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Original article

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

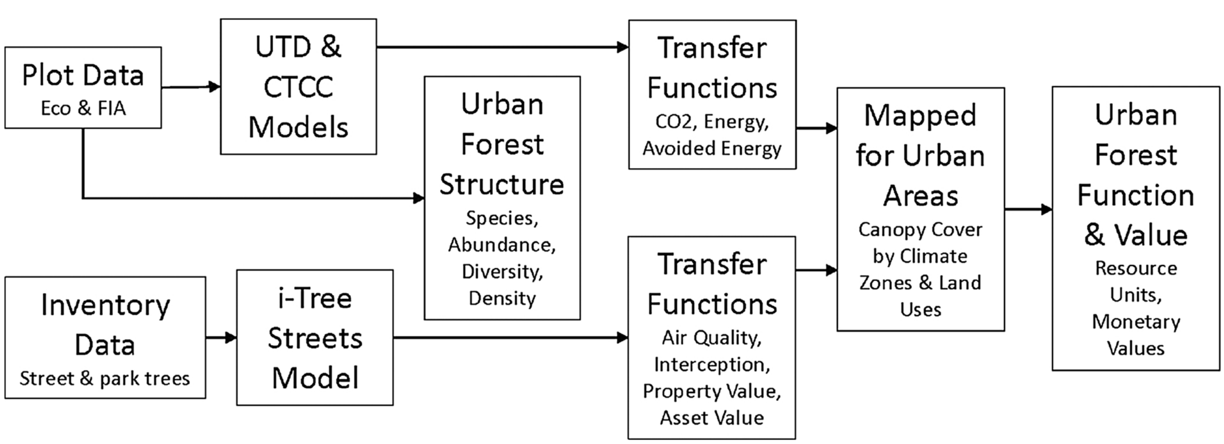

Fig. 1. Steps in the data collection, analysis and mapping process. Eco and Forest Inventory and Assessment (FIA) are field-based methods used to collect tree data. The Urban Tree Database (UTD) and CUFR Tree Carbon Calculator (CTCC) involve tree growth equations and numerical models to calculate carbon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