A time series of urban forestry in Los Angeles

**Thomas Welch Gillespie · Stephanie Pincetl ·
Shea Brossard · Jenny Smith · Sassan Saatchi ·
Diane Pataki · Jean-Daniel Saphores**

Abstract There has been an increasing interest in the evolution of urban forests. This research uses historic and digital aerial photography to quantify changes in tree density in Los Angeles, California since the 1920's. High-resolution geographic information system analysis (4 to 6 time periods) of three regions (San Fernando Valley, Hollywood, Los Angeles Basin) of Los Angeles reveals that there has not always been an increase in tree density with time. Tree densities on public and private land were highest in the 1940's in Hollywood, while the San Fernando Valley and Los Angeles Basin experienced a near linear increase in tree density on both private and public land since the 1920's. When historic tree density reconstructions were examined for the 15 Los Angeles city council districts from the 1920's, 1950's and 2006, most districts in Los Angeles have experienced a significant increase in tree density, however, there has been wide variation in tree densities among city council districts. Trees densities have generally been higher on private land since the 1920's and currently tree densities on private land are significantly higher than on public land. Results suggest the evolution of urban forests in Los Angeles mirrors the dynamics of urban forests in desert and grassland cities. It is possible to reconstruct the development of urban forests in sections of cities using historic and contemporary aerial photography. We estimated that

T. W. Gillespie (✉) · S. Brossard · J. Smith
Department of Geography, University of California Los Angeles, Los Angeles, CA 90095–1524, USA
e-mail: tg@geog.ucla.edu

S. Pincetl
Institute of the Environment, University of California Los Angeles, Los Angeles, CA 90095–1496, USA

S. Saatchi
Jet Propulsion Laboratory, CALTECH, Pasadena, CA 91109, USA

D. Pataki
Department of Ecology and Evolutionary Biology, University of California Irvine, Irvine, CA 92697, USA

J.-D. Saphores
Civil and Environmental Engineering, University of California Irvine, Irvine, CA 92697, USA

Los Angeles averages approximately 104 trees per hectare (82 private land, 22 public land) based on 2006 imagery at 0.3 m resolution, however, field validation suggests that we identified only 73% of trees. Although there is still space to plant trees on public land, private land owners will need to be heavily involved in order to achieve the goals of Los Angeles' Million Tree Initiative.

Introduction

There has been an increasing interest in tree planting in urban areas and patterns and processes associated with the evolution of urban forests (Grimm et al. 2008; McDonnell and Hahs 2008). The city of Los Angeles recently initiated the "Million Tree Initiative" in 2006 with the goal of planting a million trees in order to reduce the urban heat island effect, improve air and water quality, sequester carbon, and improve the aesthetics of neighborhoods in Los Angeles (Grimmond et al. 1996; McPherson et al. 2008; McPherson et al. 2011; Pincetl 2009). However, very little research has been undertaken on where trees historically occurred in Los Angeles and their distribution and density on public and private land.

Urban tree cover has been hypothesized to be highest in cities within naturally forested areas (15% to 55%), followed by grasslands (5% to 39%) and desert cities (1% to 26%) (Nowak et al. 1996). However, less is known about the evolution of the urban forests in Mediterranean ecosystems, which are generally covered by grasslands and woodlands that include short trees with broad canopies (McDonnell and Hahs 2008). Zipperer et al. (1997) proposed a model of urban forests in deserts and grasslands that mirrors the natural dynamics of forest succession with tree biomass minimal at pre-settlement, reaching its highest peak at establishment, and then slightly decreasing in post-development due to pruning and removal of dead trees. Los Angeles, although located in a Mediterranean climate, could exhibit a similar evolution as cities located in deserts and grasslands, and may be in the post-development phase of evolution.

There is also interest concerning the importance of trees planted on private and public lands and the origin and structure of urban landscapes. Most research on urban trees is generally limited to inventories of public land (Zipperer et al. 1997; McPherson et al. 1997), examines the economic importance of trees and housing prices on private property (Luttik 2000; McPherson et al. 2011), or combines results of tree canopy cover over both public and private property to assess tree canopy cover in urban landscapes (McPherson et al. 1997; McPherson et al. 2008; Nowak et al. 1996). The spatial pattern of urban forests has been closely linked with general zoning of different land use and building densities (Nowak et al. 1996; Pauleit and Duhme 2000). Indeed, tree canopy cover in Los Angeles has been shown to be highest in low-density residential areas (31%) and lowest in industrial and commercial areas (3% to 6%) (McPherson et al. 2008; McPherson et al. 2011). However, less is known about the density and distribution of trees on public and private land in urban areas, especially as it relates to the evolution of urban forests over time. Los Angeles may have experienced the most rapid increase in size of any urban area within a Mediterranean region. The population of Los Angeles County has grown from 170,298 in 1900, to 4,151,687 in 1950, and reached 9,848,011 in 2009 (US Census 2009). This

increase in population and associated development has also resulted in an afforestation of the city that currently has an estimated urban tree canopy cover of 21% (McPherson et al. 2008). However, there is little information on the evolution of these urban forests in Los Angeles or comparisons of tree densities and distributions on public and private land.

There have been significant advances in geographic information systems (GIS) and remote sensing that may be used to test hypotheses about the historic development of urban forests (Mast et al. 1997). Most research has quantified tree canopy cover using spaceborne satellites such as the Landsat series and QuickBird (Cauley and Goetz 2004; McPherson et al. 2008). This approach provides important and accurate data on tree canopy cover but may not be able to quantify the density of individual trees or quantify the density of trees before the launch of these spaceborne satellites. However, other studies have attempted to use historic aerial photographs, digital aerial photography, and GIS modeling to reconstruct the location and density of trees back to the 1930's (Groom et al. 2006; Mast et al. 1997; Nowak et al. 1996). These issues of tree location on public and private property over time are important in identifying patterns and processes associated with the evolution of urban forestry in Los Angeles.

This research on the evolution of urban forests in Los Angeles has three primary objectives. First, we undertake a high-resolution GIS analysis of three regions in Los Angeles since the 1920's to establish whether tree densities have increased with time. Second, we examine changes in tree density in Los Angeles for three time periods (1920's, 1950's, 2000) within the 15 city council districts to determine if tree density has increased across all city council districts. Third, we examine how tree densities on public and private land have changed over time within the 15 city council districts.

Methods

Study area

Los Angeles is located in a coastal plain surrounded by the peninsular and transverse mountain ranges. The climate is Mediterranean with rainfall occurring primarily from November to March. Annual precipitation ranges from 19–20 cm near the coast to as high as 75 cm in the mountains. There is a strong coastal to inland gradient in temperature, which ranges from 12 to 20 C° near the coast to 9 to 27 C° in the interior of the basin and valleys. Politically, Los Angeles is comprised of 15 different council districts, with approximately 250,000 people per council district. Tree canopy cover varies from 7% to 37% per council district (McPherson et al. 2008) (Fig. 1).

High-resolution GIS analysis of three regions

Our main data source is the Benjamin and Glady Thomas Air Photo Archives housed in the Department of Geography at UCLA. There are over 40,000 oblique aerial photographs from 1918 to 1971, primarily focusing on Southern California, maintained in the archives. These oblique aerial photographs were taken at a variety of altitudes, look-angles, and spatial resolutions.

We searched low altitude oblique aerial photographs from the 1920's, 1930's 1940's, 1950's, and 1960's to find comparative time series in the San Fernando Valley, Hollywood, and Los Angeles Basin. We identified the best comparative time series of oblique aerial photographs taken at similar altitudes and look-angles that covered the same ground area

Fig. 1 City of Los Angeles with city council districts
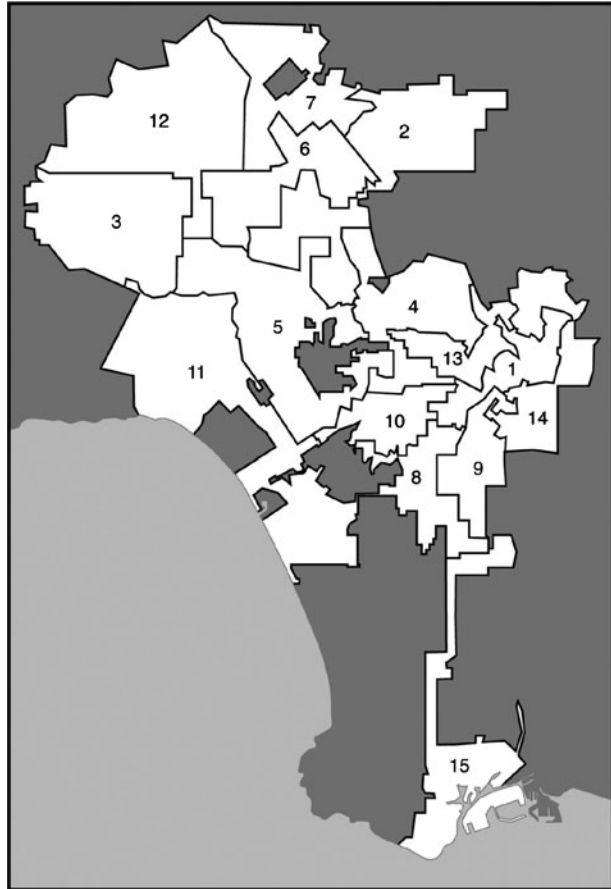
over time. Historic aerial photographs were scanned using a Hewlett-Packard ScanJet 6300 C at 600 DPI in grayscale and saved as JPEGs. This resulted in imagery with a ≤0.3 m pixel resolution (Fig. 2). The locations of each tree were digitized into a GIS coverage using 2006 color digital aerial photography as the base layer. The three areas in the San Fernando Valley, Hollywood, and Los Angeles Basin were downloaded from vertical digital aerial photography (0.3 m resolution) collected in 2006 from the Earth Resources Observation and Science (EROS) Data Center. Polygons of plot extent (San Fernando Valley 32 ha, Hollywood 39 ha, and Los Angeles Basin 32 ha) were based primarily on roads that were easy to identify for all time periods. We defined a tree as a woody plant with a single main stem or trunk, four meters or greater in height, and branches above the ground. Every tree with a crown larger than 1 m^2 that was visible within the plot area was digitized using ArcMap 9.2 to identify tree location. We identified tree location in photographs by color, crown shape, height, and when possible, shadow. Within historic oblique aerial photographs, trees in black and white photographs appeared dark colored, had distinct crown shapes (i.e. broad, rounded, spreading, columnar) that were above the ground or above structures, and in many cases shadows were visible showing tree profiles. Within vertical color digital aerial photographs, trees generally contained different shades of green foliage with distinct crown shapes that appeared to overlap ground features. Private

Fig. 2 Examples of historic aerial photography from the 1930's used to create time series of tree density and distribution from the San Fernando Valley
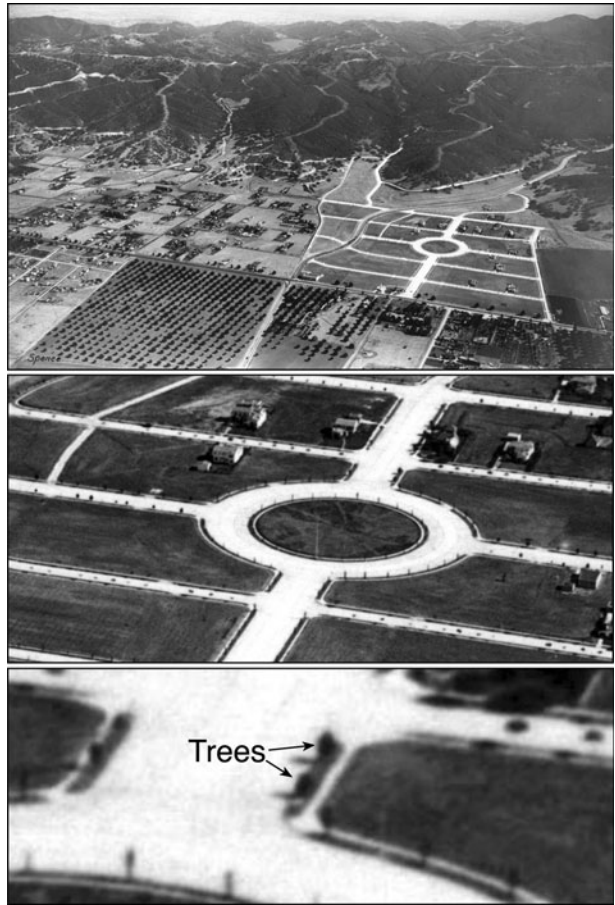
and public property boundaries were based on Zillow.com data from 2009 that identifies private property parcels. Data on location, density, and dispersion of trees on public and private land were summarized for each time period (Fig. 3).

Moderate resolution of three time periods

We searched oblique aerial photographs from the 1920's and 1950's to identify areas in each of Los Angeles' 15 city council districts where a time series on the number of individual trees on public and private land could be quantified (Table 1, Fig. 1). This resulted in aerial photographs with a diversity of look-angles and spatial resolutions. A protective transparent sleeve was overlaid onto the oblique aerial photographs. Plot area was determined by identifying overlapping areas in the time series in each city council district using clearly defined features such as roads for plot boundaries. Plots averaging 16 ha were drawn on the protective sleeve and subdivided into six to ten sections. We then manually identified the location of each visible tree for each time period. The total number of trees on public and private land was quantified and compared to the density of trees from 2006 vertical digital aerial photography. All imagery and GIS data from this research are available at http://sites.google.com/site/wftecmapper/home/million-tree-data.

1920's

1930's

1940's

Today

0   0.1 miles

Fig. 3 Examples of GIS data on tree location (*orange dots*) from the 1920's, the 1930's, the 1940's, and 2006 overlaid on vertical digital aerial photography in the San Fernando Valley

Validation of tree occurrence

In order to estimate the accuracy of our tree identification from 2006 vertical aerial photography, we undertook an analysis of trees in 1-ha plots within study sites in Los Angeles city council districts. Ten 1-ha plots were selected in city council districts that represented different land use types (residential 7, commercial 2, institutional 1). The number of trees visible in 2006 imagery for each 1-ha plot was subset. Then each site was visited in 2011 and the location of all trees on public and private property were quantified in each 1-ha plot. This identified trees that could not be identified in 2006 imagery.

Data analysis

The plot area from aerial photography and imagery for each time period was visually classified into Anderson level 1 classification of land cover (i.e. urban or built-up land, agricultural land, rangeland) (Anderson et al. 1976; Jensen 2007). The total number of trees, public trees, and private trees for each time period was quantified as the number of individuals and density per hectare. All time series data on density during different time periods were examined for a normal distribution with a one-sample Kolmogorov-Smirnov

Table 1 Los Angeles city council districts, year of aerial photography, plot size, city council district area, and percent of city council district with tree canopy cover from McPherson et al. (2008)

City Council District & Name	Year	Year	Year	Plot Size (Hectares)	District Area (Km^2)	Tree Canopy Cover (%)
District 01: Echo Park	1928	1945	2006	16	32	16
District 02: Tujunga	1922	1950	2006	13	82	27
District 03: Reseda	1928	1951	2006	5	98	26
District 04: North Hollywood	1924	1946	2006	15	62	29
District 05: Hollywood	1921	1955	2006	39	98	37
District 06: Van Nuys	1929	1950	2006	15	69	15
District 07: Pacoima	1929	1953	2006	19	64	16
District 08: Exposition Park	1921	1948	2006	14	45	11
District 09: Lynnwood	1922	1948	2006	32	39	8
District 10: Miracle Mile	1921	1946	2006	12	35	12
District 11: Venice	1924	1959	2006	11	109	24
District 12: Chatsworth	1924	1959	2006	14	118	20
District 13: Sherman Oaks	1922	1949	2006	24	32	14
District 14: LA County Hospital	1929	1959	2006	6	57	22
District 15: LA Harbor	1920	1953	2006	11	84	9

test. All variables had a normal distribution. Regressions were used to identify if there was an increase in tree density in the San Fernando Valley, Hollywood, and Los Angeles Basin. A one-way analysis of variance (ANOVA) was used to identify significant differences between total tree density, private tree density, and public tree density for three regions with high-resolution GIS data and the 15 city council districts for three time periods (1920's, 1950's, 2006). Regressions were used for each of the 15 city council districts to determine if there was an increase in the tree density within all 15 city council districts. Regressions were also used to examine relationships with tree densities on public vs. private land.

Results

High-resolution GIS analysis of three regions

When the historic aerial photography archives were researched for comparative data on tree density in three regions of Los Angeles, comparative historic photography was available for six time periods (1920's, 1930's, 1940's, 1950's, 1960's, and 2006) in Hollywood and the Los Angeles Basin, and four time periods (1920's, 1930's, 1940's, and 2006) in the San Fernando Valley (Fig. 4). There was a significant increase in total tree density with time in the San Fernando Valley ($r^2=0.963$, $P<0.019$) and Los Angeles Basin ($r^2=0.964$, $P<0.001$), but not in Hollywood ($r^2=0.084$, $P<0.579$). Tree densities on private land in the San Fernando Valley had a more linear increase with time ($r^2=0.985$, $P<0.001$) than tree densities on public land ($r^2=0.829$, $P<0.001$), while the inverse was true in the Los Angeles Basin where tree densities on public land increased more linearly ($r^2=0.832$, $P<0.001$) than tree densities on private land ($r^2=0.762$, $P<0.001$).
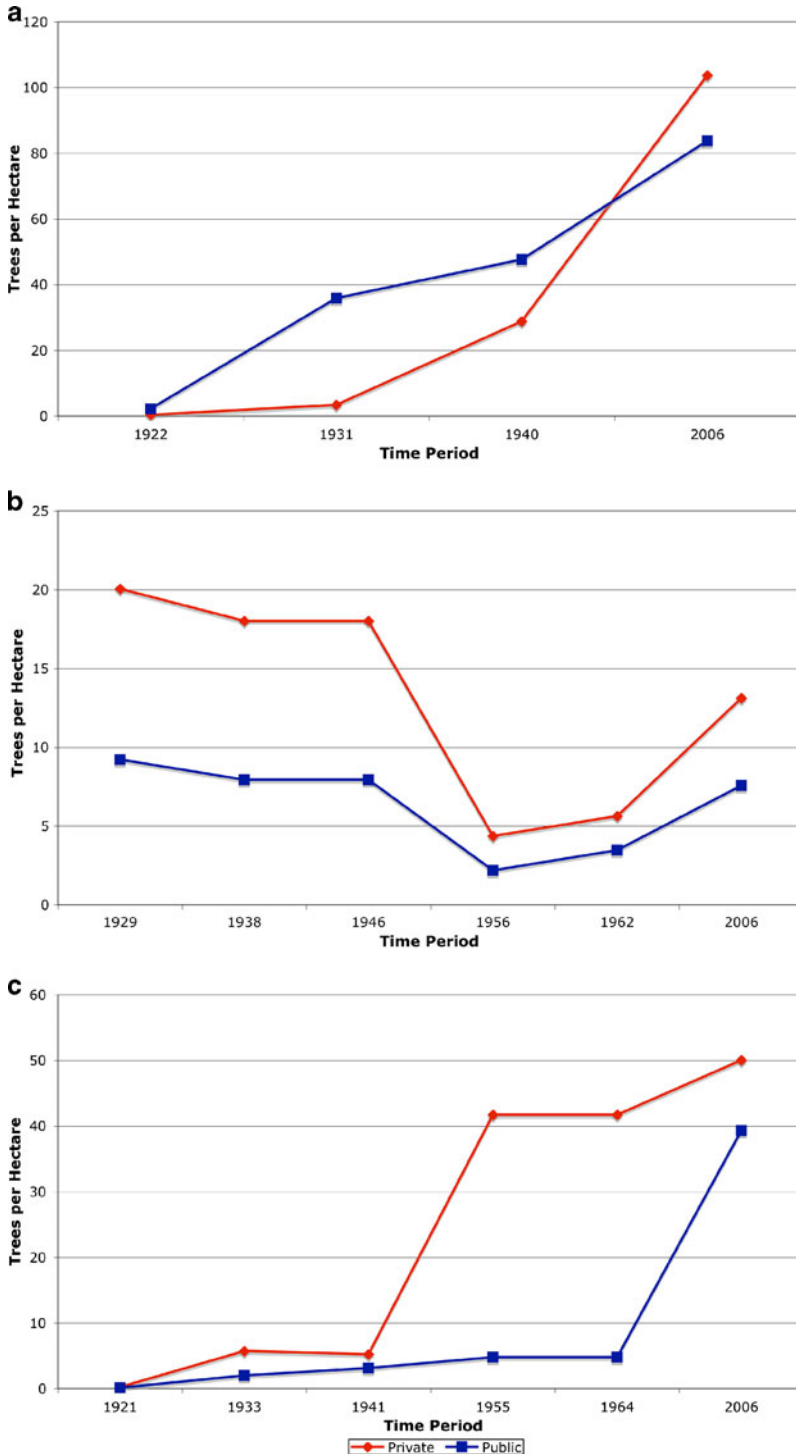
Fig. 4 Time series data for the San Fernando Valley (**a**), Hollywood (**b**), and Los Angeles Basin (**c**)

Time series for 15 city council districts

During the 1920's, a majority of the plots (11 sites) and city council districts were urban or built-up land comprised of areas of intensive use or land covered by structures. Three San Fernando Valley sites were rangeland and one site was agricultural land. By the 1950's, 12 sites were urban with the exception of the northeasternmost city council districts (number 6, 7, and 12) in the San Fernando Valley. All sites were urban by 2006.

A total of 46,772 individual trees were identified on public and private lands from the three time periods (8794 individuals in the1920's, 14,518 in the 1950's, and 23,460 in 2006). There were significant differences in total tree density in the 15 city council districts in Los Angeles between the 1920's, 1950's, and 2006 (ANOVA; F=5.57; df=2; P=0.007) (Fig. 5). Tree densities averaged 41 individuals per ha in the 1920's, 69 individuals per ha in the 1950's, and 104 individuals per ha in 2006. There were also significant differences in tree density on public land (ANOVA; F=4.04; df=2; P=0.025) and private land (ANOVA; F=3.80; df=2; P=0.031) over the three time periods. There was a significant increase in total tree density with time for all city council districts (r^2=0.141, P<0.001), most of which can be attributed to an increase in tree density on private land (r^2=0.102, P<0.001) as compared to public land (r^2=0.067, P<0.001).

Tree densities in plots from the 1920's ranged from 0 to 195 individual per hectare with Lynnwood, Venice, Sherman Oaks, Chatsworth, and the Miracle Mile having less than five trees per hectare and only Echo Park containing over 100 trees per hectare (Fig. 6). By the 1950's, five districts (Echo Park, Hollywood, Pacoima, Exposition Park, and Los Angeles Harbor) experienced a decline in tree density while the other ten districts experienced an increase in density. The total tree density per hectare by 2006 ranged from a low of 20 in Hollywood to a high of 187 in Sherman Oaks. Only three city council districts (Echo Park,
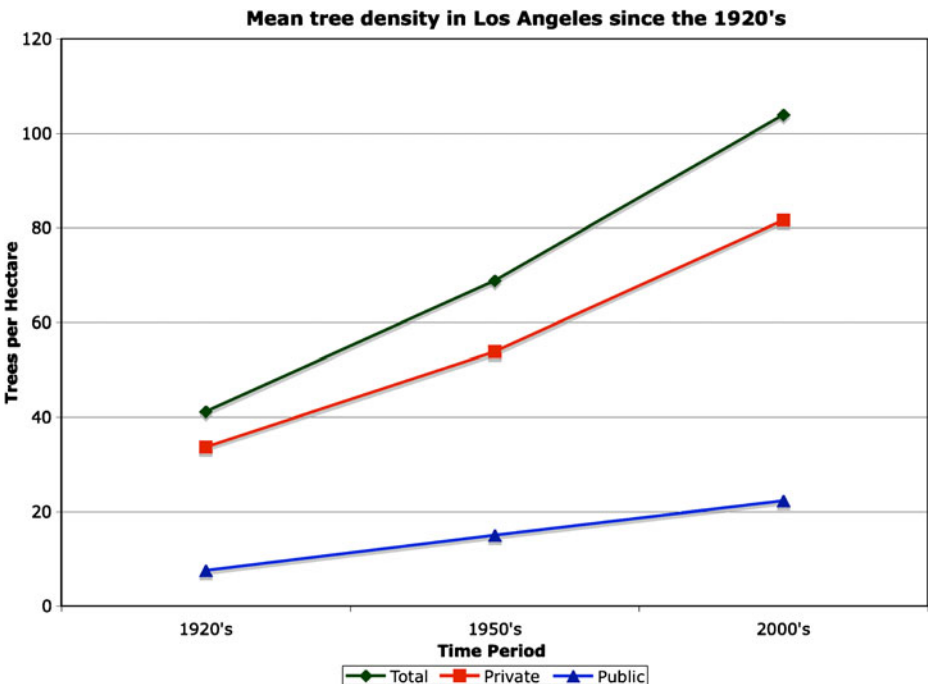
Fig. 5 Mean tree density from 15 city council districts in Los Angeles from the 1920's, the 1950's, and 2006
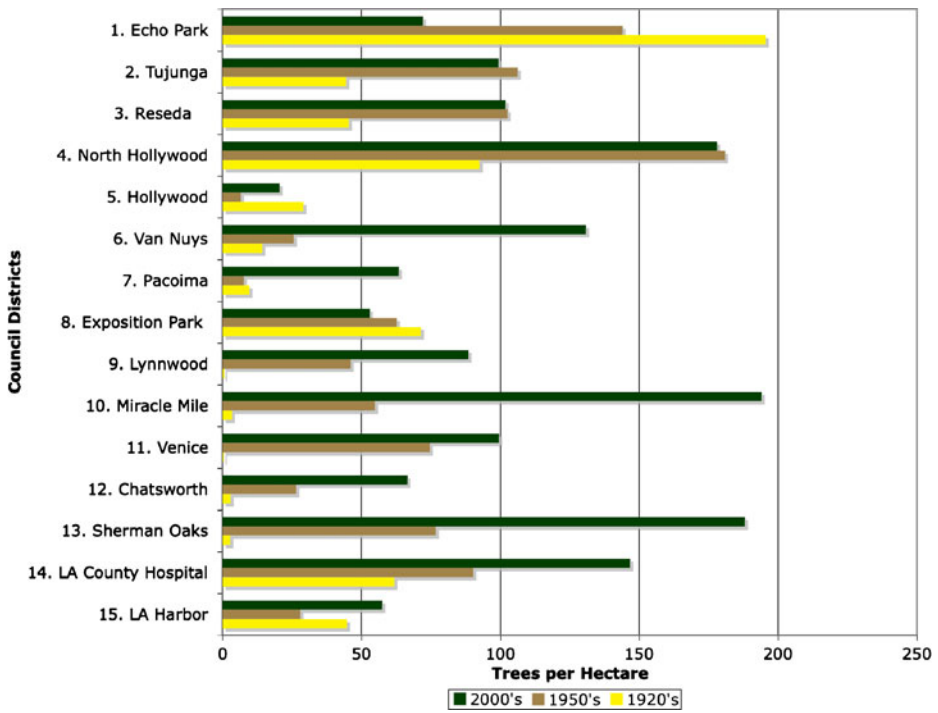
Fig. 6 Changes in tree density by city council district in Los Angeles since the 1920's

Tujunga, Exposition Park) experienced a decline in tree density since the 1950's, while all other sites remained the same or increased in tree density.

Tree canopy cover ranged from 9% to 43% among 10 1-ha plots (Table 2). There were 376 trees identified from 2006 imagery and 497 identified in the field. Within subsets of 2006 imagery, 73% of all trees were identified from 2006 imagery.

Table 2 Accuracy assessment of tree occurrence and tree canopy cover in 10 1-ha plots in study sites (residential, commercial, institutional) in the city of Los Angeles. Number of trees identified from 2006 imagery, number of trees identified in the field in 2011, tree canopy cover from McPherson et al. (2008)

City Council District & Land Use	Trees from 2006 Imagery	Trees from Field Surveys	Proportion of Trees Identified	McPherson Tree Canopy Cover
1: Residential	34	44	77%	14%
2: Residential	48	65	74%	25%
4: Commercial	21	37	57%	13%
5: Institutional	25	34	74%	36%
5: Residential	84	98	86%	43%
6: Residential	34	41	83%	9%
6: Residential	50	67	75%	21%
11: Residential	38	45	84%	26%
11: Commercial	17	30	57%	5%
12: Residential	25	37	68%	15%

Discussion

Historic oblique aerial photography is a useful tool for reconstructing urban forests over the last 90 years in Los Angeles and possibly other cities in Mediterranean regions. It is possible to digitize tree locations back to the 1920's in Los Angeles. However, a number of limitations with digitizing trees in historic and contemporary aerial photography should be mentioned. First, individual trees and crowns are easy to identify when there is a low density of trees and crowns are not touching. However, once a closed canopy is achieved, it is more difficult to accurately quantify the number of individual trees in both historic oblique and contemporary vertical imagery. Trees taller than four meters can occur below the canopy of larger trees and these are difficult to identify in vertical aerial photography. Furthermore, it is difficult to calculate the densities of certain species of trees such as figs, palms, and junipers, which can have tightly clumped stems or overlapping canopies. This results in an underestimation of the number of trees or woody plants with a single main stem or trunk, four meters or greater in height, and branches above the ground. Second, there is not always a decadal time series of oblique angle imagery available at the appropriate scale or look-angle for a number of areas in Los Angeles. Thus, a historic time series in urban areas should focus on comparing the highest resolution photography available, but this may not represent the entire city or in our case city council district as a whole. Third, historic oblique aerial photography was compared to vertical digital aerial photography from 2006, which resulted in a time lag of over 50 years. It may be the case that vertical aerial photography is more commonly available for a number of cities in
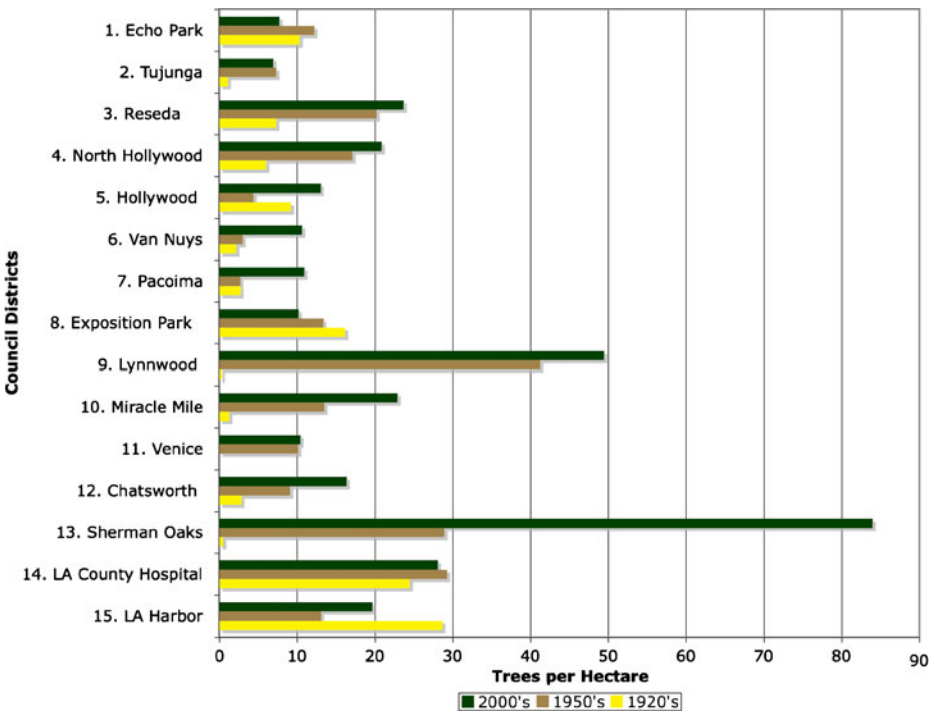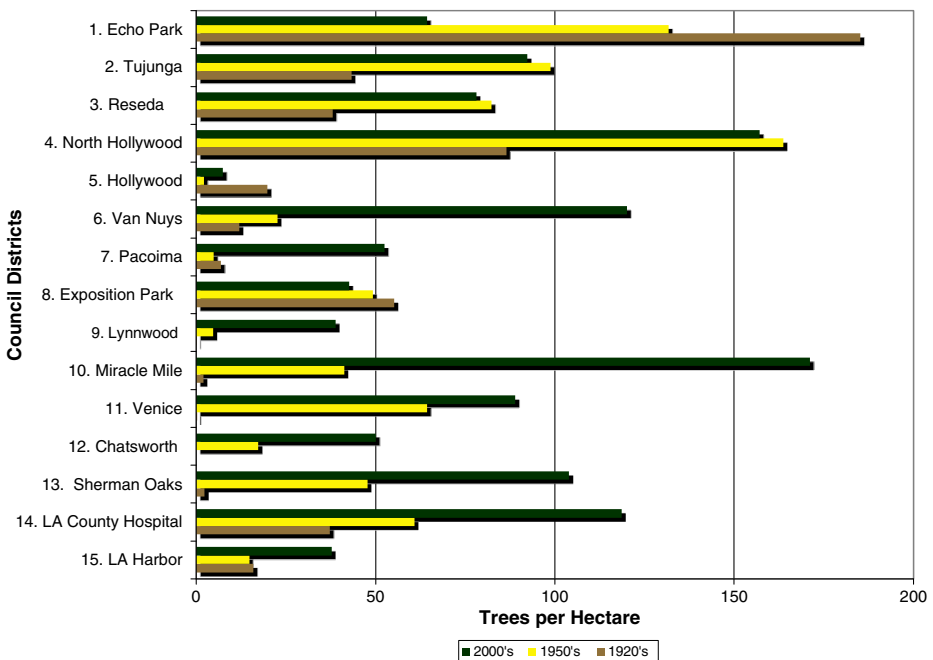

Fig. 7 Changes in tree density on public land since the 1920's in 15 city council districts in the City of Los Angeles

Mediterranean regions and an analysis of historic vertical aerial photography should be undertaken in Los Angeles. Finally, the most common metric for contemporary urban forest studies is tree canopy cover that may differ from the number of individual trees per hectare. When McPherson data on tree canopy over was compared to trees per hectare over each plot in the 15 city council districts, there was a significant correlation between tree canopy cover and tree density ($r^2=0.363$, $P<0.017$) (McPherson et al. 2008). However, despite these limitations, historic aerial photography provides a basis for studying the evolution of urban forests in cities.

In the three regions of Los Angeles where 4 to 6 time periods were examined, there does not appear to always be an increase in tree density, with tree densities in well-developed and older cities, like Hollywood, declining and tree densities in once rangelands, agricultural lands, and low density urban areas increasing. However, in all three regions tree densities are currently higher on private land compared to public land. Across all 15 city council districts, there were significant increases in tree densities; however, the relationship was not clearly linear with time. In Los Angeles, as the landscape changed to a higher density of structures, there was a significant increase in tree density. With the exception of rural landscapes that once supported orchards, most of Los Angeles was treeless in the lowlands, possibly due to a long history of agriculture, grazing, and wood collection in the area (Pincetl 2003).

Our results are similar to the Zipperer et al. (1997) proposed model of urban forests in deserts and grasslands with tree biomass minimal at pre-establishment and reaching its highest peak at establishment. However, it appears that some city council districts are still just reaching their highest peak (i.e. District 6, 7, 9, 10, 11, 12, 13, 14) while other districts are in the post-establishment phase (i.e. District 1, 2, 3, 5, 8) and slightly decreasing in post-

Fig. 8 Changes in tree density on private land since the 1920's in 15 city council districts in the City of Los Angeles

development due to pruning and removal of dead trees. In many ways the evolution of tree planting in Los Angeles is similar to desert cities like Tucson and Phoenix with thousands of trees planted in the early twentieth century (Luck and Wu 2002; McPherson and Haip 1989). However, Los Angeles may be relatively unique given the nodal development of small cities and suburban areas that have coalesced with time over a large geographic area.

The contribution of trees planted on public and private land is complex, with both significantly contributing to the overall densities of trees in Los Angeles (Figs. 7, 8). However, there is no clear evidence that trees on public land or private land were planted first. Within cities, land use is the dominant factor affecting tree cover on a local scale, and this appears to be the case in Los Angeles through time (Longcore et al. 2004). High tree densities in Los Angeles appear to be largely due to the planting of trees on private land as compared to public land. However, a majority of the study sites are composed of private as compared to public land. There does not appear to be a great deal of research on the distribution of trees or tree canopy cover on public versus private land. However, if GIS polygons on public and private land are available, it may be possible to undertake a further analysis of the distribution of tree canopy cover for cities in the United States and other regions.

The Million Tree Initiative in Los Angeles should focus on planting trees on public land and will also need to distribute trees to private property owners so that trees can be planted on private land. McPherson et al. (2011) estimated that there is potential to add 2.5 million trees in the City of Los Angeles but only 1.3 million of the potential sites are deemed realistic to plant. Our data suggests that most of the potential sites will have to be planted on private land. If the city distributes selected low maintenance, high shade potential, and water efficient trees to private landowners, this should benefit the private landowner by improving the aesthetics of the property and energy saving from shading estimated to be valued at $38 to $56 annually per tree planted (McPherson et al. 2011). This will also provide the private landowner with management decisions as to tree maintenance while reducing maintenance costs for the city.

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