.89
Total	53.07	81.10	91.44	55.52	102.48	110.63

Street trees are estimated to remove 0.29 kg $year^{-1}$ of air pollutants from the atmosphere, well within the reported range (0.13-0.53 kg $year^{-1}$). Avoided emissions from energy effects average 0.08 kg $year^{-1}$ per tree, similar to the 0.05 $year^{-1}$ reported for street trees in Berkeley. The average annual value of air pollutant uptake and release is $1.99 per tree for California, more than $1.67 in Wisconsin and less than $3.68 in Missouri.

California's street trees are estimated to intercept 26.19 million m^3 of rainfall annually, equivalent to the average amount of potable water consumed by 52,400California households each year. The average annual interception rate per tree is 2.9 m^3, less than 3.2–7 m^3 $year^{-1}$ per tree found for street trees in Modesto, Santa Monica and Berkeley. It should be noted that interception does not translate directly into stormwater runoff reduction. Rainfall intercepted over impervious surfaces reduces runoff more than interception over unsaturated pervious surfaces. The annual monetary value of interception is $4.55 per tree, substantially less than $17 and $29 in Indiana and Missouri, respectively. This value is lower for California primarily because California receives less rainfall than the other states, and precipitation tends to occur in winter months when deciduous trees are leafless (McPherson and Simpson, 2002).

The effect of street trees on property values is the single largest benefit, averaging $91.89 per tree. This number is greater than for Berkeley ($67), Missouri ($53.44) and Indiana ($28.88). The higher value for California reflects its higher median home sale prices.

The annual value of all street tree services is $1.0 billion ($58.3 million se), or $110.63 per tree ($29.17 per capita). This amount is twice the $55.52 reported for Indiana, but similar to the value reported for street trees in Missouri ($102.48).

The estimated $1 billion in annual services produced by California's street trees may understate their total value. For instance, in 2009 revenues directly associated with urban forestry in California were $2.97 billion and required 40,206 jobs (Templeton et al., 2013). Recent research in the Sacramento region found that residents in neighborhoods with more tree cover had lower body mass index, reduced likelihood of being obese or overweight, greater participation in vigorous activity, lower likelihood of asthma, higher levels of social cohesion, improvements in mental health, and better general health (Ulmer et al., in press). The cost savings associated with these health benefits could be substantial.

Street trees can be costly to plant and maintain. Tree failures can result in damage to people and property. Removing large trees and replanting can be expensive. Root conflicts with sidewalks and curbs were estimated to cost California cities approximately $70.7 million annually ($11.22 per tree) (McPherson, 2000).

A national study found that mean annual expenditures to manage municipal trees were $13.20 and $14.73 in Inland and Coastal California regions (Tschantz and Sacamano, 1994). The most recent state-wide survey found that annual management costs per municipal tree averaged $19 (Thompson, 2006). Assuming that the average annual per tree management cost is $19 and the benefit is $110.63, $5.82 in benefit is returned for every $1 spent. This return on investment is similar to the $5.60 value reported for New York City (Peper et al., 2007). The monetized value of annual services from California's street trees outweigh their costs.

4.3. Limitations

This study was hampered by the absence of tree inventories in the IW climate zone, and only one inventory in the SW zone. Conducting inventories in these zones is critical to improved quantification of state-wide structure, function and value in the future.

The scope of this assessment did not include tree condition, conflicts between trees and infrastructure and management needs. These data were seldom reported, or reported inconsistently and unsystematically. Future assessments would benefit from more standardized inventories that allow for a more complete picture of management issues.

5. Conclusions

Inventory data from over 900,000 street trees were used to quantify the structure, function and value of California's street tree population. Although these findings suggest that the number of street trees has gradually increased from 5.9 million in 1988 to 9.1 million in 2014, about one for every four residents (0.26), street tree density has declined from 65.6 to 46.6 trees per km of street length, nearly a 30% drop. There is clear need to begin planting the state's 16 million vacant sites and replacing every removed street tree. Statewide, London planetree (10.5%) is the only species that accounts for over 10% of the population, suggesting that species diversity provides an adequate buffer from catastrophic loss. However, this is not the case at the city scale, where inventories in 39 of 49 communities indicated overreliance on a single species. Species whose planting along streets could be reduced include London plane, sweetgum, Chinese pistache, velvet ash and Callery pear. It is time to initiate evaluation programs that test the adaptability of less frequently used cultivars in street-side settings. Such knowledge can guide a transition to a new palette of climate-ready trees. The age distribution of the state's street trees is relatively youthful, indicating a likely need to invest in pruning young trees for structure and form, which can reduce subsequent costs for treating defects in mature trees.

Despite decreasing street tree densities in California, the state's street trees are an infrastructure asset valued at $2.49 billion. The annual value of all street tree services is $1.0 billion ($58.3 million se), or $110.63 per tree ($29.17 per capita). Given an average annual per tree management cost of $19, $5.82 in benefit is returned for every $1 spent. These findings indicate that investing in the long-term health of municipal forests can provide positive returns.

Approximately 7.78 MMT CO_2 is stored in the state's 9.1 million street trees, and they remove 567,748 t CO_2 annually, equivalent to removing 120,000 cars from the road. As California embarks on a new generation of urban greening projects supported through the Greenhouse Gas Reduction Fund there will be unprecedented demand for tangible CO_2 reductions and co-benefits from trees. Programs that achieve higher levels of tree performance and develop more sophisticated monitoring and reporting protocols will be rewarded. To that end, this study presents actionable management recommendations to reverse undesirable trends and mitigate threats to future tree health and performance. Also, these findings provide an important baseline from which to gauge the effectiveness of future investments in California's municipal forests.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ufug.2016.03.013.

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