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Research paper

# A new approach to quantify and map carbon stored, sequestered and emissions avoided by urban forests

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## HIGHLIGHTS

- Species composition, basal area and development patterns influence carbon.
- Carbon storage was high in Sacramento due to native oaks with high wood density.
- Avoided emissions were high in Los Angeles due to trees shading multiple buildings.
- California's urban forests account for 2 percent of C stored by forests statewide.
- California's urban forests account for 12 percent of C sequestered by forests statewide.

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## ABSTRACT

This paper describes the use of field surveys, biometric information for urban tree species and remote sensing to quantify and map carbon (C) storage, sequestration and avoided emissions from energy savings. Its primary contribution is methodological; the derivation and application of urban tree canopy (UTC) based transfer functions ($\mathrm{t\,C\,ha^{-1}}$ UTC). Findings for Los Angeles and Sacramento illustrate the complex role of regional and local determinants. Although average tree density and size were substantially greater in Los Angeles, the mean C storage density ($8.15\,\mathrm{t\,ha^{-1}}$) was 53 percent of Sacramento's ($15.4\,\mathrm{t\,ha^{-1}}$). In Sacramento, native oaks with very high wood densities ($815\,\mathrm{kg\,m^{-3}}$) accounted for 30 percent of total basal area. In Los Angeles, the most dominant taxa had relatively low wood densities ($350\text{-}550\,\mathrm{kg\,m^{-3}}$). The inclusion of relatively more wooded land in the Sacramento study area may partially explain higher C storage levels. In Los Angeles, where development is relatively dense, 14 percent of all trees surveyed shaded more than one building compared to only 2 percent in Sacramento. Consequently, the transfer function for avoided emissions in Los Angeles ($2.77\,\mathrm{t\,ha^{-1}\,UTC\,yr^{-1}}$) exceeded Sacramento ($2.72\,\mathrm{t\,ha^{-1}\,UTC\,yr^{-1}}$). The approach described here improves C estimates and increases the resolution at which C can be mapped across a region. It can be used to map baseline C storage levels for climate action planning, identify conservation areas where UTC densities are highest and determine where opportunities for expanding UTC are greatest.

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## 1. Introduction

Carbon stored in urban forests is not typically included in national, statewide and regional inventories of greenhouse gas (GHG) emissions and sinks, perhaps because cities make up a small fraction of total land area and intensive management of trees can release large amounts of GHGs (Ryan et al., 2010). Although urbanized areas account for 3 percent of total land area and 81 percent of total population in the US (Cox, 2012), Heath, Smith, Skog, Nowak, and Woodall (2011) found that trees in US cities sequester about 14 percent of the amount of carbon (C) sequestered by US forests. Although relatively small in stature, urban forests store substantial amounts of carbon. Accurate quantification and mapping of these stocks is fundamental to the inclusion of urban forestry in local climate action plans and carbon offset markets. This study combines field surveys, biometric information for urban tree species, Geographic Information System (GIS) data sets and remote sensing of urban tree canopy (UTC) to quantify and map C stored, sequestered and emissions avoided in two urban forests. By incorporating age-related differences among census block groups

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that influence tree species composition and stand structure, this approach improves C estimates and increases the resolution at which C can be mapped across a region.

### 1.1. Urban forest project protocols

In California, a cap and trade program began in 2012 to drive investment in cleaner fuels and more efficient energy use. The Compliance Offset Protocol for Urban Forest Projects is one of four protocols that will guide carbon offset projects (California Air Resources Board, 2011). The current protocol focuses on offsets from tree planting projects, but the Climate Action Reserve (2010) is exploring development of a second protocol based on field surveys that are linked with urban tree canopy (UTC) mapped with remote sensing. Urban tree canopy (UTC), defined as the layer of leaves, branches and stems that cover the ground when viewed from above, is a metric used to quantify the areal extent of the urban forest (Raciti et al., 2006). Using UTC as a metric for C storage has the advantage of being readily measured and tracked over time at high spatial resolution and with increasing accuracy as technologies develop. Mapping the spatial distribution of existing and additional stocks can provide the basis for quantifying and reporting changes in C storage, as well as for planning and managing urban forests to increase C stocks. For example, maps can be used to locate areas with the greatest potential for increasing tree canopy through tree planting, as well as areas where the foremost need is to preserve C stored in existing canopy (Escobedo, Varela, Zhao, Wagner, & Zipperer, 2010; Myeong, Nowak, & Duggin, 2006).

### 1.2. Transfer functions

Broadly speaking, transfer function is a term used to describe the transfer of data for a particular “study site” to a “policy site” for which little or no data exist (Brookshire & Neill, 1992; Downing & Ozuna, 1996). In this study, transfer functions are defined as field plot-based measures of C per hectare UTC (t $\text{ha}^{-1}$ tree canopy cover) that are aggregated and applied to a region by land use class.

Two studies have derived and applied UTC-based transfer functions. Nowak and Greenfield (2010b) calculated mean UTC storage (333.7 t $\text{ha}^{-1}$ UTC) and sequestration (11.0 t $\text{ha}^{-1}$ UTC) densities using 2001 NLCD imagery and field sampling in 17 US cities. Their values may be relatively high because the classification process was found to significantly underestimate UTC (Nowak & Greenfield, 2010a). Strohbach and Haase (2012) used high resolution orthophotos to classify UTC and intensive UFORE field sampling to estimate aboveground carbon and UTC densities for 19 land use classes. They compared C estimates derived using UTC and land use class alone and found that UTC-based estimates provided higher accuracy, greater precision and improved spatial detail. The UTC-based approach eliminated variation in UTC within land use classes, an important source of error. Because field plot sampling did not fully capture the extent of UTC for each land use class, land use based C storage estimates had large standard errors in areas where UTC was highly heterogeneous, such as town centers.

To derive UTC-based transfer functions, C storage, sequestration and avoided emission values are calculated for trees in each plot and divided by the plot’s UTC. Plot data are aggregated by land use class and descriptive statistics are applied to determine sample means and standard errors. Different values reflect different stand structures and dynamics that influence C. For instance, the C storage transfer function for a hectare of UTC in an old residential neighborhood will be relatively high when the stand consists of mature oaks (*Quercus* sp.) and a lush understory. In contrast, the transfer function for a hectare of UTC in a new residential area will be lower when the stand is characterized by juvenile pear (*Pyrus* sp.) trees with a sparse understory.

The value of a transfer function reflects species composition and attributes of stand structure. Stand attributes, such as the vertical layering of woody biomass in strata, tree density and basal area influence the amount of biomass per hectare UTC and the resulting value of a transfer function. Species is important because of its influence on the tree’s biomass and partitioning into roots, bole, branches, stems and foliage. Also, the amount of biomass converted into carbon depends on the species’ wood density, which can vary widely among species.

The transfer function for each land use class is transferred to the UTC delineated from imagery for the corresponding land use. Using GIS capabilities, C values are mapped and summed based on the amount of UTC in each land use class. These maps provide spatially explicit information on the distribution of urban forest C for planning and management purposes.

### 1.3. Regional and local determinants

The magnitude of C stored, sequestered and avoided emissions by urban forests depends on regional and local determinants. Regional context influences climate, soil, potential vegetation and urban morphology (Nowak et al., 1996; Sanders, 1984). Desert cities can have lower overall C storage densities than cities in temperate climates because unmanaged open space in deserts contains less biomass than in forest biomes such as Atlanta and Baltimore (Yesilonis & Pouyat, 2012). Older, densely developed cities can contain less growing space for urban vegetation that stores less C than sprawling cities (Zipperer, Sisinni, Pouyat, & Foresman, 1997).

Local determinants of urban forest C storage include species composition, age structure, stand density and tree management practices, as well as neighborhood age and land use (Zhao, Kong, Escobedo, & Gao, 2010). Carbon storage typically decreases as impervious surfaces and land development intensity increases. In Leipzig for example, land uses with the highest C storage densities were cemeteries, parks and single-family residential areas, while commercial, industrial and multifamily residential had lower C densities (Strohbach & Haase, 2012).

Each urban forest can be viewed as a mosaic of neighborhood stands with structural features that reflect historic changes in species preferences, planting practices, land development patterns, and tree conservation and planting policies (Berland, 2012; Conway, Shakeel, & Atallah, 2011; Palmer, 1984). The importance of neighborhood age on urban forest stand density, species composition and structure has been well demonstrated. Lowry, Baker, and Ramsey (2012) found that among several physical factors, neighborhood age was the most influential factor explaining tree canopy abundance. In Baltimore, Maryland the abundance of neighborhood tree canopy increased with neighborhood age to about 45–50 years, then decreased (Grove et al., 2006). This suggests that forest and housing stocks followed a parallel inverted U relationship that traced periods of appreciation and depreciation. However, in desert cities the abundance and diversity of vegetation was found to decrease as neighborhoods aged (Hope et al., 2003; Martin & Stabler, 2004). In US cities, the majority of trees and potential tree planting sites are in low density residential land uses, so their age-related stand structure and dynamics are especially important (McPherson & Rowntree, 1993).

### 1.4. Purpose and terms defined

This study extends research cited above by incorporating age-related differences that influence species composition, stand structure and C storage in low density residential areas. The derivation and application of transfer functions is demonstrated for urban forests in Los Angeles and Sacramento, California. Relations between differences in transfer functions and causal factors such