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## Million trees Los Angeles canopy cover and benefit assessment

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## ABSTRACT

The Million Trees LA initiative intends to improve Los Angeles's environment through planting and stewardship of 1 million trees. The purpose of this study was to measure Los Angeles's existing tree canopy cover (TCC), determine if space exists for 1 million additional trees, and estimate future benefits from the planting. High-resolution QuickBird remote sensing data, aerial photographs, and geographic information systems were used to classify land cover types, measure TCC, and identify potential tree planting sites. Benefits were forecast for planting of 1 million trees between 2006 and 2010, and their growth and mortality were projected until 2040. Two scenarios reflected low (17%) and high (56%) mortality rates. Numerical models were used with geographic data and tree size information for coastal and inland climate zones to calculate annual benefits and their monetary value. Los Angeles's existing TCC was 21%, and ranged from 7 to 37% by council district. There was potential to add 2.5 million additional trees to the existing population of approximately 10.8 million, but only 1.3 million of the potential tree sites are deemed realistic to plant. Benefits for the 1-million-tree planting for the 35-year period were \$1.33 billion and \$1.95 billion for the high- and low-mortality scenarios, respectively. Average annual benefits were \$38 and \$56 per tree planted. Eighty-one percent of total benefits were aesthetic/other, 8% were stormwater runoff reduction, 6% energy savings, 4% air quality improvement, and less than 1% atmospheric carbon reduction.

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## 1. Introduction

Urbanization creates significant changes in land use and land cover, affecting the structure, pattern, and function of ecosystems. Ecologists, planners, designers, and the public are increasingly concerned about how these changes influence daily life and affect the sustainability of "quality of life" for future generations. In Los Angeles, California, a rapidly growing region of nearly 4 million people, improving air and water quality, alleviating water shortages, cooling urban heat islands, and reducing local flooding are mounting challenges. For example, between 627,800 and 1.48 million gastrointestinal illnesses are caused annually by swimming in contaminated beaches in southern California (Given et al., 2006). This public health impact corresponds to an economic loss of \$21 to \$51 million related to health care costs. Rainfall interception by Santa Monica's municipal forest (29,299 trees) reduced stormwater runoff by 193,168 m<sup>3</sup> (1.6% of total precipitation) with an estimated annual value of \$110,890 (Xiao and McPherson, 2002).

Long-term effects of exposure to high air pollution levels in southern California have been associated with decreased respiratory health (Gauderman et al., 2004). Exposure to freeway-related pollutants has been found to impair children's lungs and is associated with increased asthma (Gauderman et al., 2005). Although pollen produced by certain tree species can exacerbate the incidence of asthma, some studies report reduced respiratory disease associated with increased tree cover (Lovasi et al., 2008). Tree planting was found to reduce ozone concentrations in Los Angeles, provided species were low-emitters of biogenic volatile organic compounds (Taha, 1996). Increasing tree canopy cover is one of the most cost-effective ways to reduce urban heat islands and conserve energy for heating and cooling buildings (McPherson and Simpson, 2003; Rosenfeld et al., 1998; Rosenzweig et al., 2006).

The presence of trees and green spaces in cities is associated with increases in property values, perceived consumer friendliness, and sense of well-being (Payton et al., 2008; Wolf, 2005). Views of trees and nature from homes and offices provide restorative experiences that ease mental fatigue and help people concentrate (Kaplan and Kaplan, 1989). A series of studies on human stress caused by general urban conditions and city driving show that views of nature reduce the stress response of both body and mind (Parsons et al., 1998). Hospitalized patients with views of nature and time spent outdoors needed less medication, slept better, had a better outlook, and recovered more quickly than

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patients without connections to nature (Ulrich, 1985). A number of studies have found an association between access to green space and human health (Gidlof-Gunnarsson and Ohrstrom, 2007; Maas et al., 2006). For example, the presence of tree lined streets was associated with children walking to school (Larsen et al., 2009).

On September 29, 2006 Antonio Villaraigosa was elected mayor of the city of Los Angeles. The following day he planted a tree, kicking off his plan to plant 1 million trees in the next several years and said, “Los Angeles, the dirtiest big city in America, has the opportunity to be the greenest” (Hyman and Merl, 2006). The ambitious tree initiative was dubbed Million Trees LA (MTLA) and is integral to the city’s climate action plan, which aims to reduce greenhouse gas emissions 35% below 1990 levels by 2030 (City of Los Angeles, 2007). This research addresses questions posed by the MTLA initiative—How many trees already exist in Los Angeles? Is there room for a million more trees? What environmental and other benefits will 1 million new trees provide?

### 1.1. Tree canopy cover assessment

Tree canopy cover (TCC) is the percentage of a site covered by the canopies of trees. American Forests and others advocate that communities identify current TCC, and then set targets for TCC increase (Grove et al., 2006; Kollin, 2006). TCC is an increasingly popular metric because it is relatively easy to measure with remote sensing technology and less costly than field sampling (Poracsky and Lackner, 2004). It is comparable across a city and among cities because the size of the area measured does not matter. Success meeting TCC targets can be measured across time as well as space. Finally, TCC is an easy-to-understand concept that is useful in communicating to the public.

However, TCC is two dimensional, only indicating the spread of canopy across land surfaces. It does not provide information on the vertical extent of tree canopy, species composition, age diversity, or health. Many functional benefits have been linked to the leaf surface area of trees, which is difficult to estimate with accuracy using only TCC. Moreover, predicting future trends in urban forest structure, function, and management needs requires a richer data set than TCC alone provides.

Many studies have used remote sensing data and GIS to map TCC. American Forests has used satellite imagery and CITYgreen GIS software to map historical TCC change, as well as the value of annual benefits from urban forests for cities such as Atlanta, Georgia, Washington, D.C., and Roanoke, North Carolina (American Forests, 2002a,b). Irani and Galvin (2003) used IKONOS data (10-m spatial resolution) to map TCC in Baltimore, Maryland. Goetz et al. (2003) found the accuracy of tree cover estimates mapped with IKONOS imagery in the mid-Atlantic region to be comparable to manual aerial photo interpretation. Poracsky and Lackner (2004) compared Portland Oregon’s tree canopy in 1972, 1991, and 2002 by using Thematic Mapper and multispectral scanner data (30-m plus resolution). High-resolution infrared photography and light detection and ranging (LIDAR) data were used to map TCC in Vancouver, Washington (Kaler and Ray, 2005). Urban cover was mapped with 82% accuracy for Syracuse, New York, using high-resolution digital color-infrared imagery (Myeong et al., 2001), and similar data were used to assess New York City’s TCC (Grove et al., 2006). AVIRIS (airborne visible infrared imaging spectrometer) data were used to map urban tree species in Modesto, California, but developing spectral signatures for each species was time consuming (Xiao et al., 2004).

Potential TCC (PTCC) is the percentage of area on the ground without TCC that could be covered by additional tree canopy. Traditionally, PTCC is the amount of residual pervious surface, including all grass and bare soil. It does not include tree cover that could be

achieved by adding trees to impervious surfaces like paved parking lots and plazas.

We differentiate between two other terms related to TCC, technical potential and market potential (McPherson, 1993). Technical potential is the total amount of planting space – existing TCC plus potential TCC (TCC+PTCC) – whereas market potential is the amount of technical potential that is plantable given physical or preferential barriers that preclude planting. Physical barriers include conflicts between trees and other higher priority existing or future uses, such as sports fields, vegetable gardens, and development. Another type of market barrier is personal preference to keep certain locations free of TCC. Whereas technical potential is easily measured, market potential is a complex socio-cultural phenomenon that has not been well studied. The only study we are aware of is a survey of nonparticipants of the Sacramento Shade program (M. Sarkovich, personal communication, October 11, 2006). The two most common reasons customers chose not to accept a free shade tree were lack of space (34%), a physical constraint, and “Do Not Want Any More Trees” (25%), a personal preference. This finding applies primarily to low-density residential land uses and suggests that a substantial amount of technical potential is likely to remain tree-free because of market forces.

### 1.2. Tree benefit assessment

The i-Tree software suite contains two programs, Eco and Streets (formerly UFORE and STRATUM), that use numerical models to calculate annual benefits per tree in common engineering units called Resource Units (RUs) (Maco and McPherson, 2003; McPherson et al., 2005). Individual tree benefits are monetized using control or damage costs and then aggregated for the tree population. Both models rely on ground survey data as input, and use growth rate information to “grow” the tree for one year. The modeling approach directly connects benefits with tree size variables such as diameter at breast height (dbh), crown diameter, and leaf area to directly calculate the annual flow of benefits as trees mature and die (McPherson, 1992).

Projecting future benefits from a proposed tree planting project requires tree growth data because as trees grow larger the benefits they produce increases. Tree size and growth data have been developed in 16 US cities based on extensive measurements of about 900 trees randomly sampled – 40 trees of each of the 22 most common species (Peper et al., 2001a,b). For each species, five to ten trees from each dbh size class were measured for dbh, tree height, crown diameter, crown shape, and tree condition. Planting dates were determined from city records and other local sources. Crown volume and leaf area were estimated from computer processing of tree-crown images taken with a digital camera (Peper and McPherson, 2003). Curve-fitting models were tested for best fit to predict dbh as a function of age for each species. Leaf area, crown diameter, and tree height were then modeled as a function of dbh.

Tree size and growth data were used with numerical benefit models to calculate annual benefits at 5 year intervals for a 40-year period after planting. To account for differences in the mature size and growth rates of different tree species, results were reported for a typical small-, medium-, and large-stature tree species, where mature tree height is used to characterize each species. To make benefit calculations realistic, mortality rates were included based on surveys of regional municipal foresters and commercial arborists. Tree benefit projections were published in a series of Community Tree Guides, one for each of the 16 US regions ([http://www.fs.fed.us/psw/programs/cufr/tree\\_guides.php](http://www.fs.fed.us/psw/programs/cufr/tree_guides.php)).

This study is unique in that it combines tree benefit projections with TCC assessment to determine: (1) existing TCC, (2) PTCC, and



Fig. 1. The City of Los Angeles study area (shaded).

(3) the value of future benefits from planting 1 million trees in Los Angeles.

## 2. Methodology

### 2.1. Study site

Los Angeles (latitude: 34°06'36"N, longitude: 118°24'40"W) is one of the largest metropolitan areas in the United States (Fig. 1).

It has a land area of 1225 km<sup>2</sup> and a population of 3,694,820 (U.S. Census Bureau, 2000). There are 15 council districts and 86 neighborhood councils. Topographic gradients are small in the coastal areas and inland valleys; however, within the city limits there are mountain ranges with steep slopes. Elevation changes from sea level to 1543 m at Mount Lukens in the northeast corner of the city. Like many coastal California cities, Los Angeles has undergone a period of rapid population growth and expansion.

## 2.2. Data sets

Three types of remotely sensed data and several GIS data layers were used. Land cover classification used QuickBird satellite imagery consisting of 64 scenes collected in different seasons from 2002 to 2005. It included four multispectral bands (blue, green, red, near infrared) with 2.4-m spatial resolution and a panchromatic band with 60-cm resolution. Aerial imagery included year 2000 black-and-white images at 15-cm resolution and 2005 natural color images at 91-cm resolution, both taken when trees were in leaf. QuickBird data were pan-sharpened to produce a more defined image at 60-cm spatial resolution. Remote sensing data were georegistered and projected to the California State Plane. GIS data layers included the boundaries of the city, neighborhood councils, council districts, parcels, parks, streets and land uses. Nine original land use classes were aggregated into six classes: low density residential, medium/high density residential, industrial, commercial, institutional, and unknown.

## 2.3. Measuring existing and potential TCC

A moving masks method (Xiao et al., 2004) was used in conjunction with supervised and unsupervised classification to map land cover. The naturally vegetated mountains (203 km<sup>2</sup>) were digitized and masked out from the study area because their land cover, vegetation management, and topographic gradient were different from those of the urban areas. Four land cover types were mapped: tree (tree and shrub), grass (green grass and ground cover), dry grass/bare soil (dry grass and bare soil), and impervious surface (asphalt and concrete pavement). The NDVI (normalized difference vegetation index) was used to distinguish vegetation and no vegetation cover. Unsupervised classification was used to separate mixed pixels containing vegetation and no vegetation land cover types. In urban settings, most trees are planted in irrigated turf grass, where trees and the background cover have similar NDVI values. Supervised classification was used to separate trees from irrigated grass. The data analysis was performed in ENVI (Environment for Visualizing Images, Research Systems, Lafayette, Colorado) and ArcGIS (Environmental Systems Research Institute). Fifty randomly selected parcels were digitized from the pan-sharpened multispectral images to assess land cover classification accuracy. Classification results were compared to digitized results and summarized as an error matrix.

Existing TCC is presented at the citywide, council district and neighborhood council levels. The number of existing trees is estimated assuming an average tree crown diameter of 5 m, based on results from a field study of trees throughout Sacramento, California (McPherson, 1998).

An innovative aspect of this study was identifying potential tree planting sites for individual trees with three mature crown diameters: small (4.6-m crown diameter), medium (9.1 m), and large (15.2 m). Criteria for selecting potential planting sites were: (1) land covers for plantable sites must be grass, dry grass, or bare soil; (2) tree trunks must be at least 0.6 m from impervious surfaces and buildings; (3) the minimum pervious surface required for small, medium, and large trees was 1.5, 3.3, and 9.3 m<sup>2</sup>, respectively; (4) no crown overlap allowed between existing trees and potential trees, or between potential trees; and (5) large trees are given priority as most benefits accrue from larger trees (Wu et al., 2008). Using these decision-rules, a computer program iteratively searched, tested, and located potential tree-planting sites. A maximum of four iterations were used, which reduced computational cost but sacrificed potential tree sites in large pervious areas, especially institutional land.

The accuracy of potential planting site estimates depends on the accuracy of the initial land cover classification, as well as errors

associated with the computer-based tree site selection process. A stratified random sample of 100 parcels was located across Los Angeles. Two maps for each site were created for ground-truthing (gray-scale aerial photograph and Quickbird color infrared) with circles showing each potential tree planting site. Ground-truthing staff crossed out potential tree sites that were mislocated (i.e., in conflict with existing trees or without sufficient space) and added sites that the computer missed.

## 2.4. Tree planting scenarios

Two tree planting scenarios were based on discussions with program planners, and assumed that 1 million trees are planted during the first 5 years of the program at an increasing rate to allow the program to ramp up as resources and capacity grow:

- 2006–50,000 trees
- 2007–160,000 trees
- 2008–230,000 trees
- 2009–270,000 trees
- 2010–290,000 trees

The analysis incorporated two scenarios that reflect the range of uncertainty regarding survival rates over a 35-year period (2006–2040). A low-mortality scenario assumed annual loss rates of 1% for establishment (the first 5 years after planting) and 0.5% for the remaining 30 years. The high-mortality scenario assumed annual loss rates of 5% during establishment and 2% thereafter. Over a 35-year period overall loss rates were 17 and 56% for the high- and low-mortality scenarios.

## 2.5. Benefit estimation

Existing data on tree benefits for coastal (McPherson et al., 2000) and inland southern California (McPherson et al., 2001) were used to project future annual benefits from 1 million new trees. Results are reported in terms of future annual value per tree planted and cumulative future value for the 35-year period. Benefits are not discounted and reported as present values because there is no attempt to evaluate efficiency or compare investments. It is assumed that the city intends to invest in MTLA and our objective is to identify the relative magnitudes of future benefits. If the intent was to compare the investment in MTLA with other investment opportunities, or compare different benefit streams from several planting scenarios all future benefits would be discounted to the beginning of the investment period.

Los Angeles has a variety of climate zones because of its proximity to the Pacific Ocean and nearby mountain ranges. Portions of Los Angeles fell into two of the sixteen US climate zones designated by i-Tree Streets for benefit calculation (Brenzel, 2001). Two Los Angeles council districts (11 and 15) were in the Coastal Southern California climate zone and the remaining 13 were in Inland Empire zone, hereafter referred to as coastal and inland zones.

Growth curves for small, medium, and large tree species in each climate zone were developed from intensive measurements of street trees in Santa Monica (coastal zone) and Claremont (inland zone), and were used to account for differences in benefits produced by trees of different sizes (McPherson et al., 2000, 2001). Growth curves for the yew (*Podocarpus macrophyllus*), jacaranda (*Jacaranda mimosifolia*), and camphor (*Cinnamomum camphora*) were used in the coastal zone. In the inland zone, growth curves for crapemyrtle (*Lagerstroemia indica*), jacaranda, and evergreen ash (*Fraxinus uhdei*) were used. The mature crown diameters of these species roughly correspond with the 4.6-, 9.1-, and 15.2-m sizes used to determine potential planting sites. The selection of



**Table 1**  
Emission factors and the monetary value of reductions for the inland and coastal climate zones.

Pollutant	Electricity (kg/MWh)	Natural gas (kg/GJ)	Value (inland) (\$/t)	Value (coastal) (\$/t)
CO <sub>2</sub>	901.30	50,580	7.36	7.36
NO <sub>2</sub>	2.13	43.84	8,708	4,982
SO <sub>2</sub>	0.24	0.25	5,512	5,505
PM <sub>10</sub>	0.08	3.20	10,913	11,986
VOCs	0.0008	2.32	4,365	2,329

these species was based on data availability and is not intended to endorse their use in large numbers.

### 2.5.1. Energy savings

Effects of tree shade and urban heat island mitigation on building energy use were applied to trees planted in residential areas only. Energy effects were based on computer simulations that incorporated building, climate, and shading effects (McPherson and Simpson, 1999). Tree distribution with respect to residential buildings was determined by classifying 130 potential planting sites in 34 ground-truthed low-density housing parcels by azimuth and distance class from the building (McPherson et al., 2008).

Typical meteorological year weather data for Los Angeles International Airport (coastal) and Riverside (inland), as well as local building characteristics were used. The dollar values of electrical energy (\$0.106 per kWh) and natural gas (\$0.0063 per GJ) were based on retail residential electricity and natural gas prices obtained from the Los Angeles Department of Water and Power (LADWP).

### 2.5.2. Atmospheric carbon dioxide reductions

Sequestration, the net rate of carbon dioxide (CO<sub>2</sub>) storage in above- and below-ground biomass over the course of one growing season, was calculated by using Santa Monica (coastal) and Claremont (inland) tree growth data and biomass equations for urban trees (Pillsbury et al., 1998). The CO<sub>2</sub> released through decomposition of dead woody biomass was based on annual tree removal rates. The CO<sub>2</sub> released during tree maintenance activities was estimated based on annual consumption of gasoline and diesel fuel as 0.11 kg/cm of dbh (McPherson et al., 2000, 2001).

Reductions in building energy use result in reduced emissions of CO<sub>2</sub>. Emission reductions were calculated as the product of energy savings and CO<sub>2</sub> emission factors for electricity and heating (Table 1). Heating fuel was natural gas, and LADWP's fuel mix for electrical generation was 52% coal, 6% hydro, 26% natural gas, 11% nuclear, and 5% other. The value of CO<sub>2</sub> reductions was \$7.36 per tonne (t) of CO<sub>2</sub> (Pearce, 2003).

### 2.5.3. Air quality benefits

The hourly pollutant dry deposition per tree was expressed as the product of deposition velocity  $V_d = 1/(R_a + R_b + R_c)$  (where  $R_a$ ,  $R_b$ , and  $R_c$  are aerodynamic, boundary layer, and stomatal resistances), pollutant concentration, canopy projection area, and a time step. Hourly deposition velocities for ozone (O<sub>3</sub>), nitrogen dioxide (NO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), and particulate matter of <10-micron diameter (PM<sub>10</sub>) were calculated by using estimates for the resistances  $R_a$ ,  $R_b$ , and  $R_c$  for each hour throughout a "base year" (Scott et al., 1998). Hourly meteorological data and pollutant concentrations were obtained from monitoring stations in Hawthorne (coastal) and Azusa (inland) when pollutant concentrations were near average.

Energy savings result in reduced emissions of criteria air pollutants (volatile organic hydrocarbons [VOCs], NO<sub>2</sub>, SO<sub>2</sub>, PM<sub>10</sub>) from power plants and space-heating equipment. These avoided emissions were calculated by using LADWP emission factors for electricity and heating fuels (Table 1).

Emissions of biogenic volatile organic compounds (BVOCs) from trees affect O<sub>3</sub> formation. The hourly emission rates of the five tree species used in this analysis were minimal (Benjamin and Winer, 1998). In reality, a large-scale tree planting will include some species with emission rates higher than reported here. Although this approach understates BVOC emissions from new trees, it also understates the air quality benefit associated with lowered summertime air temperatures and the resulting reduced hydrocarbon emissions from anthropogenic and biogenic sources.

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. Lacking specific data for Los Angeles, air quality benefits were monetized as damage values (Table 1) by using regression relationships among emission values, pollutant concentrations, and population numbers for inland and coastal council districts (Wang and Santini, 1995). This regression provides estimates of the costs of damages to human health resulting from air pollution.

### 2.5.4. Stormwater runoff reductions

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 volume of water stored in tree crowns was calculated from tree crown leaf and stem surface areas and water depth on these surfaces. Hourly meteorological and rainfall data for 1996 from California Irrigation Management Information System stations in Santa Monica (coastal) and Claremont (inland) were used because total rainfall in that year was close to the average annual amount.

Stormwater runoff reduction benefits were priced by estimating costs of controlling stormwater runoff and treating sanitary waste in Los Angeles. During small rainfall events, excess capacity in sanitary treatment plants can be used to treat stormwater. In the Los Angeles region, it costs approximately \$0.48 per m<sup>3</sup> to treat sanitary waste (Condon and Moriarty, 1999). The cost of treating stormwater in central facilities is likely to be close to the cost of treating an equal amount of sanitary waste.

Although storm drains are designed to control 25-year events, localized flooding is a problem during smaller events. Approximately \$50 million is spent annually controlling floods in Los Angeles, and the annual value of peak flow reduction is \$193,050 per km<sup>2</sup> for each 25-year peak flow event (Jones and Stokes Associates, Inc., 1998). A 25-year winter event deposits 170 mm of rainfall during 67 h. Approximately \$1.42 per m<sup>3</sup> is spent annually for controlling flooding caused by such an event. Water quality and flood control benefits were summed to calculate the total hydrology benefit of \$1.90 per m<sup>3</sup>. This price was multiplied by the amount of rainfall intercepted annually.

### 2.5.5. Aesthetics and other benefits

Many benefits attributed to urban trees are difficult to price (e.g., 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 with and without trees. Anderson and Cordell (1988) found that each large front-yard tree was associated with a 0.88% increase in sales price. In this analysis,

**Table 2**  
Land cover percentages by type and land use.

Land use	tree/shrub	Irr. grass	Dry grass/soil	Impervious	Total
Low density resid.	14.5	7.2	3.4	22.5	47.6
Med.-Hi. density resid.	2.5	1.7	0.7	12.4	17.4
Industrial	0.4	0.3	0.2	9.4	10.2
Commercial	0.4	0.2	0.1	7.1	8.0
Institutional	2.8	2.7	0.9	9.0	15.5
Unknown	0.1	0.2	0.0	1.0	1.4
Total	20.8	12.4	5.5	61.4	100.0

aesthetic ( $A$ ) benefits (dollars/tree/year) were expressed for a single tree as:

$$A = L \times P$$

where  $L$  is the annual increase in tree leaf area (LA) and  $P$  is the adjusted price (dollars/m<sup>2</sup> LA):

$$P = \frac{T \times C}{M}$$

where  $T$  = large tree contribution to home sales price = 0.88% × median sales price (dollars/tree),  $C$  = tree location factor that discounts the benefit for trees outside of low-density residential areas (percentage),  $M$  = large tree LA (m<sup>2</sup>).

The median sales price for single-family homes in Los Angeles in December 2006 was \$530,000 (California Association of Realtors, 2006). The values for  $C$  were 100% for low-density residential, 70% for medium/high-density residential and 40% for other land uses (McPherson, 2001). The values for  $M$  were 250 and 334 m<sup>2</sup> for coastal and inland zones, respectively, and corresponding values for  $P$  were \$15.73 and 11.08/m<sup>2</sup> LA.

### 3. Results

#### 3.1. Existing tree canopy cover

The TCC in the city of Los Angeles was 21% (21,243 ha) (Table 2). Irrigated grass and dry grass/bare soil accounted for 12% (12,628 ha) and 6% (5581 ha) of the cover, respectively. Impervious (e.g., paving, roofs) and other surfaces (i.e., water) made up the remaining 61% (62,684 ha) of the city's land cover (excluding mountainous areas). Hence, one-third of Los Angeles's land cover was TCC and grass/bare soil with potential to become TCC.

TCC was strongly related to land use. As expected, low-density residential land uses had the highest TCC citywide (31%), whereas industrial and commercial land uses had the lowest TCC (3 and 6%) (Table 2). TCC tended to be higher in areas near mountains compared to areas closer to downtown Los Angeles (Fig. 2).

At the council district level, TCC ranged from lows of 7 to 9% in council districts 9 and 15 to a high of 37% in council district 5 (Table 3, Fig. 2). Relations between TCC and land use were evident in council districts 5 and 9. Council district 5 (37% TCC) was dominated by low-density housing (70%) and had 49% tree/grass/soil cover. In contrast, low-density housing covered only 4% of council district 9 (7% TCC), whereas industrial and commercial land uses covered 42% of the land.

There were approximately 10.8 million trees (106 trees/ha) in Los Angeles assuming an average tree crown diameter of 5 m (Table 3). Council districts estimated to have the highest tree densities were 5 (190 per ha), 4 (147 per ha), 2 (136 per ha), and 3 (133 per ha). Council districts with the lowest tree densities were 9 (38 per ha), 15 (45 per ha), 8 (54 per ha), and 10 (61 per ha).

Overall classification accuracy was 88.6% based on the pixel-by-pixel comparison. The accuracy for classifying existing TCC was 74.3% (McPherson et al., 2008). Not surprisingly, TCC was most

often misclassified as irrigated grass (13%), and vice versa (17%). In the parcel-scale analysis, impervious surface was underestimated by 3.5% and TCC was overestimated by 5.0%. Factors that affected mapping accuracy included the treatment of the shadowed area and minimum mapping units during digitizing.

#### 3.2. Potential tree planting sites

After calibrating computer-estimated potential tree sites with ground-truthed data, approximately 2.47 million potential tree planting sites were identified in Los Angeles (Table 3). This potential for new trees covers 12,634 ha, or 12% of the city. Hence, if all potential tree sites were filled and the canopy matured, TCC would increase from 21% to 33%. Fifty-two percent of these potential sites were for small trees (4.6-m crown diameter at maturity), 38% for medium trees (9.1 m), and 10% for large trees (15.2 m) (Table 3). Potential planting sites in parking lots accounted for 10.5% of all potential tree sites.

The distribution of potential tree sites differed by land use. Low-density residential areas contained the largest number of potential sites (1.4 million, 58%), followed by institutional (377,574, 15%) and medium/high-density residential (360,382, 15%). Industrial and commercial land uses each contained about 6% (about 140,000) of the total potential tree planting sites.

Six council districts (2, 3, 7, 11, 12, and 15) had potential for over 200,000 new trees, with these trees adding an additional 11 to 20% TCC when mature and assuming no mortality (Fig. 2). Five council districts (1, 9, 10, 13, and 14) had space for fewer than 100,000 trees, with potential to increase TCC by 7 to 12%. Not surprisingly, council district 5 had the most existing TCC (37.2%) and the least potential TCC (6.8%).

In summary, the existing TCC of Los Angeles was 20.8%, comprising approximately 10.8 million trees. There was potential to add 2.5 million additional trees or 12.4% TCC. Thus, technical potential for Los Angeles was 33.2% TCC or about 13.3 million trees. It is realistic to assume that about 50% of the unplanted sites are feasible to plant. Hence, market potential was 27.5% TCC or 12.1 million trees. Planting 1 million trees is feasible, and if accomplished would increase TCC by about 5%, thereby saturating 96% of existing market potential.

#### 3.3. Benefits from planting 1 million trees

After 35 years (2040), the number of surviving trees was estimated to be 444,889 and 828,924 and for the high- and low-mortality scenarios, respectively. In both scenarios, the 1-million planted trees were distributed among land uses such that 55% were in low-density residential, 17% in institutional, 14% in medium/high-density residential, 9% in commercial, and 5% in industrial. Nearly one-half of the trees were small, 42% medium, and 9% large at maturity.

Benefits calculated annually and totaled for the 35-year period were \$1.33 and \$1.95 billion for the high- and low-mortality scenarios, respectively (Table 4). These values translate into

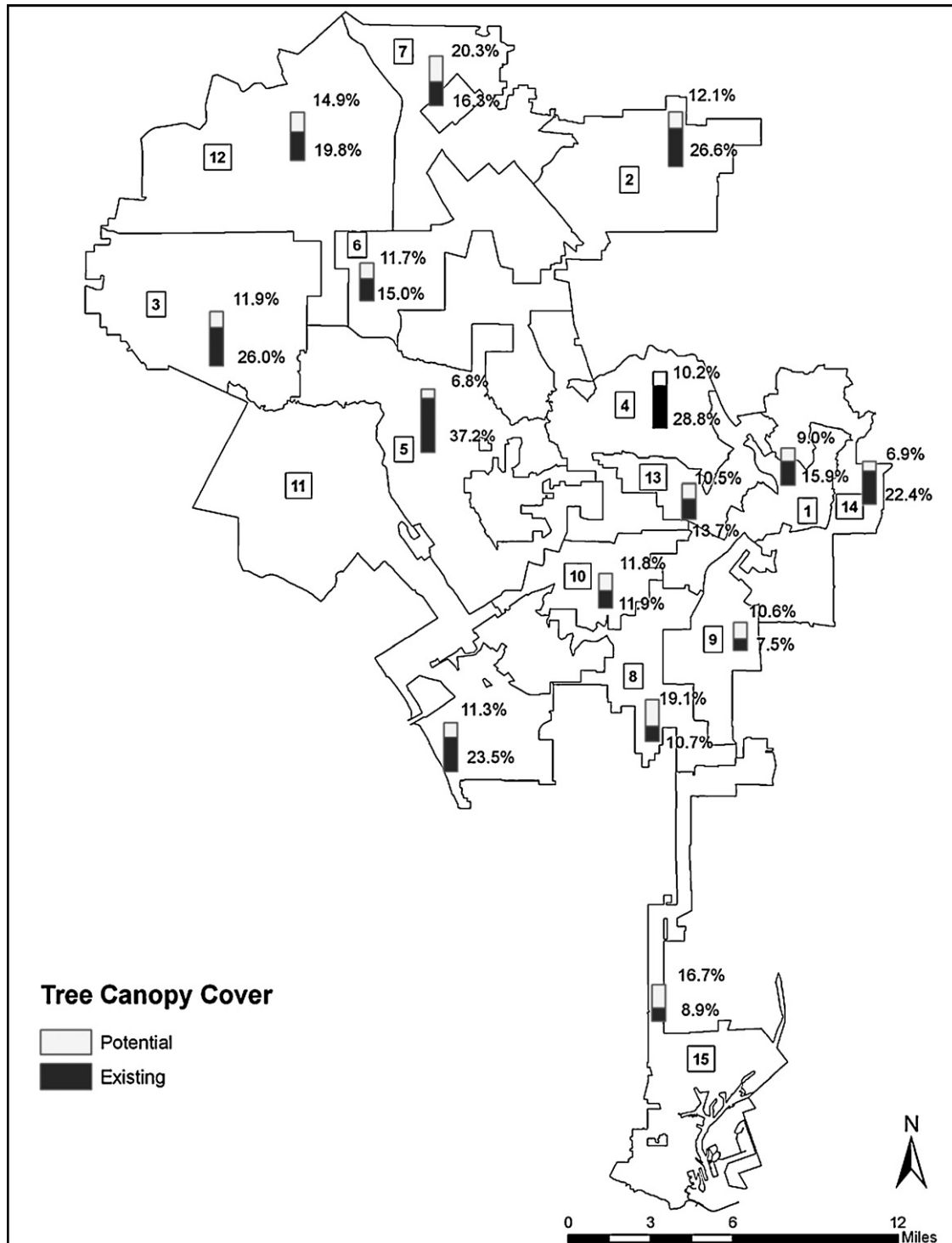


Fig. 2. Existing and potential tree canopy cover percentages by Council District.

\$1328 and \$1951 per tree planted, or \$38 and \$56 per tree per year.

In the low-mortality scenario 81% of total benefits were aesthetic/other, 8% stormwater runoff reduction, 6% energy savings, 4% air quality improvement, and less than 1% atmospheric carbon reduction (Table 4).

The distribution of benefits among council districts was closely related to climate zone and the mix of land uses (Fig. 3). Benefits per tree were about 50% less (\$700 to 1000 instead of \$1300 to 2400) in the coastal zone (council districts 11 and 15) than the inland zone

because the trees were smaller, air pollutant concentrations lower, and building heating and cooling loads less because of the milder climate.

Districts with relatively less land for housing and relatively more land for commercial, industrial, and institutional use had lower benefits per tree planted. Energy savings were less because benefits were not calculated for nonresidential buildings. For example, residential land uses occupied only 35% to 37% of the land in council districts 1 and 9, and average benefits were among the lowest per tree (about \$1200 and \$1800 for high- and low-mortality scenarios)

**Table 3**  
Information on existing and potential tree canopy cover, numbers, and density by Council District.

Council District	Existing TCC (%)	Existing Trees <sup>a</sup>	Tree density (tree/ha) <sup>a</sup>	Potential trees			Potential Total	TCC (%)
				Small	Medium	Large		
1	15.9	261,106	81.2	23,821	18,320	7,087	49,228	9.0
2	26.6	1,112,597	135.5	109,200	78,161	16,590	203,950	12.1
3	26.0	1,308,371	132.7	144,751	89,421	18,905	253,078	11.9
4	28.8	913,276	146.5	70,179	45,282	12,265	127,726	10.2
5	37.2	1,865,642	189.6	107,119	52,056	8,465	167,640	6.8
6	15.0	525,922	76.2	66,538	64,545	15,175	146,258	11.7
7	16.3	530,302	83.0	116,529	86,463	29,355	232,347	20.3
8	10.7	245,831	54.4	84,116	61,943	17,577	163,637	19.1
9	7.5	148,242	38.3	40,970	31,665	7,481	80,115	10.6
10	11.9	210,003	60.8	47,971	27,641	8,037	83,649	11.8
11	23.5	1,256,654	119.8	132,350	84,742	22,527	239,619	11.3
12	19.8	1,195,275	101.0	180,791	127,648	34,104	342,543	14.9
13	13.7	221,038	69.6	37,459	24,539	6,150	68,148	10.5
14	22.4	644,639	114.0	39,821	29,272	7,244	76,337	6.9
15	8.9	385,730	45.4	90,963	116,363	27,585	234,912	16.7
	20.8	10,824,628	106.0	1,292,578	938,062	238,546	2,469,186	12.4

<sup>a</sup> Assumes average tree crown diameter is 5 m.

(Fig. 3). On the other hand, in council districts 2, 7, and 8, residential land uses exceeded 52% of total land, and average benefits were the highest (greater than \$2,300 per tree for the low-mortality scenario).

Citywide, the average benefit per tree averaged about \$1,000 for low density residential land use. This amount was five times greater than nearly \$200 per tree for institutional and medium/high density residential land uses.

Aesthetic/other benefits ranged from \$1.1 to \$1.6 billion, or \$31 to \$45 per tree per year for the high- and low-mortality scenarios (Table 4). These amounts reflect the economic contribution of trees to property sales prices and retail sales, as well as other benefits such as beautification, privacy, wildlife habitat, sense of place, and psychological and spiritual well-being.

By intercepting rainfall in their crowns, trees reduced stormwater runoff and thereby protected water quality. Over the 35-year span of the project, planting of 1 million trees was estimated to reduce runoff by approximately 51 to 80 million m<sup>3</sup>. The value of this benefit was estimated to range from \$97 to \$153 million (Table 4). The average annual interception rate per tree ranged from a low of 0.4 m<sup>3</sup> for the crapemyrtle (representative of small trees in the inland zone) to a high of 5.6 m<sup>3</sup> for the jacaranda (representative of medium trees in the inland zone). The difference is related to tree size and foliage period. The crapemyrtle is small at maturity and is deciduous during the rainy winter season, whereas the jacaranda develops a broad spreading crown and is in-leaf during the rainy season.

By shading residential buildings and lowering summertime air temperatures, the planting of 1 million trees was projected to reduce electricity consumed for air conditioning by 917,000 MWh on average. However, this cooling savings was partially offset by increased heating costs from tree shade that obstructs winter sunlight. Tree shade was expected to increase natural gas required

for heating by 134,206 GJ on average, valued at \$851,000. Despite this cost, net energy savings were projected to range from \$76 to \$117 million for the high- and low-mortality scenarios, respectively (Table 4).

Over its 35-year planning horizon, the 1-million-tree planting was projected to reduce atmospheric CO<sub>2</sub> by 693,000 t to 1.2 million t, or \$5.1 to \$8.5 million for the high- and low-mortality scenarios, respectively (Table 4). Emission reductions at power plants associated with effects of the trees on building energy use (576,000 t) were greater than biological sequestration of CO<sub>2</sub> by the trees themselves (448,000 t). A relatively small amount of CO<sub>2</sub> was projected to be released during tree care and decomposition of dead biomass (102,000 t). The CO<sub>2</sub> reduction benefit varied widely based on tree size. For example, in the inland zone for the low-mortality scenario, the small crapemyrtle annually sequestered and reduced emissions by only 2 kg and 25 kg per tree on average, compared to 68 kg and 100 kg for the large evergreen ash.

By improving air quality, the tree planting will enhance human health and environmental quality in Los Angeles. The value of this benefit was estimated to range from \$53 to \$83 million over the 35-year planning horizon (Table 4). Interception of PM<sub>10</sub> and uptake of O<sub>3</sub> and NO<sub>2</sub> were especially valuable. PM<sub>10</sub> interception ranged from 1674 t to 2618 t (\$19 to \$29 million) for the high- and low-mortality scenarios, respectively. For the low-mortality example, annual PM<sub>10</sub> deposition rates averaged 0.06 to 0.09 kg per tree for the medium tree in coastal and inland zones, while corresponding emission reductions ranged from 0.02 to 0.05 kg.

The 1 million trees were projected to reduce O<sub>3</sub> by 2204–3459 t (\$18 to \$28 million). Average annual deposition rates ranged from 0.11 to 0.16 kg per medium tree in the low-mortality scenario for the coastal and inland zones, respectively. Uptake of NO<sub>2</sub>, an ozone precursor, was estimated to range from 1768 to 2757 t (\$15 to \$23 million) over the 35-year period. This benefit accounted for 27%

**Table 4**  
Total value of benefits over the 35-year period by benefit type for the high- and low-mortality scenarios (assumes 444,889 and 828,924 trees survive, respectively).

	High mortality			Low mortality		
	Total \$M	\$/tree/year	%	Total \$M	\$/tree/year	%
Energy	75.7	2.16	5.7	117.4	3.35	6.0
Air quality	53.3	1.52	4.0	83.4	2.38	4.3
Carbon die	5.1	0.15	0.4	8.5	0.24	0.4
Runoff	97.4	2.78	7.3	153.1	4.37	7.9
Aesthetics	1,096.2	31.32	82.6	1,588.1	45.38	81.4
Total	1,327.8	37.94	100.0	1,950.5	55.73	100.0



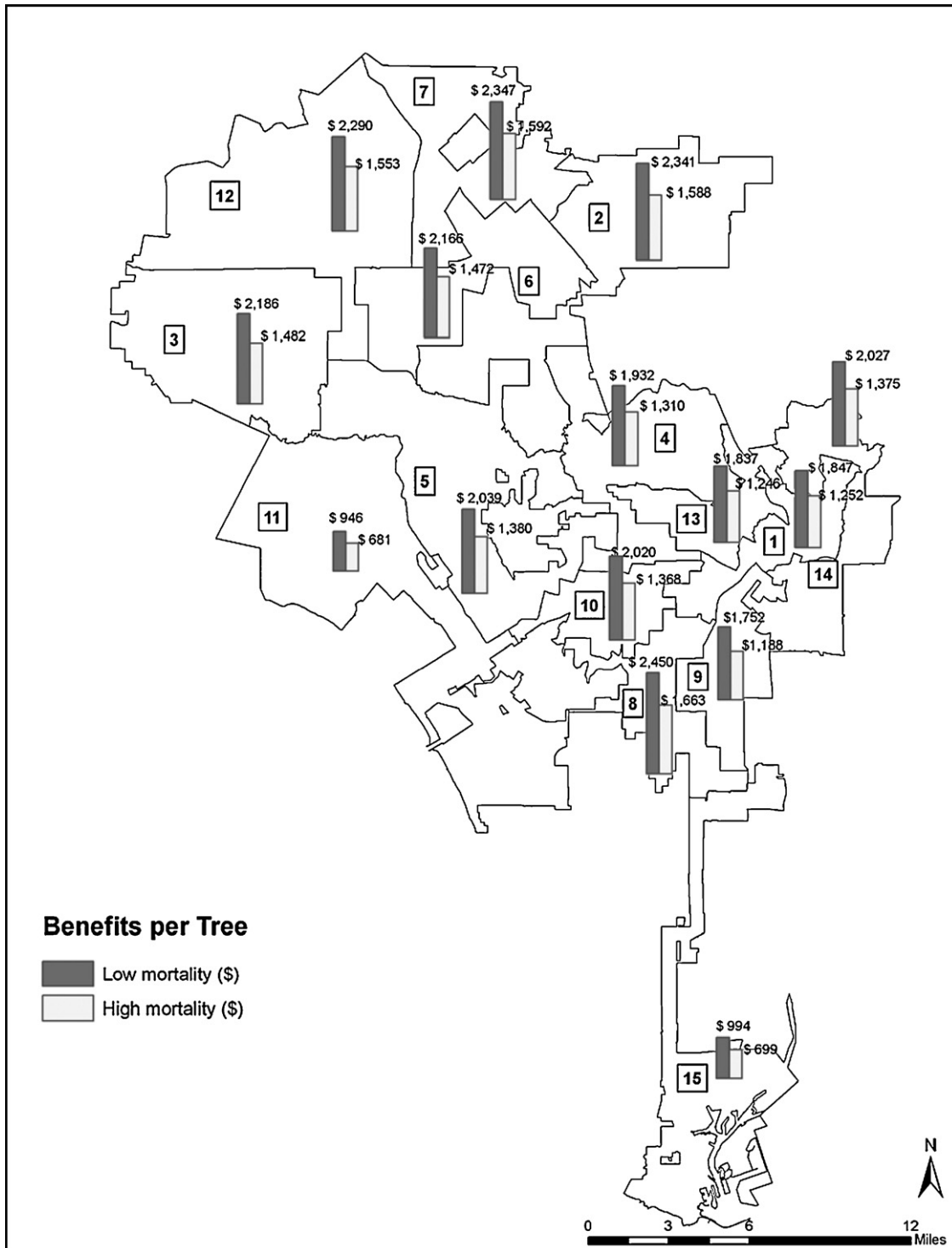


Fig. 3. Average benefit per tree over the 35-year period for the low- and high-mortality scenarios.

of the total air quality benefit. A small amount of VOC emissions from power plants were estimated to be reduced because of energy savings.

**4. Discussion**

In Los Angeles the existing TCC (20.8%) was close to values reported for Baltimore (20%) and New York City (23%) (Galvin et al., 2006; Grove et al., 2006) (Table 5). This is surprising given Los Angeles's Mediterranean climate, which makes irrigation essential

for establishment and growth of many tree species. However, the technical potential TCC was much less in Los Angeles (33%) than 66% and 73% reported for New York City and Baltimore. In Los Angeles, the PTCC represented only a 12% increase in TCC above the existing 21%. In New York City and Baltimore, the PTCC was an increase of 43% and 53% above existing TCC, respectively. This finding suggests that there is much less available growing space for trees in Los Angeles than in the other cities. Although there is no definitive explanation for this result, one reason may be the masking of mountain areas from our study site, which eliminated potential

**Table 5**  
Percentages of tree canopy cover for three US cities.

	Existing	Potential	Tech Pot	Market Pot	Target
Los Angeles	21	12	33	28	26
New York City	23	43	66	33	30
Baltimore	20	53	73	46	46

tree planting sites. Analogous semi-natural areas in New York City and Baltimore provide tree planting potential because they are not entirely forested.

In Los Angeles and Baltimore the target TCCs were set at 26% and 46%, each filling about 50% of the PTCC. In New York City, the 30% TCC target was a much smaller percentage of the PTCC (17%). The lower target in New York City may reflect the fact that a larger proportion of PTCC is in open spaces where new plantings would conflict with existing uses such as ball fields and prairie landscapes.

Results of this benefit assessment were similar to findings previously reported in tree guides for coastal southern California and Inland Empire communities (McPherson et al., 2000, 2001). Differences were expected because simulations for this study used more recent air quality data and median home sales prices, and different benefit prices and tree mortality rates. In the coastal southern California tree guide, average annual benefits for the small and medium street trees were \$22 and \$48, compared to \$38 for this study (low-mortality scenario). In the Inland Empire tree guide, average annual benefits were \$15 and \$61 compared with \$56 for this study. Hence, benefit values reported here are reasonable when compared with previously reported findings from similar analyses for the same regions.

There are several sources of error associated with these benefit projections. One source of error pertains to land cover classification. Inaccurate land cover classification results in inaccurate assessments of potential tree planting sites when pervious sites without trees are misclassified as having trees or as impervious, and impervious sites are misclassified as pervious and without trees. Our image classification assessment indicates that overall classification accuracy is 88.6% based on a pixel-by-pixel comparison.

Although ground-truthing of computer-based estimates of potential tree sites led to a calibration of the estimates, other errors can reduce the accuracy of estimates. For example, the computer-based method can miss potential tree sites in large open spaces because a limited number of iterations are run for each tree size class. Potential tree planting sites in parking lots in medium/high-density housing areas were not included. Informal findings indicate that the largest discrepancies between computer- and human-based potential tree sites were for institutional and industrial land uses, whereas estimates for residential land uses were in close agreement.

Modeling error influences the accuracy of benefit estimates. Use of only three representative species in two climate zones is an obvious simplification of the actual tree planting program. In reality, over 100 species will be planted throughout the city, which has a myriad of microclimates. Therefore, these results are only accurate to the extent that the actual trees planted resemble the size and foliage characteristics of the species mix used here.

Over three-quarters of total value were for aesthetic and other benefits, and our understanding of this type of benefit is least certain. This approach relied on research conducted in Georgia that may not be directly transferable to Los Angeles. Further research is needed improve estimates of psychological, social, and economic benefits, and to better understand attitudes that thwart participation in tree planting stewardship activities.

The benefits quantified here should be considered a conservative estimate. They do not include many other benefits that are more difficult to monetize. For example, tree shade on streets

can help offset pavement management costs by protecting paving from weathering (McPherson and Muchnick, 2005). This study did not quantify MTLA program costs, which include planning, site preparation, tree production and planting, stewardship (e.g., irrigation, pruning), monitoring, outreach, and administration. Future research is needed to calculate MTLA's net benefits, as well as environmental impacts at each stage of its life cycle.

Los Angeles is a vibrant city that has continued to invest in its tree canopy as it grows. Over 300,000 trees have been planted by the Million Trees LA program since its inception. The challenge ahead is to better integrate the green infrastructure with the gray infrastructure by providing adequate space for trees, designing plantings to maximize net benefits over the long term, and tracking trees to assess their survival, growth, and health. This is no easy task given financial constraints and trends toward higher density development that put space for trees at a premium.

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