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The structure, function and value of urban forests in California communities

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ABSTRACT

This study used tree data from field plots in urban areas to describe forest structure in urban areas throughout California. The plot data were used with numerical models to calculate several ecosystem services produced by trees. A series of transfer functions were calculated to scale-up results from the plots to the landscape using urban tree canopy (UTC) mapped at 1-m resolution for each combination of 6 land use classes and climate zones. California's UTC covered 15% of the urban area and contained 173.2 million trees, five per city resident. UTC per capita was lowest among U.S. states (90.8 m^2), indicating ample opportunity for tree planting. Oaks were the most abundant taxon (22%) and overall plantings were youthful. The annual value of ecosystem services was estimated at $8.3 billion and the urban forests asset value was $181 billion. Assuming an average annual per tree management cost of $19 and benefit of $47.83, $2.52 in benefit was returned for every dollar spent. The threat posed by Invasive Shot Hole Borer (*Euwallacea* sp.) illustrates that urban forests are a relatively fragile resource whose contributions to human health and well-being can be suddenly jeopardized. One scenario projected that should Southern California cities lose 50% (11.6 million) of all susceptible trees, the value of ecoservices foregone over 10 years was $616.6 million. The approximate cost of removing and replacing the trees was $15.9 billion. Strategies to reduce the risk of catastrophic loss by increasing the resilience of California's urban forests are discussed.

1. Introduction

Healthy urban forests can produce ecosystem functions, goods and services that benefit humans and the environment. Ecosystem services, or ecoservices, include energy conservation, air quality improvement, carbon storage, stormwater runoff reduction and wildlife habitat (Nowak and Crane, 2002; Nowak et al., 2006; Simpson and McPherson, 1998; Tzilkowski et al., 1986; Xiao et al., 1998). Trees can raise property values (Donovan and Butry, 2010), produce goods such as food and wood products, and provide social, economic, aesthetic and health benefits (Hartig et al., 2014; Lee and Maheswaran, 2011; Lohr et al., 2004; Wolf, 2003). The extent to which residents benefit from these goods and services depends on their location relative to urban tree canopy and on canopy health (Escobedo and Nowak, 2009).

However, trees in cities face a plethora of threats that can reduce these benefits and increase expenditures for pruning, removal and replacement. For example, recent drought left California with a cumulative rainfall deficit described as a one in a 1000 year event (Robeson, 2016). Drought and reduced irrigation combined with pest infestations were thought to generate a large pulse in urban tree mortality (Fear, Feb. 27, 2016). Although anecdotal data support the notion of increased urban tree mortality, there are no baseline data from which to determine if such a change occurred.

The primary purpose of this study is to provide baseline data on the structure, function and value of urban forests in California communities. We recognize that a study of the "urban forest" includes all trees within urban areas, in distinction to a previous study of California street trees (McPhersonet al., 2016a). Here we extend the value of previous work (McPherson and Simpson, 2003; McPherson et al., 2013; Nowak et al., 2013) by using new field plot data sets, current urban tree canopy and land use maps and improved numerical models to calculate effects of city trees on air quality, building energy use, atmospheric carbon dioxide (CO_2), rainfall interception and property values. These baseline data can be used as a basis for change detection and in the California

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Department of Forestry and Fire Protection's (CAL FIRE) strategy formulation and implementation of urban forestry technical assistance programs and grants to California communities.

A second objective of this research is to illustrate how information on urban forest structure, function and value can inform planning and management. Managing California's urban forests to be healthy and resilient requires a clear understanding of current conditions and threats. One such threat is the Invasive Shot Hole Borer (ISHB) (*Euwallacea* sp.), an ambrosia beetle that has killed tens of thousands of trees in Southern California. It drills into trees and can transmit pathogenic fungi (*Fusarium euwallacea* and *Graphium* sp.) that block water and nutrients from the roots to other parts of the tree (Eskalen et al., 2013). Tree dieback (Fusarium Dieback, FD) and death can occur rapidly. The ISHB-FD complex threaten millions of city trees, avocado and citrus groves, as well as native trees in riparian and forest areas. In what we term a "management example" we illustrate how the potential loss of trees to this disease complex can have a cascade of adverse effects on management costs and ecosystems services the trees provided.

2. Methods

2.1. Approach

This study used tree data from field plots in urban areas to describe forest structure (e.g., tree numbers, density, basal area, species composition) for six land use categories in six California climate zones. The plot data were used with numerical models to calculate forest functions (e.g., energy effects, carbon stored), the ecoservices produced by trees. A series of transfer functions were calculated to scale-up results from the plots to the landscape using urban tree canopy (UTC). Urban tree cover was mapped at 1-m resolution and a unique transfer function, such as kWh of air conditioning energy saved annually per hectare UTC (kWh year^{-1} ha^{-1} tree cover), was applied to each combination of land use class and climate zone. Once totaled state-wide, urban forest values were monetized in 2015 U.S. dollars (Fig. 1).

2.2. Geographic data

In 2010 California was home to 37.3 million residents (U.S. Census Bureau, 2012). Urban areas, defined by the U.S. Census Bureau as densely developed areas containing > 50,000 inhabitants with a density level of 1295 persons or greater/km^2, covered 21,280 km^2 or 5% of the land base and contained 95% of the state's population (35.2 million).

We subdivided the state 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) (McPherson, 2010) (Fig. 2). Most Californian urban areas experience a Mediterranean climate with mild, wet winters and warm, dry summers. However, cities in coastal and inland zones and varying elevations can have very different climates (Table S1). These differences are embedded in subsequent models as they can influence tree growth and carbon storage rates, and many other ecoservices that trees deliver. Temperature data are indicators of building energy heating and cooling loads. Annual precipitation affects the amount of irrigation trees need to grow in California's climate, as well as potential rainfall interception by tree crowns.A state-wide land use map for urban areas was developed with six classes from parcel data (Table 1). Parcel boundaries were from Digital Map Products (2013), and attributes for parcels were from CoreLogic/DataQuick (2013). Because each county had different classification schemes, we created a uniform map of parcels by conducting a county-by-county update of the parcel data.

2.3. Field data

Two types of field plot data were utilized. i-Tree Eco (formerly UFORE, https://www.itreetools.org) plot data (703 plots) were obtained for Los Angeles (in 2007–08), Santa Barbara (2012) and the Sacramento area (2007). Each plot survey was based on random sampling of 0.04 ha plots (Nowak et al., 2008). The second set of data (682 plots, in 2011) consisted of 0.067 ha (four 0.017 ha subplots) plots based on the U.S. Forest Service Forest Inventory and Analysis (FIA) plot protocols (Cumming et al., 2008).

The number of plots analyzed varied by climate zone and a total of 3796 trees were sampled (Table S2). Plot data used included the percentage of tree canopy cover, tree species, stem diameter at breast height (1.37 m above ground, dbh), tree and crown height, crown width, and distance and azimuth to the nearest building with space conditioning. Plot data were used to model energy effects, carbon storage, carbon sequestration and avoided emissions. Additionally, municipal street tree inventory data, representing over 900,000 trees (Table S2) were used to calculate transfer functions for services where the exact location of the tree relative to buildings was unimportant (i.e., air pollutant removal, rainfall interception, property value/other benefits).

Tree numbers and standard errors were estimated as the product of tree densities and land areas for each land use class and climate zone. Calculation of tree density needed to adjust for differences in the plot layouts between the Eco and FIA plots described in the online Supplementary Material (S.1.), and entailed application of statistical equations and a bootstrap process to construct means and standard errors. For land uses and climate zones without tree data or measured plots, an average tree density was calculated using density values from similar climate zones. For the Interior West (Interior West), averages

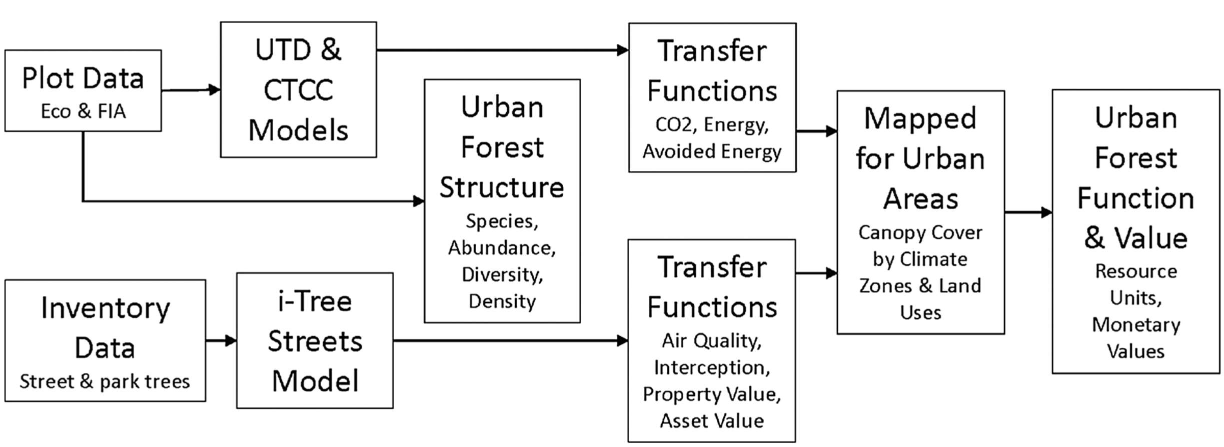

Fig. 1. Steps in the data collection, analysis and mapping process. Eco and Forest Inventory and Assessment (FIA) are field-based methods used to collect tree data. The Urban Tree Database (UTD) and CUFR Tree Carbon Calculator (CTCC) involve tree growth equations and numerical models to calculate carbon stored and energy effects.

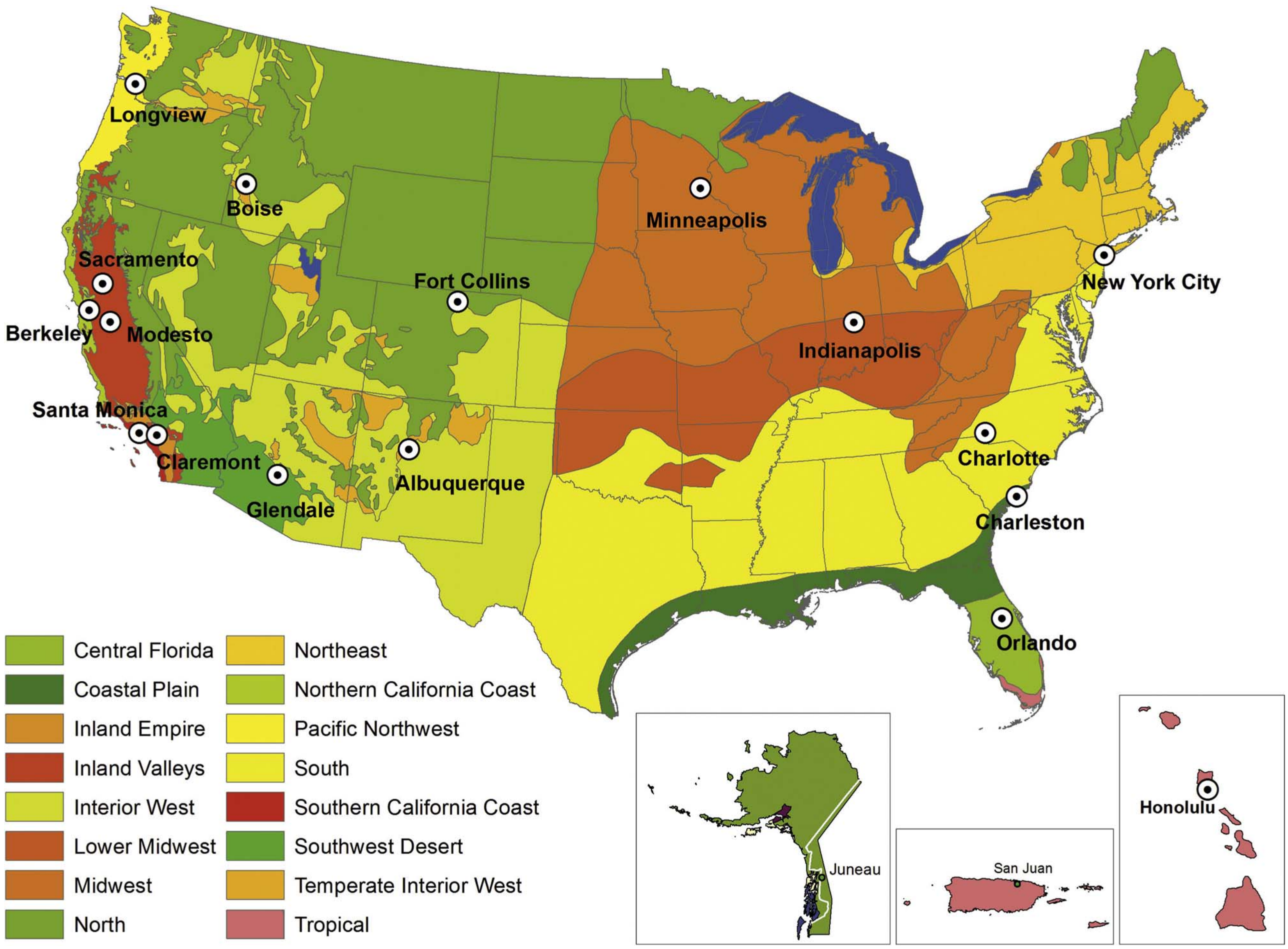

Fig. 2. Locations of climate zones, Forest Inventory and Assessment (FIA) and Eco (formerly UFORE) field plots and cities with street tree inventories used in this study.

Table 1
Land use categories and descriptions.

Code	Land Use	Description
C/I/I	Commercial/Industrial/Institutional	All non-residential building types.
OS	Open Space	Open space of any kind, including agriculture and urban vacant.
MFR	Residential High	High-density single family homes, multi-family homes, apartments and condominiums (20+ dwelling units/ha).
SFR	Residential Low	Low-density single family homes (< 20 dwelling units/ha)
TR	Transportation corridors	All roads, highways, rights-of-way and railroad lines. Airports and train stations in the C/I/I category.
WO	Other	Water or unknown/other categories.

were calculated using density data from the Inland Empire (Inland Empire), Inland Valleys (Inland Valley) and Southwest Desert (SWDsrt). For the Southwest Desert, averages for Multi-Family Residential (RMF) land use type were calculated using data from the Inland Empire and Inland Valley. Missing mean density values and standard errors for the Water/Other (WO) land use were calculated using data from the Inland Valley and Northern California Coast. The impacts of using these average values for the missing data were small. The Interior West climate zone accounted for only 5.5% of total urban area, RMF in the Southwest Desert zone was 5.2% of total RMF land use and WO land use in all zones totaled to only 1% of urban land.

2.4. Urban tree canopy data and transfer functions

The urban tree canopy cover map was classified by EarthDefine (http://www.earthdefine.com/spatialcover_landcover/), based on 2012 National Agricultural Imagery Program (NAIP) aerial imagery. The NAIP imagery included four multispectral bands (blue, green, red and near infrared) with a 1-m spatial resolution, and was acquired during the leaf-on season (April 23–July 20, 2012). Object-based image analysis was used to segment images and combine adjacent pixels that fell into the same class. Visual accuracy assessments were conducted by climate zone and land use type for forested and non-forested areas within urban areas.

Ecoservices provided by trees to human beneficiaries are classified according to their spatial scale as global and local (Costanza, 2008). Removal of CO_2 from the atmosphere by urban forests is global because the atmosphere is so well-mixed it does not matter where the trees are located. The effects of urban forests on building energy use is a local-scale service because it depends on the proximity of trees to buildings. In this study, the effects of tree shade on building energy performance were modeled with data from the CUFR Tree Carbon Calculator (CTCC) (McPherson et al., 2008). The CTCC, a free Excel spreadsheet application, was produced by US Forest Service researchers from over 800 simulations for each of the six California reference cities using different combinations of tree sizes, locations, and building age classes (Simpson, 2002). The CTCC also incorporates effects of a tree on wind speed and air temperature through cooling from evapotranspiration. If a sampled tree was located within 18 m of a conditioned building, information on its distance and compass bearing relative to a building, building age class (which influences energy use) and types of heating and cooling equipment were collected and used as inputs to calculate annual heating and cooling energy effects. In cases where a tree shaded more than one building, effects were summed. Heating and cooling energy effects were calculated using values for each tree in each Eco and FIA plot and divided by the plot's UTC. Plot data were aggregated by land use class for each climate zone and descriptive statistics applied to determine sample means and standard errors. Within each climate zone, transfer functions for each land use (J_k) were applied to the total UTC for that land use and results were summed. For example, the total amount of cooling energy saved *AC* was

$$\text{Total AC} = \Sigma_k J_k \times \text{Total UTC}^{(k)} \quad (1)$$

For climate zones lacking plot data, mean transfer functions were calculated using data from similar climate zones, as described previously for tree density.

Energy savings result in reduced emissions of CO_2 and criteria air pollutants (volatile organic hydrocarbons [VOCs], NO_2, SO_2, PM_{10}) from power plants and space-heating equipment. Cooling savings reduce emissions from power plants that produce electricity, the amount depending on the fuel mix. Electricity emissions reductions were based on the fuel mixes and emission factors for each utility (Table S3 and S4). Heating savings reduce emissions from the combustion of natural gas, fuel oil or other heating fuels. Avoided emissions were calculated using values for trees in each Eco and FIA plot and divided by the plot's UTC. The dollar values of electrical energy and natural gas were based on retail residential electricity and natural gas prices obtained from each utility. Prices for electricity ($/MWh) and natural gas ($/GJ), respectively were Inland Empire and Southern California Coast = $150 and $8.79, Inland Valley and Northern California Coast = $136.27 and $9.30, and Interior West and Southwest Desert = $149.24 and $7.76. The estimated value of avoided CO_2 emissions due to energy effects and CO_2 sequestered assumed a price of $12.02 per metric tonne (t) CO_2, based on the California Carbon Allowance Futures annual average for 2014 (Climate Policy Initiative, 2014).

To estimate carbon (C) stocks, the biomass for each tree was calculated using urban-based allometric equations because open-growing city trees partition carbon differently than forest trees (Lefsky and McHale, 2008; Pillsbury et al., 1998). Input variables included tree species, climate zone, dbh, and height. Most allometric equations yielded aboveground wood volume. Species-specific dry weight density factors were used to convert green volume into dry weight (McPherson et al., 2016b). The amount of belowground biomass in roots of urban trees is not well researched. This study assumed that root biomass was 28% of total tree biomass (Cairns et al., 1997; Husch et al., 2003; Wenger, 1984). Wood volume (dry weight) was converted to C by multiplying by the constant 0.50 (Leith, 1975), and C was converted to CO_2 by multiplying by 3.667. We recognize that C stocks are normally reported in units of C, but we use CO_2 in this study to insure that results are readily accessible to policy makers, who measure and regulate emissions and forest offsets in CO_2 equivalents. Also, this choice facilitates comparisons with results from a related assessment of California's street tree population.

The amount of CO_2 sequestered in year x was calculated as the amount stored in year x + 1 minus the amount stored in year x. To project tree size at year x + 1 we used growth curves from the Urban Tree Database, which were developed from samples of about 700 street and park trees representing the 20–22 predominant species in each climate zone's reference city (McPherson et al., 2016b). Each tree in the sample plots was matched to one of the representative species to ensure that the appropriate allometric and growth equations were applied to calculate biomass and annual sequestration rates. If species did not match directly, they were assigned using a species in the same genus with similar growth characteristics.

Other local-scale ecoservices modeled in this study were rainfall interception, air quality effects and property values/other benefits. 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 uptake of air pollutants by urban forests can lower concentrations and affect human health (Derkzen et al., 2015; Nowak et al., 2014). However, pollutant concentrations can be increased if the tree canopy restricts polluted air from mixing with the surrounding atmosphere (Vos et al., 2013). Effects of trees at this very local scale were not modeled in this study. Rather, hourly pollutant dry deposition per tree was calculated at the regional scale using deposition velocities, hourly meteorological data and pollutant concentrations from local monitoring stations (Scott et al., 1998). Many benefits attributed to urban trees are difficult to price (e.g., increased property values, beautification, privacy, wildlife habitat, sense of place, human health and 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 modeled these "other" benefits of trees by applying the contribution to residential sales prices of a large front yard tree (0.88%) (McPherson et al., 2005).

Transfer functions were calculated for each of 49 California municipal street tree inventories previously processed in i-Tree Streets (v.5.1.5) by dividing the total value of each service by the total UTC for the city's street trees (McPherson et al., 2016a). Mean values were calculated for each climate zone and multiplied by the total UTC in each climate zone. Totals for each climate zone 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. Transfer functions can be found in the online Supplementary Material (Tables S3 and S4).

The monetary value of tree effects on air quality reflects the value that society places on clean air, as indicated by willingness to pay for pollutant reductions. Air quality effects were monetized as the mean cost of pollution offset transactions (California Air Resources Board, 2011b). The mean state-wide values used in this study per tonne were: NO_2 and O_3 = $51,966, PM_{10} = $44,120, SO_2 = $72,665 and VOC = $47,879. The rainfall interception benefit was priced by estimating costs of controlling stormwater runoff. Water quality and/or flood control costs were calculated per unit volume of runoff controlled and this price was multiplied by the amount of rainfall intercepted annually. Prices for rainfall interception ($/$m^3$) were Inland Empire and Southern California Coast = $1.91, Inland Valley = $2.01, Interior West = $1.32, Northern California Coast = $1.06 and Southwest Desert = $1.27. Median home sales prices were gathered for January to April 2014 (Trulia.com, 2014) (Table S5).

The values for these ecosystem services have been 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 asset value of California's urban forests was calculated. The calculation was based on tree replacement costs and included field data on species, size and condition (Council of Tree and Landscape Appraisers, 2000).

2.5. Management example

During the past decade the Invasive Shot Hole Borer-Fusarium Disease complex (ISHB-FD) has spread throughout southern California. The scope of this analysis covers susceptible trees in three climate zones where the complex has been reported: Southern California Coast, Inland Empire and Southwest Desert. ISHB attacks many species of trees, with over 200 host species identified, including 11 native to California

(Eskalen et al., 2013). For this study, species at risk were those listed as ISHB host species and susceptible to FD, as reported by Eskalen et al. (2013) and in the recently updated list of 55 ISHB-FD hosts at http://eskalenlab.ucr.edu/shotholeborerhosts.html. Susceptible taxa were matched with the list of species surveyed in field plots. The numbers of species at risk and their respective standard errors were totaled for each of the three climate zones and region-wide. The spread of the ISHB-FD complex was assumed to last 10 years after the ISHB-FD complex was projected to be reported in substantial numbers in each climate zone (Southern California Coast: 2016–25, Inland Empire: 2020–29, Southwest Desert: 2022–31) (Kabashima, 2017).

Following other approaches used to simulate the spread of invasive pests (BenDor et al., 2006), maximum loss rates of 50 and 80% for the 10 year periods were modeled using a logistic curve:

$$L = ((\cos(G \times \pi + \pi) + 1)/2) \quad (2)$$

where L is the fraction of maximum tree loss (50 and 80%) at year G, which is the fraction of the 10-year loss period. The S-shaped logistic curve was selected because it matched the three phases of pest invasion; 1) low initial losses due to the lag or "incubator" effect, 2) explosive increase in losses after widespread dispersion, and 3) lower loss rates due to management interventions that control spread and severity (Hoddle, 2017). Two values were calculated for the species at risk in each climate zone. The potential annual value of ecosystem services at risk was the product of the average annual value of ecoservices per tree and the number of trees at risk. These values were summed across climate zones to derive the region-wide total, which can be understood as the annual value of ecoservices foregone (i.e., energy effects, carbon sequestration and avoided emissions, air pollutant removal, rainfall interception, property value/other benefits) should the trees die. Similarly, the potential asset value at risk was calculated for each climate zone as the product of the average annual asset value per tree and the number of trees at risk. These values approximate the costs of removing and replacing dead trees with similar trees based on their species, size and condition.

3. Results

3.1. Structure

Urban tree canopy covered 320,028 ha or 15% of the urban area in California (Table 2) and was greatest in the Northern California Coast (22.1%) and Inland Valley (17.4%) climate zones (Table 2). The average UTC area per capita was 90.8 m^2.

State-wide, there were an estimated 173.2 million trees (3.4 million se), or 80.9 trees/ha, with most trees located in Northern California Coast (33.7%) and Inland Valley (24.3%). Stocking levels were above the state-wide average of 4.9 trees per capita in the Northern California Coast and Inland Valley zones (8.4 and 5.6, respectively), as well as the Interior West (7.9). Land uses with the most trees were single family residential (39%), open space (20%) and commercial/industrial/institutional (19%).

The sample of 3796 trees from plots comprised 338 taxa. State-wide the most abundant genera were oak (*Quercus*, 22.0%), cherry (*Prunus*, 6.6%), juniper (*Juniperus*, 5.5%), cypress (*Cupressus*, 4.2%) and pine (*Pinus*, 3.5%) (Table 3). Oak were among the most abundant genera in nearly every climate zone. Trees belonging to the top five genera accounted for over 70% of the populations in the Northern California Coast and Southwest Desert zones, but only 30% in the Southern California Coast. Pine, eucalyptus (*Eucalyptus*) and oak were the dominant genera state-wide based on basal area (Table 3). In the Northern California Coast zone maple (*Acer*) and redwood (*Sequoia*) dominated, while fan palm (*Washingtonia*) dominated in the Southwest Desert, followed by pine and ash (*Fraxinus*).

Plot tree dbh was used as a proxy for tree age. State-wide, California's urban forest was youthful, with 50% of trees in the smallest dbh class and relatively few old and mature trees (Fig. 3). Populations in the Inland Valley, Southern California Coast and Southwest Desert had relatively greater numbers of maturing trees.

3.2. Functions and values

State-wide annual electricity savings from air conditioning reductions totaled 3850 GWh $year^{-1}$ (75.3 GWh $year^{-1}$ se) (Table 4). City trees reduced annual natural gas used for heating by 2.18 million GJ $year^{-1}$ (42,672 GJ $year^{-1}$ se). The total annual monetary value of cooling and heating energy savings was $548.4 million and $20.3 million, respectively (Table 5). The average annual benefit per tree was $3.17 and $0.11 for cooling and heating, or $3.28 total.

California's 173 million trees stored 103 MMT (2.0 MMT se) CO_2 (Table 4). The amount of CO_2 sequestered was 7.2 MMT $year^{-1}$ (141,330 t $year^{-1}$ se). This value does not include emissions associated with decomposition of dead trees, pruned wood and chips or those associated with combustion of fossil fuels during tree care activities. Urban forests in the Northern California Coast (2.7 MMT $year^{-1}$) and Inland Valley (2.2 MMT $year^{-1}$) climate zones sequestered the most CO_2. Annual avoided CO_2 emissions from building energy savings totaled 1.3 MMT $year^{-1}$ (25,446 t $year^{-1}$ se). Total annual avoided emissions were greatest in the Inland Valley (0.56 MMT $year^{-1}$) and Inland Empire (0.44 MMT $year^{-1}$). Annual CO_2 removed from the atmosphere totaled 8.5 MMT $year^{-1}$ (166,776 t $year^{-1}$ se) state-wide, and was greatest in the Northern California Coast (2.9 MMT $year^{-1}$) and Inland Valley (2.7 MMT $year^{-1}$). The associated monetary value was $102.35 million ($2.0 million se) per year or $0.59 per tree on average (Table 5).

Net air pollutant uptake by the state's 173 million city trees totaled 3537 t $year^{-1}$ (69.2 t $year^{-1}$ se) (Table 4). Net uptake was greatest in the Inland Valley (5252 t $year^{-1}$) and Southern California Coast (3484 t $year^{-1}$) zones. Ozone (11,293 t $year^{-1}$) was removed in the greatest quantity. The net annual value of trees' effects on air quality was $56.2 million ($1.1 million se) or $0.32 per tree ($0.01 $year^{-1}$ se) (Table 5). BVOCs released by trees exceeded avoided emissions of VOCs from energy savings, netting release of 23,599 t $year^{-1}$ (461.6 t $year^{-1}$ se). Net emissions were highest in the Northern California Coast (7924 t $year^{-1}$), Inland Empire (6282 t $year^{-1}$) and Inland Valley (5505 t $year^{-1}$).

Table 2
Structural information (standard error) in each climate zone and state-wide (InlEmp = Inland Empire, InlVal = Inland Valleys, NoCalC – Northern California Coast, SoCalC = Southern California Coast, SWDsrt = Southwest Desert, InterW = Interior West, Calif = California).

Category	InlEmp	InlVal	NoCalC	SoCalC	SWDsrt	InterW	Calif
Urban area (km^2)	4,741	6,218	3,828	5,064	1,187	364	21,402
Urban population	8,826,385	7,556,268	6,913,793	10,583,707	1,100,041	249,482	35,229,676
Tree canopy (%)	9.9	17.4	22.1	13.8	4.8	14.0	15.0
Tree canopy (m^2/capita)	53.2	143.0	122.2	66.0	51.5	203.9	90.8
Tree numbers (1000,000s)	28.1 (0.44)	42.1 (0.27)	58.4 (2.00)	38.9 (0.47)	3.7 (0.18)	2.0 (0.03)	173.2 (3.39)
Trees/capita	3.2	5.6	8.4	3.7	3.4	7.9	4.9
Tree density (tree/ha)	59.3	67.7	152.5	76.9	31.3	53.9	80.9

Table 3
Relative abundance and basal area for the top five genera in each climate zone and state-wide (InlEmp = Inland Empire, InlVal = Inland Valleys, NoCalC − Northern California Coast, SoCalC = Southern California Coast, SWDsrt = Southwest Desert).

InlEmp	InlVal	NoCalC	SoCalC	SWDsrt	California
Abundance					
Prunus (11.9%)	*Quercus* (18.4%)	*Quercus* (41.0%)	*Quercus* (8.5%)	*Washingtonia* (20.5%)	*Quercus* (22.0%)
Cupressus (8.8%)	*Prunus* (13.3%)	*Juniperus* (13.6%)	*Eucalyptus* (7.5%)	*Pinus* (17.9%)	*Prunus* (6.6%)
Quercus (8.3%)	*Sequoia* (5.5%)	*Yucca* (7.7%)	*Sygarus* (5.2%)	*Juniperus* (15.2%)	*Juniperus* (5.5%)
Persea (6.2%)	*Cupressus* (5.3%)	*Umbellularia* (6.0%)	*Acacia* (4.6%)	*Citrus* (12.4%)	*Cupressus* (4.2%)
Lagerstroemia (4.4%)	*Acer* (4.7%)	*Pinus* (3.2%)	*Myoporum* (4.5%)	*Phoenix* (6.1%)	*Pinus* (3.5%)
Basal Area					
Pinus (13.0%)	*Quercus* (13.2%)	*Acer* (11.6%)	*Pinus* (11.9%)	*Washingtonia* (35.3%)	*Pinus* (10.1%)
Eucalyptus (10.5%)	*Pinus* (7.7%)	*Sequoia* (11.6%)	*Eucalyptus* (8.6%)	*Pinus* (23.6%)	*Eucalyptus* (7.6%)
Fraxinus (10.2%)	*Zelkova* (6.2%)	*Quercus* (9.5%)	*Phoenix* (7.3%)	*Fraxinus* (11.8%)	*Quercus* (6.4%)
Washingtonia (4.7%)	*Eucalyptus* (5.1%)	*Phoenix* (7.6%)	*Platanus* (6.0%)	*Phoenix* (9.5%)	*Phoenix* (5.2%)
Olea (4.6%)	*Ulmus* (4.9%)	*Eucalyptus* (6.5%)	*Cedrus* (3.9%)	*Sygarus* (4.2%)	*Platanus* (4.5%)

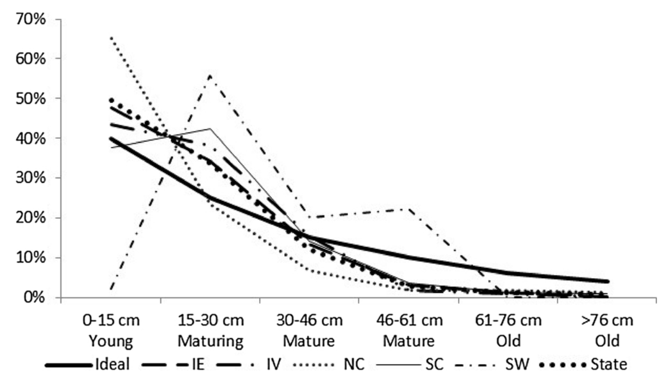

Fig. 3. Patterns of tree age structure based on dbh classes in each climate zone and the "ideal", which has a large percentage of juveniles to offset highest rates of mortality (Inland Empire = Inland Empire, InlVal = Inland Valleys, NoCalC = Northern California Coast, SoCalC = Southern California Coast, SWDsrt = Desert Southwest, Calif = California).

California's 173 million trees intercepted 196 million m^3 $year^{-1}$ (3.8 million m^3 $year^{-1}$ se) of rainfall annually (Table 4). Trees in the Northern California Coast (60.6 million m^3 $year^{-1}$) zone intercepted the most rainfall. Rainfall interception reduced annual stormwater management costs by an estimated $324.6 million ($6.3 million se), with the greatest benefit in the Inland Valley ($97.8 million) (Table 5). The average annual benefit per tree was $1.87 ($0.04 $year^{-1}$ se).

Trees in California cities contributed to the sales prices of homes and provided other benefits in the amount of $7.2 billion ($141.5 million se) per year (Table 5). Property values and other benefits were greatest in the Inland Valley ($2.2 billion) and Southern California Coast ($2.1 billion) zones.

The total annual value of all ecoservices was $8.29 billion ($162.1 million se), or $47.83 per tree ($0.94 $year^{-1}$ se) and $235 per capita (Table 5). When the state's urban trees were considered as a capital investment similar to other infrastructure, their asset value was $181 billion ($3.54 billion se) or $1045 per tree ($20.44 se).

3.3. Management example

Approximately 23.2 million trees or 32.8% of the Southern California region's 70.8 million trees were susceptible to the ISHB-FD complex (Table 6). The 49 potential host species accounted for 18% of the 273 total taxon in the three climate zones. Taxon most at risk were: *Quercus agrifolia* (4.5 million trees), *Persea americana* (2.5 million), *Prunus* sp. (1.9 million), *Citrus* sp. (1.8 million), *Pittosporum* sp. (1.5 million), *Platanus,* sp. (1.3 million), *Acacia sp.* (1.1 million) and *Liquidamber* sp. (1.1 million). Should 50% of the 23.2 million trees at risk die, the estimated value of ecoservices foregone over 10 years was $616.8 million. The approximate cost for removing and replacing the trees with similar species and size was $15.9 billion. Asset losses were projected to be greatest in the Southern California Coast zone ($9.4 billion), peaking in 2020 at $1.5 billion (Fig. 4). Projected losses for the

Table 4
Functional services produced by the tree population in each climate zone and state-wide (se) (InlEmp = Inland Empire, InlVal = Inland Valleys, NoCalC − Northern California Coast, SoCalC = Southern California Coast, SWDsrt = Southwest Desert, InterW = Interior West, Calif = California).

Resource Units	InlEmp	se	InlVal	se	NoCalC	se	SoCalC	se	SWDsrt	se	InterW	se	Calif	se
Energy														
Cooling	1,372	21.6	1,886	12.0	234	8.0	175	2.1	118	5.6	66	1.0	3,851	75.3
Heating	−337	5.3	240	1.5	1,928	66.1	321	3.9	29	1.4	1	0.0	2,181	42.7
CO_2														
Stored	11,504	181.1	35,545	226.7	33,769	1,158.3	19,824	238.4	965	46.0	1,389	20.7	102,996	2,014.7
Sequestered	785	12.4	2,172	13.9	2,746	94.2	1,341	16.1	89	4.2	93	1.4	7,225	141.3
Avoided	443	7.0	561	3.6	165	5.7	75	0.9	35	1.7	21	0.3	1,301	25.4
Seq. + Avoided Total	1,228	19.3	2,733	17.4	2,911	99.8	1,416	17.0	125	5.9	114	1.7	8,526	166.8
Air Quality														
NO_2 uptake + avoided	1,280	20.2	2,308	14.7	800	27.4	1,819	21.9	156	7.4	119	1.8	6,481	126.8
O_3 uptake	2,121	33.4	4,902	31.3	1,103	37.8	2,977	35.8	90	4.3	100	1.5	11,293	220.9
SO_2 uptake + avoided	1,044	16.4	481	3.1	271	9.3	343	4.1	103	4.9	89	1.3	2,331	45.6
PM_{10} uptake + avoided	1,284	20.2	3,066	19.6	726	24.9	1,808	21.7	93	4.4	53	0.8	7,030	137.5
BVOC + VOC	−6,282	98.9	−5,505	35.1	−7,924	271.8	−3,464	41.6	−349	16.6	−76	1.1	−23,599	461.6
Net Total Removal	−553	189.1	5,252	103.7	−5,025	371.3	3,484	125.2	93	37.7	285	6.5	3,537	69.2
Rainfall														
Interception	42,129	663	48,708	311	60,551	2077	40,194	483	3,194	152	1,188	18	195,964	3,833

Units: Cooling (GWh/yr), Heating (TJ/yr), Air Quality (1 metric tonne/yr), Interception (1000 m^3/yr).
Units: CO_2 stored (1,000 t), CO_2 Sequestered, Avoided (1,000 t/yr)

Table 5
Annual monetary value of ecoservices and total asset value (all in million $US) by climate zone and state-wide (se) (InlEmp = Inland Empire, InlVal = Inland Valleys, NoCalC – Northern California Coast, SoCalC = Southern California Coast, SWDsrt = Southwest Desert, InterW = Interior West, Calif = California).

Ecoservice	InlEmp	se	InlVal	se	NoCalC	se	SoCalC	se	SWDsrt	se	InterW	se	Calif	se
Energy	202.8	3.2	259.3	1.7	49.8	1.7	29.1	0.3	17.8	0.8	9.9	0.1	568.6	11.1
Carbon Dioxide	14.8	0.2	32.8	0.2	34.9	1.2	17.0	0.2	1.5	0.1	1.4	0.0	102.4	2.0
Air Quality	1.7	0.01	57.9	0.03	−47.1	0.17	38.7	0.04	1.6	0.00	3.4	0.00	56.2	1.10
Stormwater	80.5	1.3	97.8	0.6	64.0	2.2	76.8	0.9	4.1	0.2	1.6	0.0	324.6	6.3
Property Value/Other	1,058.2	16.7	2,250.0	14.4	1,673.4	57.4	2,132.0	25.6	109.3	5.2	11.2	0.2	7,234.1	141.5
Ecoservice Total	1,358.0	21.4	2,697.8	16.9	1,774.9	62.7	2,293.6	27.2	134.2	6.3	27.4	0.4	8,285.9	162.1
Total Asset Value	28,980.8	456.3	49,464.7	315.5	31,915.4	1,094.7	61,558.3	740.3	8,114.3	386.5	978.3	14.6	181,012.0	3,540.7

Inland Empire and Southwest Desert zones peaked in 2022 ($808 million) and 2027 ($189 million), respectively. The asset loss estimated for the 80% scenario was $25.4 billion and the value of foregone ecoservices approached $1 billion (Table 6). These estimates may be conservative because they do not include costs associated with damage to people and property from tree failures, as well as increased risk of fire and other hazards.

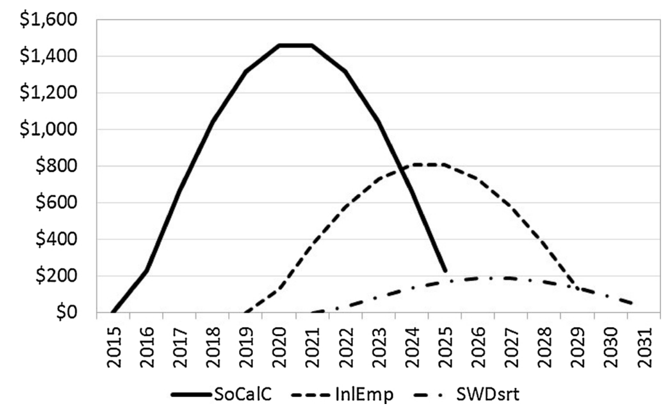

Fig. 4. Projected annual loss of asset value (in million $US) as trees die, are removed and replaced over 10-year periods in each of the three climate zones. This scenario assumes that 50% of the susceptible trees die. (SoCalC = Southern California Coast, InlEmp = Inland Empire, SWDsrt = Southwest Desert).

4. Discussion

4.1. Structure

The 173.2 million trees reported in this study is similar to the previously estimated 177.3 million trees (McPherson and Simpson, 2003), however that estimate was from old aerial photos (1988–1992) and for residential land uses only. Vacant tree sites were not recorded in this study. Assuming the ratio of vacant sites to live trees found for residential land uses is unchanged from 2003 (1.36:1), there are approximately 236.1 million vacant sites. If this number is correct, 42% of all sites have trees, indicating that there is ample opportunity for new tree planting. Given that the state has 9.1 million street trees (McPherson et al., 2016a), street trees account for about 5% of California's entire urban forest.

Although California cities contain almost five trees for every resident on average, stocking levels varied threefold by climate zone. Xeric zones had the lowest stocking, 3.4 and 3.2 trees per capita in the arid Southwest Desert and Inland Empire. Mesic Northern California Coast had the highest stocking (8.4). Explanatory variables include differences in climate, which influences natural regeneration, as well as urban development densities and land use patterns. Relatively high stocking in the Interior West zone (7.8 trees per capita) is partially due to its temperate climate, which is conducive to natural regeneration in communities in forested areas, such as surrounding Lake Tahoe.

A fourfold difference in the average amount of UTC per capita across California climate zones reflects the same high variability reported for stocking levels. Zones with the lowest UTC per capita were the most xeric (Southwest Desert and Inland Empire). Zones with the highest UTC per capita had the lowest mean temperature (Interior West) and received the most precipitation (Northern California Coast). Population density may play a role as well, influencing the relative amount of pervious surfaces available for tree planting. Although the more arid climates of Inland Valley cities are less conducive to tree cover than Southern California Coast cities, average UTC per capita was greater (143 vs 66 m^2 per capita). Lower population densities of Inland Valley cities like Modesto and Sacramento (2953 and 8101 km^{-2}) compared to Southern California Coast cities like Santa Monica and Los Angeles (22,580 and 29,990 km^{-2}) may be partially responsible. Although California is home to about 10% of the U.S. population, it claims 20 of the top 100 most densely populated cities (http://zipatlas.com/us/ca/city-comparison/population-density.htm). California's relatively densely populated cities may help explain why it has the lowest amount of UTC per capita in the U.S. (90.8 m^2).

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. 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). Although the state's cities contain a diverse assemblage of tree species (338 taxa), this study found that nearly one-half of all individuals belong to the top five genera of oak (22%), cherry, juniper, cypress and pine. Muller and Bornstein (2010) reported that species richness was high in California communities (mean of 185 taxa per community) but recent plantings

Table 6
Two scenarios (50% and 80% loss rates over 10 years) illustrate potential economic impacts (in million $US) of the Invasive Shot Hole Borer-Fusarium Dieback complex on urban trees in three Southern California climates zones (SoCalC = Southern California Coast, InlEmp = Inland Empire, SWDsrt = Southwest Desert).

	SoCalC	se	InlEmp	se	SWDsrt	se	Total	Tot se
Trees at Risk (millions)	11.94	7.54	10.14	7.73	1.12	1.03	23.21	16.30
50% Loss – Million Dead	5.97	3.77	5.07	3.87	0.56	0.52	11.60	8.15
Ecoservices Lost (M$/yr)	351.75	2.67	244.90	2.94	20.20	0.89	616.84	6.50
Asset Value Lost (M$)	9,440.69	71.65	5,226.25	62.73	1,221.00	53.70	15,887.93	188.08
80% Loss – Million Dead	9.56	6.03	8.11	6.19	0.90	0.83	18.56	13.04
Ecoservices Lost (M$/yr)	562.79	4.27	391.84	4.70	32.32	1.42	986.95	10.40
Asset Value Lost (M$)	15,105.10	114.64	8,362.00	100.37	1,953.60	85.92	25,420.70	300.93

lacked diversity. The metric of no single genus accounting for more than 20% of the population was exceeded state-wide (oak at 22%) and in the Northern California Coast (oak at 41%) and Southwest Desert (fan palm at 21%) climate zones. However, lack of taxonomic diversity is ameliorated by a more even distribution of basal area among genera. State-wide, oak accounted for only 6.4% of total basal area, while the most dominant genus, pine, accounted for 10.1%. In the Northern California Coast zone, where oak were over-abundant, they accounted for only 9.5% of total basal area. Although oak were ubiquitous, their relatively small size partially mitigates the threat of catastrophic loss. Nevertheless, there is need for species diversification.

4.2. Function and value

The value of ecoservices that urban forests provide have analogies that may make their impacts more easily understood. Some analogies are listed below. The discussion that follows compares our findings with similar studies and offers possible explanations for differences we report across climate zones. Results are presented on a per tree basis for ease of comparison.

The amount of electricity saved annually by California's urban forests (3851 GWH) is equivalent to the amount required to air condition 210,280 California households each year. The amount of CO_2 removed and avoided emissions annually (8.5 MMT) is equivalent to removing 1.8 million cars from the road, 14% of the state's 13 million registered vehicles. California's urban forests intercepted rainfall (196 million m^3) equivalent to the average amount of potable water consumed by 424,200 California households each year. The asset value of California's urban forests ($181 billion) is equivalent to 3.7% of the total value of state- and county-assessed property in California ($4.9 trillion in 2014–15) (California State Board of Equalization, 2014).

The average electricity savings per tree of 22.2 kWh $year^{-1}$ (Table 4) is less than values for street trees in California cities (36–138 kWh $year^{-1}$) (McPherson et al., 2016a). This is largely due to proximity of street trees to buildings, whereas many non-street trees are too far from buildings to shade them. Per tree total savings ranged from $7.21 in the Inland Empire to $0.75 in the Southern California Coast. Savings were least in the coastal climate zones (< $1) and greatest in the inland zones ($4.79–$7.21). In inland climate zones, tree shade and lower temperatures from evapotranspirational cooling reduced air conditioning loads the most because summers are hot and dry. Cooling savings ranged from 32 to 49 kWh $year^{-1}$ per tree in the hotter Southwest Desert, Inland Valley, and Inland Empire climate zones. The effect of trees on energy used for heating was most important in the coastal climate zones, where trees reduced wind speeds and air infiltration (Simpson and McPherson, 1996).

The CO_2 sequestration value reported here is higher than reported using the national average carbon density rates from 34 U.S. cities (8.5 vs. 5.9 MMT $year^{-1}$) (Nowak et al., 2013). Our higher sequestration rate could be due to using growth rates (McPherson et al., 2016b) and biomass equations (Pillsbury et al., 1998) from trees measured in California cities. On average, CO_2 was stored, sequestered and avoided per tree was 595 kg (11.6 kg se), 41.7 kg $year^{-1}$ (0.8 kg $year^{-1}$ se), and 7.5 kg $year^{-1}$ (0.1 kg $year^{-1}$ se), respectively. The per tree estimates varied considerably among climate zones (Table 4). The average amount stored per tree was 3.2 times greater in the Inland Valley (844 kg) than the Southwest Desert (260 kg). Storage and sequestration rates were least in the Southwest Desert and Inland Empire zones, where aridity can limit tree growth. Rates were greatest in the more temperate Inland Valley, Interior West and Northern California Coast zones. Because avoided CO_2 emissions are related to reductions in space cooling and heating, it is not surprising that rates were greatest in the Inland Empire and Inland Valley zones, where energy savings were the most.

California's urban forests were estimated to remove 0.02 kg $year^{-1}$ per tree of air pollutants from the atmosphere. The variability in net uptake rates was relatively small (−0.09–0.15 kg $year^{-1}$), while the monetary value for pollutant removal varied threefold among climate zones, ranging from $-0.81 $year^{-1}$ per tree (Northern California Coast) to $1.73 (Interior West). Trees were net emitters in the Northern California Coast and Inland Empire zones. In these zones at least two of the top five genera in terms of relative basal area were classified as high BVOC-emitting (i.e., *Quercus*, *Eucalyptus*, *Sequoia*) (Benjamin et al., 1996). The net uptake rates reported here are well below the reported ranges for other U.S. states from i-Tree analyses (0.09–0.46 kg $year^{-1}$) (Nowak et al., 2012). This difference is partially due to the contribution of BVOC emissions, which were included here and omitted from i-Tree analyses. We recognize that by taking a conservative approach we may be overestimating this air pollution disservice. For example, in coastal areas where sea breezes and cool temperatures are common during summer, tree BVOC emissions may not contribute to local ground-level ozone pollution because required precursors for ozone formation are absent (Escobedo et al., 2011). However, these BVOC emissions may travel inland and contribute to ozone formation where precursors are present.

Annual rainfall interception averaged 1.1 m^3 $year^{-1}$ per tree (0.02 m^3 $year^{-1}$ se) and ranged threefold from 0.6 (Interior West) to 1.6 m^3 (Inland Empire). This finding is partially explained by a preponderance of conifers (*Pinus*), broadleaf evergreens (*Eucalyptus, Olea*) and palms (*Washingtonia*) that were in-leaf during the Inland Empire's rainy winter season. The value of annual interception per tree ranged from $0.80 to $2.86 and was lowest in the Interior West zone where deciduous trees dominated (e.g., *Fraxinus*, *Platanus*, *Acer*).

The effect of trees on property values and other less tangible benefits was the single largest benefit (87% of total), averaging $41.76 $year^{-1}$ per tree. The values ranged almost tenfold among climate zones ($5.73–$54.75). This result largely reflects differences in the median sales prices of residential properties. Home sales prices were greatest in the coastal and Inland Valley zones, and lowest in the Interior West and Southwest Desert zones (McPherson et al., 2005).

The average annual value of all ecoservices was $47.83 per tree ($235 per capita). Values ranged almost fivefold, from $13.98 in the Interior West to $64.07 in the Inland Valley. Trees can be costly to plant and maintain and their ecosystem disservices can negatively affect human well-being and impose financial burdens (Escobedo et al., 2011). Examples include health impacts from pollen and emissions of BVOCs, damage from falling trees and branches, blocked views and obstructed solar access (Dwyer et al., 1992; McPherson and Ferrini, 2010). For example, root conflicts with sidewalks and curbs were estimated to cost California cities approximately $70.7 million annually ($11.22 per tree) (McPherson, 2000). 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 $47.83, $2.52 in benefit is returned for every $1 spent. Using this $19 value for annual costs, a tree in the Interior West zone may be a net cost because benefits ($13.98) are less than costs, while the benefit-cost ratio for a tree in the Inland Valley zone is 3.37:1. In reality, this $19 is likely to vary among zones and represents the highest likely cost because most city trees on private and institutional properties are not maintained as intensively as municipal trees, where risks and costs of failure are greatest. The average asset value per tree was $1045, and ranged threefold from $499 (Interior West) to $1581 (Southern California Coast) (Table 5).

4.3. Management implications

Despite their value to California communities, urban trees are a surprisingly fragile resource whose asset value can be jeopardized in a short time. There is need to reduce the risk of catastrophic loss by increasing the resilience of California's urban forests. Policies are needed that promote the planting and stewardship of tree species that will be less vulnerable to invasive pests, as well as well-adapted to future growing conditions. Tree pandemics like the ISHB-FD complex may become more common in California as a consequence of increasing global trade. These pests will attack multiple genera, so planting a diversity of species within a genus is not a good defense. Instead, Ball and Tyo (2016) recommend limiting the use of a genus to 10%, and to 5% if it has many species spread across all three continents in the Western Hemisphere. Such widespread genera are at greatest risk because of previous exposure to exotic pests. Genera that are relatively pest-free have few species and are native to a single continent (e.g., *Ginkgo biloba*, *Maclura pomifera*, *Parrotia persica*). Another strategy to increase resilience is ongoing evaluation of climate-ready species that are drought tolerant and compatible to city conditions. Science-based data are needed for tree selection that identify taxon especially well adapted to climate change stressors such as heat, drought, extreme winds and pests (McPherson and Berry, 2015). Tree selection will need to weigh the tradeoffs between the ability of each species to tolerate these stressors, while at the same time minimizing disservices and achieving multiple objectives, such as CO_2 storage, energy savings, rainfall interception and food (Livesley et al., 2016).

4.4. Uncertainty, limitations and uses

This study is novel for its integration of different field data sets with delineation of UTC and modeling of ecoservices. Future research, development and application are needed to overcome some of its uncertainties and limitations, which are discussed in this section.

Estimates of tree numbers are subject to multiple sources of uncertainty. Measurement and sampling error influence the accuracy of estimates from plot data. In this study, standard errors are 1–5% of estimates. Because measurement errors have a small effect (± 1–3%) we infer that sampling error is an important source of error, especially in the Southwest Desert and Interior West climate zones. Increased sampling in these zones will improve quantification of state-wide structure, function and value in the future. In addition to increasing the number of urban field plots, measurement of all plots at regular intervals will provide core data for change detection.

Formulaic errors occur in modeling of ecoservices. For example, relations between different levels of UTC and summertime air temperatures are not well-researched. Another source of error stems from differences between the airport climate data (i.e., Los Angeles International Airport) used to model energy effects and the actual climate of the study area (i.e., Los Angeles urban area). Because of the uncertainty associated with modeling effects of trees on building energy use, energy estimates may be accurate within ± 25% (California Air Resources Board, 2011a; Hildebrandt and Sarkovich, 1998).

The lack of biometric data from the field remains a serious limitation to our ability to calibrate biomass equations and assign error estimates. In this study, differences between modeled and actual tree growth adds uncertainty to CO_2 sequestration estimates. Species assignment errors result from matching species sampled in the field and the magnitude of this error depends on the proportion of population that must be assigned a species match, as well as goodness of fit in terms of matching size and growth rate. Given the attention paid during this study to species matching, as well as assigning allometric equations and dry weight wood density values, estimates of carbon storage and sequestration may have uncertainty as great as ± 10% (Aguaron and McPherson, 2012).

Pollutant deposition estimates are sensitive to uncertainties associated with canopy resistance, resuspension rates and the spatial distribution of air pollutants and UTC. For example, deposition to urban forests during warm periods may be underestimated if the stomata of well-watered trees remain open. In the present model, hourly meteorological data from a single station for each climate zone may not be spatially representative of conditions in local atmospheric surface layers (Serna-Chavez et al., 2014). Estimates of air pollutant uptake may be accurate within ± 25%.

Estimates of rainfall interception are sensitive to uncertainties regarding rainfall patterns, tree leaf area and surface storage capacities. Rainfall amount, intensity and duration can vary considerably within a climate zone, a factor not considered by our model. Although tree leaf area estimates were derived from extensive measurements on over 14,000 street trees across the U.S.A. (McPherson et al., 2016b), actual leaf area may differ for sampled trees because of their health and management. Leaf surface storage capacity, the depth of water that foliage can capture, was recently found to vary threefold among 20 tree species (Xiao and McPherson, 2016). A shortcoming is that our model used the same value (1 mm) for all species. Given these limitations, interception estimates may have uncertainty as great as ± 20%.

The contribution of trees to real estate value and other benefits is largely based on previous research that found a large front yard tree was associated with a 0.88% increase in median home sales prices (Anderson and Cordell, 1988). Whether this relationship applies in other regions has not been tested. In our model, median home sales prices were adjusted by climate zone and a single value was used across the zone. If trees were disproportionately located in higher income areas, as studies suggest (Schwarz et al., 2015), using the zone's median sales price may underestimate property value added. Extrapolating value from large front yard trees to smaller trees in less conspicuous locations is fraught with uncertainty. Estimates of property value and other benefits may be accurate within ± 35%. It is important to note that the greatest uncertainty is associated with estimates of these property value and other benefits, and they were estimated to account for 87% of total annual ecoservices.

Our estimates of ecoservices reflect an incomplete understanding of the processes themselves (Schulp et al., 2014). Our choice of ecoservices to quantify was limited to those for which numerical models were available. There are many important benefits produced by trees that are not quantified and monetized in this study. These include effects of urban forests on local economies, wildlife, biodiversity and human health and well-being. 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). Hopefully, future studies will have access to improved models for a wider variety of ecoservices.

Urban tree canopy classification error directly affects the accuracy of the analysis because transfer functions are applied to UTC polygons. UTC was underestimated by 3% for this study (15% vs. 18%) (Bjorkman et al., 2015). One explanation is that the minimum mapping unit (20.2 m^2) used in image classification missed small, single trees. As a result, ecoservices are likely underestimated. Other sources of uncertainty are associated with mapping land use classes and boundaries of GIS data sets, such as urban areas. Mismatches among GIS data sets can result in misapplication of transfer functions. In the future, UTC classification accuracy can be improved with use of object-based image analysis systems, multiple-source data sets (i.e., LiDAR) and rigorous quality control (O'Neil-Dunne et al., 2012).

In summary, the transfer function approach makes it possible to map ecoservices at higher spatial resolution than other approaches because it directly links to UTC and land use class. Given the limited number of field plots surveyed, sampling and estimation errors are relatively large, while measurement errors are relatively small. Formulaic errors add considerable uncertainty to these results. Estimates of function and value reported here are conservative because UTC was underestimated. However, the bound of values reported here are based solely on sampling error, and do not include estimation and UTC classification error.

This study did not include tree condition, conflicts between trees and infrastructure, management needs and costs. These data were either not collected or reported inconsistently and unsystematically. Future assessments would benefit from more standardized data and information on expenditures associated with tree planting and care.

Time gaps between acquisition of remotely sensed data (2012), field sampling (from 2007 to 2012) and land use data (2013) can result in inaccurate maps and ecosystem service estimation. Up-to-date data that overlap spatially and temporally can improve the accuracy of mapping and ecosystem service modeling.

A valuable aspect of this study are the archived plot (https://doi.org/10.2737/RDS-2017-0011) and municipal tree inventory (https://doi.org/10.2737/RDS-2017-0010) datasets and the high resolution maps of UTC and land use data (ftp:\\frapftp.fire.ca.gov). These data are being used by CAL FIRE to identify priority areas for planting and tree conservation, including in disadvantaged communities.

5. Conclusions

California's urban forests contain 173 million trees that are a $181 billion asset that is producing annual ecosystem services valued in excess of $8 billion. Although these benefits are substantial, they could be greater. Stocking level and canopy cover per capita are relatively low, indicating that there is ample opportunity to plant trees. Moreover, existing canopy is threatened by invasive pests, population growth and a changing climate. Because California is such an attractive place to live, work, and play it is experiencing rapid growth, which is accelerating the arrival of invasive pests through global trade, along with water and energy demand problems. More sustainable infill growth is placing higher concentrations of people in urban environments where green space is a critical component to quality of life. Protecting existing canopy and finding adequate space for new trees in these densely engineered developments is a challenge, as is achieving a more equitable distribution of tree canopy across the socio-economic landscape. These problems urgently need solutions.

The task ahead for California is to transition to more stable and resilient urban forests. Tree selection is an important decision point for managers wanting to make this transition. The goal is to avoid catastrophic tree loss by gradually shifting the palette to species better adapted to future stressors such as invasive pests and climate change. This study provides information that can be used to detect change and evaluate the success of transitioning strategies. Also, these data are being used by CAL FIRE to plan and prioritize management investments to promote more effective and equitable planting and stewardship programs. By so doing, California's urban forest will become larger, more resilient, and better able to meet the challenges of tomorrow.

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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.2017.09.013.

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