Potential energy savings in buildings by an urban tree planting programme in California

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Abstract: Tree canopy cover data from aerial photographs and building energy simulations were applied to estimate energy savings from existing trees and new plantings in California. There are approximately 177.3 million energy-conserving trees in California communities and 241.6 million empty planting sites. Existing trees are projected to reduce annual air conditioning energy use by 2.5% with a wholesale value of $ 485.8 million. Peak load reduction by existing trees saves utilities 10% valued at approximately $ 778.5 million annually, or $ 4.39/tree. Planting 50 million trees to shade east and west walls of residential buildings is projected to reduce cooling by 1.1% and peak load demand by 4.5% over a 15-year period. The present wholesale value of annual cooling reductions for the 15-year period is $ 3.6 billion ($ 71/tree planted). Assuming total planting and stewardship costs of $ 2.5 billion ($ 50/tree), the cost of peak load reduction is $ 63/kW, considerably less than the $ 150/kW benchmark for cost-effectiveness. Influences of tree location near buildings and regional climate differences on potential energy savings are discussed.

Key words: urban forests, peak load reduction, energy conservation

Introduction

California is home to over 30 million people and the world's sixth largest economy. Its population is expected to nearly double to 60 million in the next 40 years, with concomitant increased demand for energy resources (California Department of Finance 1998). Providing adequate supplies of energy to fuel growth has proven to be a challenge, as evidenced by rolling blackouts during 2001 (Berthelsen & Winokur 2001).

Rapid growth of California cities is associated with a steady increase in ambient downtown temperatures of about 0.4 °C (0.7 °F) per decade. Because electric cooling load demand of cities increases about 3–4% per °C (1–2% per °F) increase in temperature, approximately 3–8% of electric demand for cooling is used to compensate for this urban heat island effect (Akbari et al. 1992). Warmer temperature in cities compared to surrounding rural areas has other implications, such as increases in carbon dioxide emissions from fossil fuel power plants, municipal water demand, unhealthy ozone levels, and human discomfort and disease. In addition, climate change may double the rate of urban warming, underscoring the need for more energy-efficient landscapes in new urban developments.

Urban forests modify climate and conserve building

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energy use through 1) shading, which reduces the amount of radiant energy absorbed and stored by built surfaces, 2) evapotranspiration (ET), which converts liquid water in plants to vapor, thereby cooling the air, and 3) wind speed reduction, which reduces the infiltration of outside air into interior spaces (Heisler 1986). Trees and other greenspace within individual building sites may lower air temperatures 3 °C (5 °F) compared to areas outside the greenspace.

Although shade trees have potential to conserve energy, if located to shade solar collectors and south-facing windows they can reduce collector efficiency and increase winter heating costs. Other potential drawbacks include:

- conflicts between trees and sidewalks, power lines, and street lights when trees are improperly sited,
- falling limbs, fruit, and leaves that create hazards and require clean-up,
- certain species release allergens and emit biogenic volatile organic compounds (BVOCs) that contribute to ozone formation,
- many types of trees require ample amounts of water to grow,
- slow growth rates and high mortality rates can reduce tree planting cost-effectiveness.

Judicious tree selection and location are critical to maximizing energy benefits and minimizing the problems noted above (McPherson et al. 1999, 2000, 2001).

There are an estimated 6 million street and park trees and a total 148.6 million trees in urban areas in California (Bernhardt & Swiecki 1993; Dwyer et al. 2000). However, information is lacking on how these trees influence building energy use and the potential for new tree planting. Although previous research has addressed these questions at the scales of individual home sites (Meier 1991) and cities (Simpson 1998), statewide impacts have never been studied. Information at this scale is important to California government officials and electric utilities, who are actively investing in peak load reduction strategies. Moreover, because California is as large as many countries in Europe and Asia, the methods described here could be applied to conduct large-scale analyses elsewhere. Thus, the objectives of this study were to determine the effects of:

- existing trees on statewide and regional energy consumption for space heating and cooling and peak electricity demand,
- future tree plantings on statewide and regional energy consumption for space heating and cooling and peak electricity demand,
- regional differences on annual energy savings, peak load reductions, and cost-effectiveness.

Methodology

Aerial photo analysis

Data from aerial photography were previously collected for 21 California cities with print scales from 1:12,000 and 1:4,800 and dates ranging from 1988 to 1992 (USDA Forest Service 1997). The point below each randomly located dot was classified by land-use type, cover type, and the site's effect on building energy use (Fig. 1). A minimum of 3,495 sample points were analyzed from photos that covered the entire area of each city. Data were grouped by four land use classes: single family residential (SFR), multi-family residential (MFR), commercial/industrial (C/I), and institutional/transportation (I/T). Because our estimates focus on trees and planting sites with energy-saving potential, locations on agricultural, wildland, and abandoned areas within cities are excluded.

Points falling on tree canopy or plantable pervious cover were further classified into site locations based on whether their effect on heating and cooling energy use was positive, negative, or neutral. Trees or empty planting sites located within 12.2 m of east and west sides of buildings were in "positive sites" because trees provide benefits from shade. South trees located within 6.1 m from buildings were in "neutral sites" since benefits from limited summer shade are likely to be offset by undesirable winter shade. Points located between 6.1 m and 12.2 m of the south side of buildings were in "negative sites" because most shade occurs during the heating season. Points located to the north or greater than 12.2 m from buildings in other directions were in "neutral sites" because their shade would not fall on buildings. Trees at all sites were assumed to produce energy benefits from reduced ambient temperatures and wind speeds (climate effect). These site classifications reflect our general knowledge of how time, season, and tree location influence shading on buildings (Heisler 1986).

The number of existing trees and potential tree planting sites were calculated assuming an average tree cover density of 609 trees/ha (average crown projection area of 16.4 m² per tree) (Table 1). This tree density was derived from tree cover densities for land uses within city and suburban sectors of Sacramento and applied to all sample cities and land uses (McPherson 1998). The total number of trees T_{ik} for land use 'i' and site 'k' was calculated as

$$T_{ik} = p_{ik} * A/b$$

where

p_{ik} = proportion of interpreted points covering land use i on site k (i.e., positive, neutral, or negative sites),

A = city area,

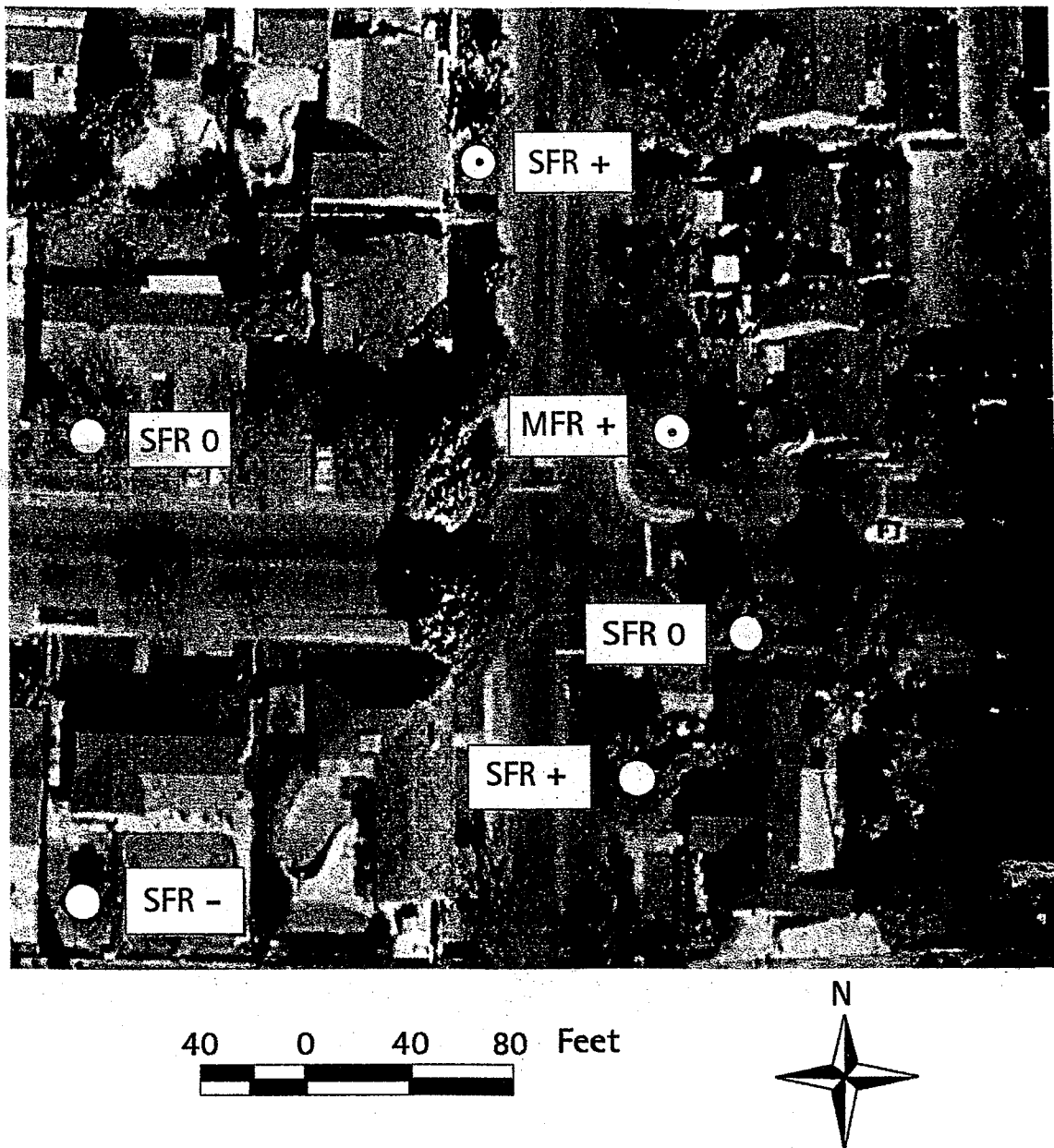b = average tree crown projection area.

Fig. 1. Aerial image similar to those interpreted showing random dots landing on existing tree cover (unfilled circles) and empty tree sites (filled circles). Land use (single family residential [SFR], multi-family residential [MFR]) and site location (positive, neutral, negative) are shown for each point.

And the standard error was calculated as

$$SE\,(T_{ik}) = A/b\,*SQRT[V\,(p_{ik})]$$

where $V(p_{ik})$ is the variance of p_{ik} and calculated as

$$V(p_{ik}) = p_{ik}\,(1 - p_{ik})\,/\,\text{Total \# of interpreted points}$$

This standard error for numbers of trees characterizes measurement error, but underestimates total error because other sources of error are present (discussed later in this paper).

Scaling-up from the sample to climate zones

California has the most diverse set of climatic conditions of any state in the US. The California Energy Commission (1995) analyzed data from over 600 weather stations and divided the state into 16 distinct and reasonably consistent climate zones based mostly on summer and winter mean temperatures. Climate zone boundaries are fairly consistent with jurisdictional boundaries and avoid creating pockets within zones.

Table 1. Tree cover data from previous aerial photo interpretation, estimated tree numbers (in thousands), and population and housing estimates (dwelling units [DUs] in thousands) for 1990 and 2000 used to scale-up sample data. Trees (se) is the standard error of the estimate of tree numbers

Region	Sample Cities	Tree Cover (%)	1990 Trees	Trees(se)	1990 City Pop.	1990 City DUs	2000 Zone Pop.	2000 Zone DUs
North Coast	Eureka	21.6	85.3	4.9	27.0	11.8	1,068.6	450.1
Cental Coast	Atherton	47.5	360.3	6.8	7.2	2.5	6,109.9	2,238.8
	Menlo Park	23.9	363.1	12.5	28.4	12.4		
	Santa Maria	5.4	109.2	7.8	61.6	21.2		
South Coast	Los Angeles	15.4	14,684.4	469.4	3,485.6	1,300.0	4,969.9	1,834.2
South Valleys	Pasadena	22.5	724.8	23.0	131.6	53.0	10,770.7	3,492.8
Inland Empire	Escondido	18.1	493.0	22.1	108.6	42.1	2,887.3	1,009.4
	Poway	10	290.7	16.3	43.4	14.4		
North Ctr Valley	Chico	11.4	308.3	15.4	40.0	16.2	786.9	345.0
	Redding	15.5	381.5	26.3	66.5	27.2		
	Yuba City	11.7	101.3	4.6	27.4	11.0		
Mid Ctr Valley	Merced	5.7	123.9	8.2	56.2	18.9	3,887.6	1,433.1
	Sacramento	14.1	2,065.4	76.1	369.4	153.4		
South Ctr Valley	Bakersfield	5.7	497.0	26.3	175.0	66.2	1,966.5	663.5
	Visalia	12.5	228.4	13.2	75.7	27.2		
High Desert	Lancaster	0.4	53.0	7.5	97.3	36.2	757.1	271.8
	Victorville	1.7	57.8	6.6	40.7	15.6		
Low Desert	Cathederal City	3.9	103.1	8.3	30.1	15.2	540.8	229.8
	Coachella	7.9	19.0	2.9	16.9	3.8		
	Desert Hot Springs	1.5	21.8	2.8	11.7	5.5		
	Palm Springs	3.9	367.1	23.8	40.1	30.5		
Mountains	South Lake Tahoe	41.7	340.5	7.5	21.6	14.1	582.0	286.0
							34,327.3	12,254.5

Table 2. Representative cities, air temperatures, radiation, and heating and cooling degree days for the 11 climate zones

Region	City	Avg. Daily Min. Temp (°C)	Avg. Daily Max. Temp (°C)	Direct Solar Radiation (W/m²)	Diffuse Solar Radiation (W/m²)	HDD	CDD
North Coast	Santa Rose	7.3	22.2	5.2	1.6	3,340	323
Central Coast	Sunnyvale	8.2	22.2	5.6	1.5	2,366	325
South Coast	San Diego	12.2	22.2	5.3	1.8	1,355	472
South Valleys	Burbank	11.2	25.2	5.6	1.7	1,488	893
Inland Empire	Riverside	10.2	25.8	5.7	1.8	1,570	1,243
North Central Valley	Red Bluff	9.1	23.7	6.2	1.4	2,518	1,337
Middle Central Valley	Sacramento	8.6	23.1	6.3	1.4	2,764	708
South Central Valley	Fresno	10.8	25.1	6.5	1.5	2,300	1,908
High Desert	China Lake	7.5	24.4	7.3	1.4	2,706	1,719
Low Desert	El Centro	14.6	31.3	6.6	1.6	776	4,018
Mountains	Mt. Shasta	2.1	18.2	5.4	1.5	5,600	253

One heating degree day (HDD) accumulates for every degree that the mean outside Temperature is below 65 °F (18.3 °C) for a 24-hr period.
One cooling degree day (CDD) accumulates for every degree that the mean outside temperature is above 65 °F (18.3 °C) for a 24-hr period.

We reduced these 16 zones to 11 because canopy cover data were not available for cities in certain climate zones (Fig. 2, Table 2). Climate zones that were joined were adjacent to each other, with relatively similar climates.

Tree numbers by location for each sample city were stratified into the 11 climate zones. Tree ratios, the number of trees per person or per dwelling unit, were calculated by land use and tree site (i.e., positive, neutral, or negative) for each sample city using 1990 demographic data (U.S. Census Bureau 1996) (Table 1). Tree ratios for SFR and MFR land uses were calculated per dwelling unit, and ratios for C/I and I/T land uses on a per capita basis. Tree ratios for sample cities in the same climate zone were averaged to derive zone-wide

estimates. 2000 population and housing data were aggregated for all California cities and unincorporated areas by climate zone (California Department of Finance 2000) (Table 1). Ratios were multiplied by their respective year 2000 population and dwelling unit numbers to estimate the total numbers of existing trees and potential tree planting sites by land use and tree site for each climate zone. This scale-up assumes that tree distributions in 2000 are the same as those sampled in 1990. If new development patterns resulted in fewer tree sites than observed in 1990, this assumption may overestimate the number of sites.

The 21-city sample did not contain a city in the South Coast climate zone. Land cover and land use data were used from an earlier aerial photo analysis of
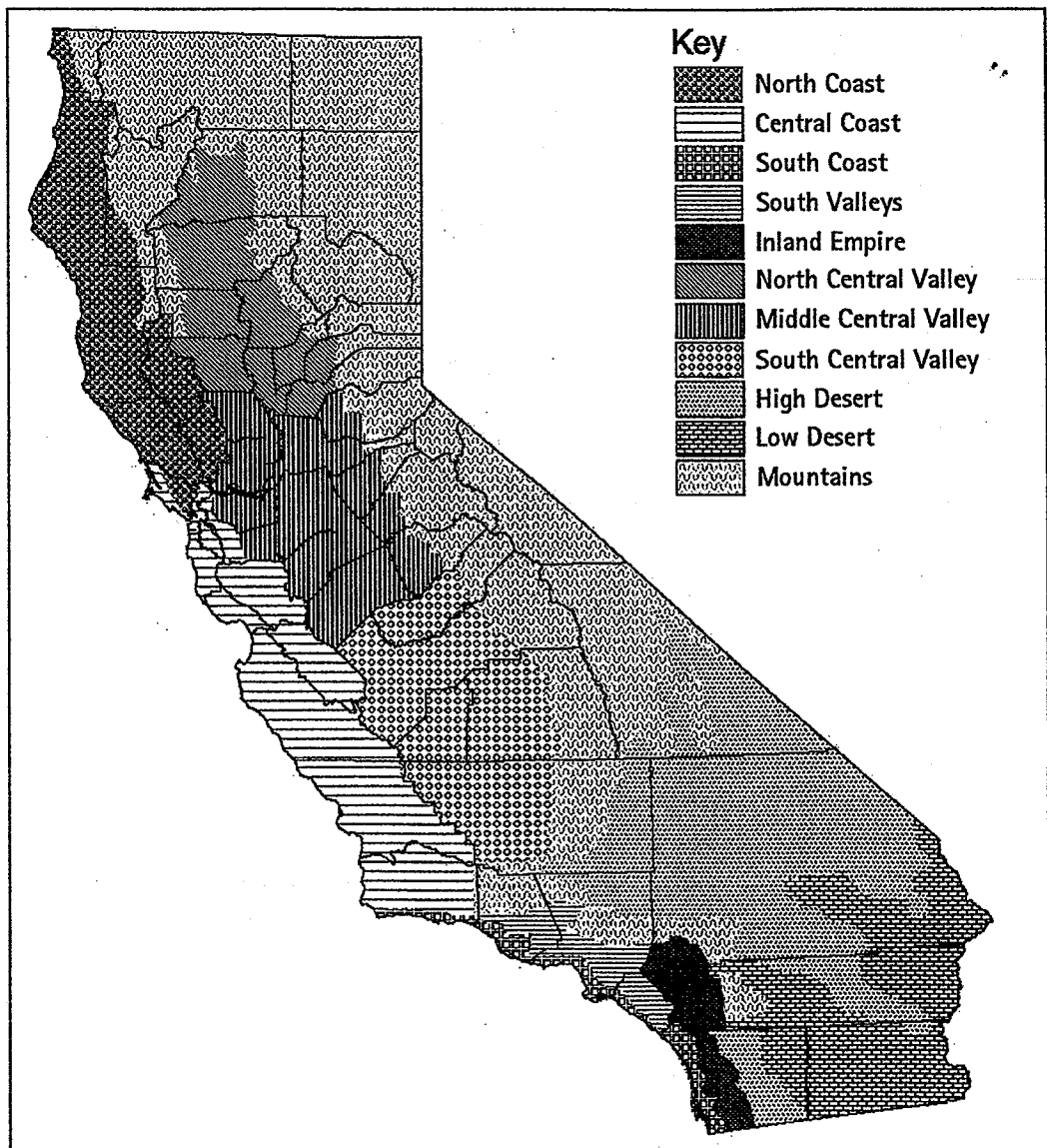

Fig. 2. Climate zones and county boundaries.

Los Angeles (McPherson et al. 1993), but data lacked specific information on tree sites. Tree site data from the 21-city study for Pasadena were applied to the tree canopy cover and plantable pervious land cover data for Los Angeles. Thus, while estimates of the overall numbers of trees and empty sites are specific to the Los Angeles imagery, the locations of trees and sites around buildings were extrapolated from nearby Pasadena and may not accurately reflect conditions in Los Angeles. Also, anomalously high canopy cover (47.5%) and trees/capita (50) for Atherton led to its removal from the database, leaving two sample cities for the Central Coast region (Menlo Park, Santa Maria) (Table 1).

▨ Computer simulations

This study relied largely on results from previous computer simulations of the relative effects of different tree configurations on building energy use (McPherson & Sacamano 1992; Simpson et al. 1994; Simpson & McPherson 1996; McPherson & Simpson 1999). Energy savings were determined by comparing predictions for identical unshaded (base case) and shaded buildings. Base case results were calibrated and adjusted with residential energy use data from each utility (Table 3). Annual impacts on cooling (kWh) and heating (MJ) per residential unit (Unit Energy Consumption or UEC), and peak demand or capacity (kW) per residential unit (Unit Power Consumption or UPC)

were based on hourly simulations using representative weather data for cites in each of the 11 climate zones (Mallette et al. 1983) (Table 3) A detailed description of how energy effects were estimated is described in the full technical report (McPherson & Simpson 2001).

UECs and ΔUECs in this study were based on results for 139 m^2 and 163.6 m^2 wood frame homes that meet California Energy Efficiency Standards (Title-24). The single-family residences had R-39 insulation in the roof and R-19 insulation in the walls, energy efficient heating (Annual Fuel Utilization Efficiency = 78%) and cooling (Seasonal Energy Efficiency Ratio = 10 [ratio of cooling output in kBtuh to power consumption in kWh]) equipment, dual-pane windows, and cooling by natural ventilation when the outside temperature dropped below the thermostat setpoint (25.6 °C). Results for smaller buildings were increased by the ratio of their conditioned floor areas (CFA) (163.6/139 = 1.18) to provide for more direct comparisons across regions, and to reflect the larger size of newer home construction. The use of this ratio is an approximation because smaller buildings have relatively larger surface area to volume ratios and greater conduction heat gains/losses per unit volume than larger buildings. Because the scaling adjustment here is small, its effect on the modeling results is minor.

In these studies shade was simulated using the deciduous Chinese lantern tree (*Koelreuteria bipinnata*). This species is commonly planted except in the mountains, has a broad, umbrella shaped crown, is a low to moder-

Table 3. Simulated heating and cooling loads for the base case buildings and regional air conditioning saturations weighted by equipment type

Region	Base Case Buildings			
	Annual Cooling (kWh)	Peak AC (kw)	Annual Heating (GJ)	SF Res. AC Saturation (%)
North Coast	881	2.51	21.7	39.7
Central Coast	539	2.29	13.5	32.4
South Coast	603	2.17	7.2	30.3
South Valleys	1,904	3.08	10.3	55.6
Inland Empire	2,493	3.30	14.5	59.5
North Ctr Valley	2,135	3.17	23.4	70.8
Mid Ctr Valley	1,490	3.15	20.5	68.6
South Ctr Valley	2,968	3.32	16.2	70.2
High Desert	2,646	2.94	28.9	78.0
Low Desert	5,453	3.32	5.5	78.0
Mountains	559	2.28	83.0	10.0

SF Res AC Saturation is the percentage of single family residential units with cental air conditioning. The calculation weights evaporative and room AC based on typical electric use relative to central AC.

ate water user, moderately pest resistant, and low emitter of volatile organic compounds. Results of shading at 5, 10, and 15 years after planting are reported and assume respective tree heights and crown spreads of 4 m, 5.8 m, and 7.3 m. These dimensions are consistent with measured data for street trees in Modesto and Santa Monica (Peper et al. 2001a, 2001b). Trees were estimated to block 85% of summer irradiance (April through November in most climate zones) and 30% during the winter leaf-off period (McPherson 1984). Shade effects from individual trees were simulated assuming trees were placed 3.8 m from east and west walls.

UECs were adjusted to account for forecasted saturation of central air conditioners, room air conditioners, and evaporative coolers in each utility service area (California Energy Commission 2000a) (Table 3). In this study the term saturation refers to the percentage of total dwelling units with air conditioning equipment. Equipment factors of 33% and 25% were assigned to homes with evaporative coolers and room air conditioners, respectively. These factors were combined with equipment saturations to account for reduced energy use and savings compared to those simulated for homes with central air conditioning. ΔUECs for multifamily residential buildings due to tree planting were estimated by adjusting single family ΔUEC for differences in energy use, shading, and climate effects between building types. UEC data were taken from US Energy Information Administration (1993a, 1993b) climate zones representative of California (zones 3, 4, and 5). Similar adjustments were used to account for UEC and CFA differences between single-family detached residences for which simulations were done, and attached residences and mobile homes.

Calibration and validation of simulation results

To improve the accuracy of initial simulation results they were calibrated with other findings until reasonably similar to those from the limited set of relevant simulation and field studies. Meier (1990/91) reviewed results from five studies that measured energy savings from landscaping and reported that air conditioning energy savings commonly measured 25–50%, but non of these studies were in California. In the only California field study (Akbari et al. 1997), 16 trees in containers, 8 large (7 m tall) and 8 small (3 m), were located to shade the walls of two residential buildings in Sacramento, California. The trees were reported to reduce annual air conditioning use by 26% for one building and 47% for the other. This difference in savings was due to different shading treatments and measurement sequences. After adjusting for tree size, the annual cooling savings were 3–8% per large tree (7 m). Our final simulations results for Sacramento (Mid-Central

Valley) found that shade from a south tree (7.3 m tall) reduced annual cooling by 5% (76 kWh).

Computer simulations conducted by Akbari et al. (1990) in Sacramento were based on three trees and included effects of increasing roof albedo. After accounting for these effects the estimated savings from shade and climate effects was 424 kWh/tree. Estimated savings of 350 kWh from our 7.3 m tall west tree is somewhat less than this amount of 424 kWh/tree.

In simulation studies Huang et al. (1987) found annual savings of 261 kWh/tree in Sacramento, for similar houses, compared with 237–350 kWh/tree found in this study. Their trees had greater crown diameter (10 m vs. 7.3 m), but shading was "generalized" and not located to maximize summer shading. When shading was maximized, their savings increased to 343 kWh/tree, similar to our 350 kWh amount for a west tree.

Peak savings were also reported by Huang et al. (1987) of 0.66 kW/tree for Sacramento compared to 0.35 kW/tree found here for a west tree. Their savings increased to 1.24 kW/tree for a strategically located tree. Akbari et al. (1990) found an average peak cooling savings of 0.52 kW/tree in Sacramento. Smaller savings reported for this study are partly the result of the smaller trees (10 m vs. 7.3 m) and different modeling algorithms. Given this limited basis for comparison, it appeared that our final simulation results were reasonably similar to those reported in other studies.

Forecasted electricity and natural gas prices and demands

For this analysis we assumed that the base contract price of $ 69/MWh ($ 66.34 in 1998 real dollars) remained constant because in 2001 California purchased long-term contracts for electricity at an average price of $ 69/MWh. Another 10% was added for ancillary services that utilities provide, as well as 10% for additional spot market contracts. The total wholesale price was $ 79.61/MWh. We use wholesale prices and take a utility perspective in this analysis because investment in a large-scale tree planting program would need to be economically acceptable to utilities and their regulators. The retail price paid by residential customers is approximately twice the wholesale price because of additional costs for transmission and other services.

Annual natural gas prices were based on forecasted values obtained for residential, commercial, and industrial end-uses from Pacific Gas & Electric, Southern California Gas, and San Diego Gas & Electric (California Energy Commission 2000b). Prices for the 15-year planning period averaged $ 6.06/GJ ($ 6.39/MBtu) and $ 4.67/GJ ($ 4.93/MBtu) for residential and commercial/industrial uses, respectively.

The present value of benefits (PVBs) from heating and cooling savings were calculated assuming a 5% nominal discount rate for a 15-year planning horizon (2001–2015). The 15-year planning period is a compromise between the short-term financial and political need for return-on-investment and the long-term life span of trees. Because statewide, shade trees slightly increase annual heating costs, the PVBs for heating alone can be negative.

The net present value of benefits (NPVB) was calculated by subtracting total discounted costs from total PVBs. The ratio of benefits to costs was also calculated. All trees were assumed to be planted in 2001 at an average cost of $ 50 per tree. This cost includes expenditures for administration, marketing, and stewardship, as well as costs associated with tree purchase and planting (5-gallon trees). Shade tree programs sponsored by the Sacramento Municipal Utility District (SMUD) and Los Angeles Department of Water and Power (LADWP) have budgeted costs of about $ 50 per tree.

In 2001 it cost $ 150–250 to produce, purchase, or conserve a kW at the summertime peak (Messenger, personal communication). Hence, peak load reduction measures that cost less than $ 150 per kW saved are considered cost-effective. This price of $ 150 per kW avoided at the peak was used to estimate the value of peak load reduction.

Forecasted demand data were used to estimate the relative effect of existing and newly planted shade trees on statewide energy use during the next 15 years. Annual forecasts by end use were obtained for 2000–2010 and extrapolated to 2015 using a linear trend function (California Energy Commission 2000a).

▨ Simulation scenarios and modeling assumptions

Results are presented for existing trees and a scenario that assumes strategic planting within 12.2 m of the east and west sides of residential buildings. Previous analyses in Sacramento, CA indicate that some residents will not accept additional shade trees even though vacant planting sites are available (Sarkovich, personal communication). Therefore, we assume planting of 50 million trees in sites that occupy 66% of all vacant sites within 12.2 m of east and west walls of residential buildings. A second scenario planted trees at 66% of all residential sites to compare the effects of trees located away from buildings (climate only) with those that are strategically located to provide east and west shade (shade + climate).

The planting scenarios assume that 15% of planted trees die and are removed during the 5-year establishment period after planting. An additional 5% of the number planted are assumed to have died by year 10 and another 5% by year 15. Thus, 75% of the trees

planted are assumed to survive after 15 years. This survival rate is similar to rates reported for street trees that are more prone to vandalism and stress than trees in residential yards (Miller & Miller 1981).

Results

Tree numbers and locations

▨ Existing trees

There are approximately 177.3 million (standard error [se] 2.8 million) existing trees with energy-saving potential in California cities (Fig. 3). Thirty percent of all trees are in the South Valleys zone. Overall, there are 5.2 trees per capita (34.3 million human population). The ratio of trees per capita is highest in the Mountains and North Central Valley climate zones and lowest in the High Desert.

Seventy-one percent of all trees are on single-family residential (SFR) land uses and 6% are on multi-family residential (MFR) land. The average number of residential trees per dwelling unit is 11.2, with ratios as high as 27.3 in the mountain climate zone, and as low as 2.3 in the high desert. Trees on institutional/transportation (I/T) land uses account for 17% of the total, with 6% on commercial/industrial (C/I) land uses. Forty-seven percent of all trees are located in "positive" sites east and west of buildings so as to provide shade and climate benefits, while 2% are in "negative" locations (6–12 m south of buildings) and 51% are in "neutral" locations that produce only climate benefits.

▨ Potential planting sites

There are approximately 241.6 million (se 3.2 million) empty planting sites with energy conservation potential
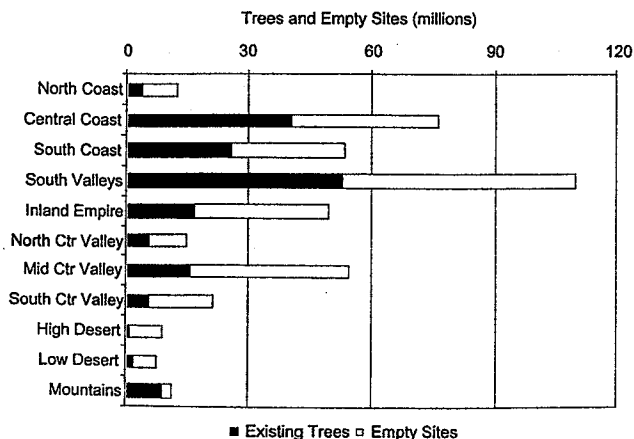

Fig. 3. Estimated current numbers of existing shade trees and empty tree planting sites in millions by climate zone.

(Fig. 3). Empty planting sites are more evenly distributed among climate zones than existing trees, although zones with the most trees also tend to have the most planting sites. There are 7.0 empty sites per capita on average, with highest ratios in the North Central Valley, High Desert, Inland Empire, and Low Desert zones, and the lowest ratios in the more heavily treed Mountains, South Valleys, and South Coast.

The distribution of empty planting sites among land uses is similar to the distribution of existing trees: 63% are on SFR land uses, 4% MFR, 26% I/T, and 7% C/I. The average number of empty residential planting sites per dwelling unit is 13.2, with ratios as high as 28.3 and 21.5 in the Inland Empire and High Desert zones, and as low as 6.7 and 7.8 in the Central Coast and Mountains, respectively. Forty percent of all potential tree sites are in "positive" locations, 4% are in "negative" locations, and 56% are in "neutral" locations that produce only climate benefits.

The technical potential for shade trees, defined as all planting sites including those with trees, is 418.9 million (se 4.2 million) in California. Statewide, technical potential is 12.2 sites per capita, and ranges from 10 (South Valleys) to 20 sites (Mountains). Current shade tree saturation, the percentage of technical potential with energy-conserving shade trees, is 42%. Saturation is highest in the Mountains (76%) and Central Coast (53%) and lowest in the High (8%) and Low (24%) Deserts. Saturation is greater in residential land uses (45% SF and 56% MF) than C/I (39%) and I/T (32%). East and west sites (positive) have higher saturations (46%) than south sites (negative) (33%).

Zones with the greatest number of empty planting sites are the South Valleys, Mid-Central Valley, Central Coast, Inland Empire, and South Coast. Together, sites in these five zones account for 79% of all empty sites. For these five zones, tree saturation is lowest in the Mid-Central Valley and Inland Empire zones, indicating that these zones have the greatest opportunity for new tree planting.

Building energy savings

Existing trees

California's 177 million energy conserving urban trees reduce annual electricity use for cooling by 6,407.8 GWh (2.5%), providing a wholesale savings to utilities of approximately $ 485.8 million (Table 4). The savings to customers is about twice this amount, or $ 970 million. Residential savings is 5,302 GWh (6.9% of total residential use) and C/I savings is 1,105 GWh (0.8% of total commercial use). The average savings for all trees is 36 kWh/tree ($ 3/tree), and trees shading SF residences are most efficient (41 kWh/tree). Electricity savings are greatest in the South Valleys, Central Coast, and Mid-Central Valley, while average savings per tree are greatest in the South Central Valley, High Desert, and Low Desert/North Central Valley.

Existing trees in California communities have an even greater effect on peak electricity consumption, reducing peak use by 5,190.2 MW (10%) over the 15-year period. Assuming a price of $ 150/kW, the value of peak load reduction is $ 778.5 million. Peak load savings are greatest in the South Valleys, Central Coast, South Coast, and Inland Empire. Average savings per tree is 0.03 kW, with values ranging from 0.02 (Mountains and other zones) to 0.09 (Low Desert). These relatively low values are partially due to tree location. Only 25% of existing trees are opposite west- and south-facing walls where benefits from shade are greatest for peak load reduction.

Existing trees increase natural gas consumption for space heating by 4.4 million GJ (2.8%), costing $ 27.4 million. Although trees reduce winter air infiltration rates, thus saving energy used for heating, this benefit is more than offset by increased heating demand due to shading from leaves and branches when solar access is a benefit. Statewide, existing trees near single-family buildings increase natural gas consumption 6.1 million GJ ($ 35 million). Trees near other buildings (e.g., multi-family residential, commercial) have a slightly

Table 4. Simulated annual cooling, peak cooling, and annual heating savings from existing trees. For the 50 million planted tree scenario, annual savings are shown at 5-year intervals after planting, assume 25% tree mortality over the 15-year period, and dollar savings are discounted at a 5% nominal rate

Tree numbers	Cooling Saved (GWh)	Cooling Saved (million $)	Peak Cooling Saved (MW)	Peak Cooling Saved (million $)	Heating Saved (GJ)	Heating Saved (million $)
177 million existing	6,408	485.8	5,190	778.5	−4.4	−27.4
50 million at 5 years	1,792	142.7	641	108.8	−4.1	−22.8
50 million at 10 years	3,949	314.4	3,427	657.9	−6.2	−34.5
50 million at 15 years	6,093	485.0	6,545	1,421.8	−7.7	−43.1

positive effect on natural gas use for heating because these larger structures are less influenced by shade effects and more influenced by climate effects compared to detached homes. The average annual cost per tree statewide is only $ 0.15 (60.1 MJ). Average annual effects on heating are most costly in the Mid-Central Valley (219 MJ/tree, $ 0.54) and most beneficial in the Mountains (397 MJ/tree, $ 0.91).

The net economic impact of existing California shade trees on cooling and heating is $ 458 million (se $ 4.1 million). Annual net benefits per tree are greatest in zones with the hottest summers ($ 4–$ 7), such as Desert, Inland Empire, and Central Valley, and savings are least in the cooler Mountains and Coastal zones ($ 1–$ 3). Statewide, tree-related additional heating costs are only 5.6% of total annual cooling savings.

🟦 *Planting 50 million trees*

In this scenario 50 million trees are planted to shade east and west walls with approximately 38 million surviving 15 years later. Ninety-three percent of the trees are planted in SFR land use and the remainder in MFR land. Over the 15-year planning period these trees are estimated to reduce electricity consumption by 46,981 GWh (1.1%) and peak demand by 39,974 MW (4.5%) (Table 4). The discounted savings associated with these projected reductions is $ 3.6 billion ($ 71/tree) and $ 7.6 billion ($ 150/tree), respectively. Heating energy use increases by 74.9 million GJ (2.8%) with a discounted cost of $ 398 million ($ 8/tree). The PVB (discounted cooling savings minus heating costs) for the 15-year period is $ 3.16 billion (se $ 17.9 million) ($ 63/tree). Ninety-seven percent of total PVBs are

from SFR trees ($ 65/tree) and 3% are from MFR trees ($ 28/tree).

Assuming program costs of $ 50 per tree, and total costs of $ 2.5 billion for 50 million trees, the net present value of benefits is $ 660,000, or $ 13/tree planted. The discounted payback period is 13 years and the benefit-cost ratio is 1:1.27. For every $ 1 invested in the hypothetical program, $ 1.27 is returned in annual net cooling and heating benefits. The benefit-cost ratio jumps to 1:1.42 when only the PVBs for annual cooling savings are considered.

During the year 2015 California is projected to add 550,000 new residents and electricity consumption will increase by 5,000 GWh. The projected annual electricity savings of 6,093 GWh ($ 485 million, 1.8% of projected demand) due to shade trees planted 15 years earlier will entirely offset the increased electricity demand associated with the state's new residents and associated development (Table 4).

Effects of tree location and climate zone

West trees produced greater annual cooling savings than east trees, which produced greater savings than south trees except in the South Coast zone, where morning fog reduces cooling benefits from east trees (Table 5). Savings from west trees were about 50–100% greater than savings from east trees. A similar pattern is observed for peak cooling savings, but the benefit from west trees is more pronounced. Annual cooling savings from trees located too far from homes to provide direct shade (climate only trees) is generally 25–50% of savings from west trees.

Table 5. Simulated annual energy saving effects of one existing tree (4.6 m crown diameter) at different locations around the base case residences. Climate only trees do not shade buildings (> 12.2 m)

Region	Annual Cooling Savings (kWh/tree)				Peak Cooling Savings (kWh/tree)				Annual Heating (MJ/tree)			
	South	East	West	Climate only	South	East	West	Climate only	South	East	West	Cimate only
North Coast	31	38	59	27	0.03	0.03	0.06	0.03	−469	−165	−230	151
Central Coast	16	22	38	22	0.02	0.02	0.04	0.03	−448	−101	−162	94
South Coast	18	15	23	16	0.03	0.02	0.04	0.03	−186	−59	−98	45
South Valleys	32	36	60	25	0.02	0.02	0.05	0.02	−273	−95	−48	22
Inland Empire	45	51	85	37	0.03	0.03	0.06	0.03	−252	−119	−81	32
North Ctr Valley	62	81	139	36	0.02	0.02	0.05	0.01	−474	−140	−205	60
Mid Ctr Valley	42	58	114	28	0.01	0.02	0.04	0.01	−520	−210	−210	52
South Ctr Valley	76	107	164	53	0.03	0.03	0.07	0.02	−344	−113	−220	41
High Desert	72	74	170	47	0.05	0.04	0.13	0.04	−501	−154	−239	63
Low Desert	66	94	112	48	0.08	0.09	0.16	0.07	−101	−49	−12	21
Mountains	4	5	7	4	0.02	0.02	0.03	0.02	13	−18	13	284

South, east, and west trees increase heating costs except in the Mountains zone, where south and west trees provide slight heating savings (13 MJ/tree, $ 0.07 US) (Table 5). The adverse effects of tree shade on heating is greatest for south trees. In most zones, shade from west trees increases heating costs more than shade from east trees. Trees located too far away to shade homes provide heating savings through reduced wind speeds and cold air infiltration.

The influence of climate on cooling and heating savings is considerable. Both annual and peak cooling energy savings are greatest in the Desert, Central Valley, and Inland Empire zones and least in the Coastal and South Valleys zones. The magnitude of cooling savings tends to increase with the amount of solar radiation, which trees obstruct, as well as CDD (Table 2). For this reason, climate effects are relatively more important in climate zones with the least solar radiation, such as the coastal zones. Shading effects are most important to cooling savings in the hot, arid desert zones.

The influence of climate on heating costs is coupled to air temperature and HDD, but solar radiation also plays a role. For example, heating impacts for climate only trees track HDD quite closely, with savings greatest in the Mountains and North Coast zones. The adverse impacts of shade on heating are greatest in zones with the most solar radiation, such as the Desert and Central Valley zones. However, it is important to note that the economic consequences of these adverse impacts is minor, with the maximum per tree cost only $ 2.69 US (520 MJ/ south tree in the Mid Central Valley).

Cost-effectiveness

PVBs per tree planted indicate the break-even cost for a shade tree program assuming wholesale energy prices. In this analysis PVBs include effects on annual heating and cooling, but not peak demand. PVBs per tree planted ranged from $ 5 in the Mountains to $ 146 in the South Central Valley (Fig. 4). Assuming program costs of $ 50/tree planted, potentially cost-effective programs are in the Inland Empire, Central Valley, and Desert zones.

The 50 million trees were estimated to reduce peak load demand by 39,974 MW over 15 years at a total cost of $ 2.5 billion assuming $ 50/tree. The cost of peak load reduction is $ 63/kW saved. Because this cost is considerably less than the $ 150/kW benchmark for cost-effectiveness, investment in a shade tree program could be a cost-effective peak load management measure in certain regions of California.

Discussion

Limitations and uncertainties

The standard errors of estimates presented with these results include only measurement errors, and are therefore underestimates. The effects of sampling and modeling errors are also important to consider. Sampling error reflects variability city-to-city and because the 21-city sample was not a simple random sample the error is impossible to quantify. Eliminating Atherton from the sample and applying tree location data from Pasadena to Los Angeles also introduces non-randomness and sampling errors.

Modeling error occurs when estimates of tree numbers are transformed from the 1990 tree count to expected numbers in 2000. The potential size of this error and its effect on bias and precision is unclear. Using average tree cover density to estimate tree numbers and empty planting sites is another source of modeling error. The impact of this error is probably small. If a density value higher than the one used here was selected, the result would be higher estimates of tree numbers. However, this increase would be offset because each tree would be smaller and cooling savings per tree would be less. Also, computer simulations contain modeling error because they rely on a limited set of weather data and building and tree types. Results presented here are sensitive to discount rates, energy prices, tree planting costs, building characteristics, tree
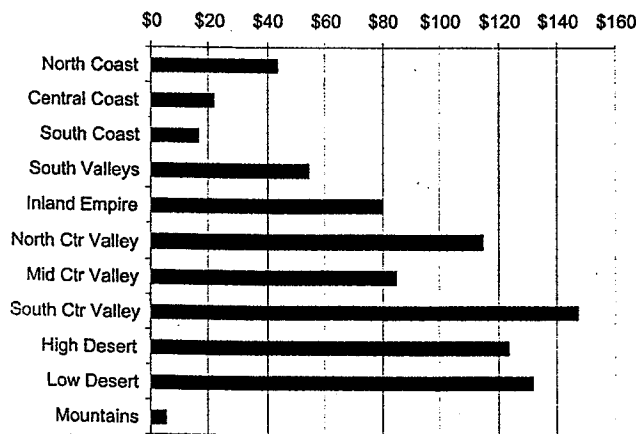

Fig. 4. Present value of benefits (PVBs) per tree planted (50 million trees) to shade east and west walls around single-family residences in each region. This calculation assumes a 5% nominal discount rate, 25% mortality for the 15-year planning horizon, and includes effects on annual heating and cooling, but not peak demand. If tree planting and stewardship costs were $ 50/tree, programs would be cost-effective in regions where PVBs are greater than $ 50.

mortality, and other factors that cause cost-effectiveness to increase or decrease. An analysis of how each of these factors influences the findings is beyond the scope of this study.

These findings indicate that there are approximately 177.3 million energy-conserving trees in California communities. This estimate is relatively close to the estimate of 148.6 million trees in urban areas of California derived from satellite data by Dwyer et al. (2000). Their estimate applies to communities with at least 2,500 people. Our estimate applies to all urban and rural communities. McPherson (1998) estimated that there were 6 trees/capita in Sacramento County, slightly more than the 5.2 trees/capita reported here. The Sacramento number includes all trees, whereas this study omits trees in agricultural, wildland, and abandoned areas.

Previous shade tree program impact evaluations found that findings are sensitive to tree growth and mortality rates (Hildebrandt & Sarkovich 1998). Our analysis assumed a single growth rate for all trees, where in fact growth will vary across climate zones, among species, and by location. SMUD's analysis of PVBs over a 30-year period assumed low and high mortality rates of 25% and 45%, respectively. This analysis assumed a 25% mortality rate over a 15-year period, a relatively high mortality rate. Lower mortality rates result in greater benefits, but may require increased investment in tree planting, care, education, and monitoring.

One limitation to conducting this type of study elsewhere may be availability of computer programs and expertise to simulate both tree shade and building energy performance. DOE 2 (Birdsall et al. 1994) and Micropas (McPherson et al. 1985; Enercomp 1992) are programs that integrate tree shading with building energy analysis. Both are complex and require considerable technical expertise to assign appropriate inputs and fully interpret results. Aerial photo analysis of tree cover follows standard procedures that are more easily replicated than computer simulations.

One drawback associated with tree planting is the delay between investment and realization of return on investment. Although simulated benefits from planting 50 million trees steadily accrued through the 15-year period (Table 4), the discounted payback period of 13 years is longer than most private sector investors like. To reduce the payback period planners could target climate zones where trees provide the greatest benefits, try to reduce planting costs, increase survival rates, and select rapid growing trees. However, institutional and governmental investors could regard tree planting as a long-term strategy to diversify their portfolio. In this case, the strategy might be to plant large-stature, long-lived trees that will provide benefits well beyond those simulated in this analysis.

Implications of findings

There are several ways that this information can be used to increase energy efficiency in California. First, strategically located shade trees should be planted with new home construction. The CEC and the state's homebuilders should adopt strategic shade tree planting as a mandatory energy conservation measure under Title-24 Energy Efficiency Standards for Residential Buildings. Second, where cost effective, California should implement shade tree programs that retrofit existing buildings with strategically located shade trees. Third, communities should rededicate themselves to increasing their street and park tree canopy cover. Reinvestment in California's green infrastructure is needed to reverse the disturbing decade-long trend of reduced tree program budgets, fewer trees being planted, and increased use of small-stature trees (Thompson & Ahern 2000).

Although these findings do not have direct application in locations outside California, several important relationships have relevance to planners everywhere. Energy savings from shade tree programs will be greatest in cooling dominated climate zones and least in heating dominated regions. In cooling dominated climates, a tree opposite the west-facing wall provides greatest net energy benefit. This benefit tends to be greatest in hot, arid climates, where trees effectively reduce irradiance and drybulb temperature during a relatively long cooling season. Net energy savings are less in more heavily populated coastal regions because temperatures are moderated and fog may reduce irradiance. In heating dominated climate zones it is important to optimize wind speed reductions during winter by placing evergreen trees between the building and prevailing wind. Locating trees for summer shade is less important than ensuring that trees do not obstruct winter irradiance from the south. Shading buildings during the cooling season can be an issue when building envelopes contain large amounts of glass that result in overheating or buildings to have air conditioning.

Summary and conclusions

California's urban forests are often taken for granted, but they are quietly working full-time to make cities more livable. Approximately 177.3 million trees in energy conserving locations shelter buildings and moderate urban climates. As a result, utilities save $ 485.8 million annually in wholesale electricity purchases and generation costs (6,408 GWh, $ 3/tree), while ratepayers save about twice this much in retail expenditures for air conditioning. Annual cooling reductions are equivalent to power produced by 7.3 100 MW plants,

enough power for 730,000 homes. These same trees reduce the summer peak demand by 10% (5,190 MW) and provide a host of other benefits that make them an invaluable component of every community's green infrastructure.

Only 42% of all tree sites in California cities are filled and planting 50 million trees in residential sites to shade east and west walls would fill 21% of all vacant sites. After 15 years their total cooling savings (46,981 GWh, $ 3.6 billion, $ 71/tree planted) would offset 60% of increased electricity consumption associated with California's 8 million new residents. These trees would reduce peak loads by 4.5% (39,974 MW). The present value of peak load reduction is $ 7.6 billion or $ 63/kW, substantially less than the $ 150/kW benchmark for cost-effectiveness. Shade tree programs are cost-effective peak load reduction measures in many parts of California.

Strategically locating trees to shade west walls/windows in climate zones where PVBs are highest will increase net benefits. Although shade trees do not curtail peak loads immediately, they do promise reductions that will increase as trees grow larger. Planting trees now for future peak load reduction, annual cooling savings, improved air quality, and climate change mitigation is a sensible way to soften the impact that California's growing population will have on limited energy resources and quality of life.

References

Akbari H, Bretz SE, Kurn DM & Hanford JW (1997) Peak power and cooling energy savings of shade trees. Energy and Buildings 25: 139–148

Akbari H, Davis S, Dorsano S, Huang J & Winnett S (1992) Cooling our communities: A guidebook on tree planting and light-colored surfacing. US Environmental Protection Agency, Washington, DC

Akbari H, Rosenfeld AH & Taha H (1990) Summer heat islands, urban trees, and white surfaces. ASHRAE Transactions 96, Pt.1: 1381–1388

Bernhardt E & Swiecki TJ (1993) The state of urban forestry in California: results of the 1992 California urban forest survey. California Department of Forestry and Fire Protection, Sacramento

Berthelsen C & Winokur S (2001) Soaring electric use more fiction than fact. San Francisco Chronicle: Sunday, March 11, p 1

Birdsall BE, Buhl WF, Ellington KL, Erdem AE, Winkelmann FC, Hirsch JJ & Gates S (1994) DOE-2 Basics Version 2.1E, Lawrence Berkeley Laboratory, Berkeley, CA

California Department of Finance (1998) County population projections with age, sex, and racial/ethnic detail. Department of Finance, Sacramento

California Department of Finance (2000) City/county population and housing estimates, January 1, 2000. California Department of Finance, Sacramento, CA

California Energy Commission (1995) California climate zone descriptions for new buildings. California Energy Commission, Sacramento, CA

California Energy Commission (2000a) California energy demand 2000–2010. California Energy Commission, Sacramento

California Energy Commission (2000b) Natural gas analysis and model development unit. California Energy Commission, Sacramento, CA

Dwyer JF, Nowak DJ, Noble MH & Sisinni SM (2000) Connecting people with ecosystems in the 21st Century: An assessment of nation's urban forests. USDA Forest Service, Pacific Northwest Research Station, Portland, OR

Enercomp (1992) Micropas4 user manual. Enercomp, Inc. Sacramento, CA

Heisler GM (1986) Energy savings with trees. Journal of Arboriculture 12: 113–125

Hildebrandt EW & Sarkovich M (1998) Assessing the cost-effectiveness of SMUD's shade tree program. Atmospheric Environment 32: 85–94

Huang YJ, Akbari H, Taha H & Rosenfeld AH (1987) The potential of vegetation in reducing summer cooling loads in residential buildings. Journal of Climate and Applied Meteorology 26: 1103–1116

Mallette EE, Miller KA, Miwa J & Eckstrom R (1983) California climate zone descriptions for new residential construction in climate zones 1 through 16. California Energy Commission, Sacramento

McPherson EG (1984) Solar control planting design. pp. 141–164. In: Energy-conserving site design (Ed. EG McPherson): 141–164. American Society of Landscape Architects, Washington D.C.

McPherson EG (1998) Structure and sustainability of Sacramento's urban forest. Journal of Arboriculture 24: 174–190

McPherson EG, Brown R & Rowntree RA (1985) Simulating tree shadow patterns for building energy analysis. pp. 378–382. In: Solar 85 – Proceedings of the National Passive Solar Conference (Ed. AT Wilson & W Glennie): 378–382. American Solar Energy Society, Boulder, CO

McPherson EG & Sacamano PL (1992) Energy savings with trees in southern California. USDA Forest Service, Northeastern Forest Experiment Station, Chicago, IL

McPherson EG, Sacamano PL & Wensman S (1993) Modeling benefits and costs of community tree plantings. USDA Forest Service, Pacific Southwest Research Station, Davis, CA

McPherson EG & Simpson JR (1999) Carbon dioxide reductions through urban forestry: Guidelines for professional and volunteer tree planters. General Technical Report 171.

USDA Forest Service, Pacific Southwest Research Station, Albany, CA

McPherson EG & Simpson JR (2001) Effects of California's urban forests on energy use and potential savings from large-scale tree planting. Center for Urban Forest Research, Davis, CA

McPherson EG, Simpson JR, Peper PJ & Xiao Q (1999) Tree guidelines for San Joaquin Valley communities. Local Government Commission, Sacramento, CA

McPherson EG, Simpson JR, Peper PJ, Scott KI & Xiao Q (2000) Tree guidelines for coastal southern California communities. Local Government Commission, Sacramento, CA

McPherson EG, Simpson JR, Peper PJ, Xiao Q, Pittenger DR & Hodel DR (2001) Tree guidelines for inland empire communities. Local Government Commission, Sacramento, CA

Meier AK (1991) Strategic landscaping and air-conditioning savings: a literature review. Energy and Buildings 15–16: 479–486

Miller RH & Miller RW (1991) Planting survival of selected street tree taxa. Journal of Arboriculture 17: 185–191

Peper PJ, McPherson EG & Mori SM (2001a) Equations for predicting diameter, height, crown width and leaf area of San Joaquin Valley street trees. Journal of Arboriculture 27: 306–317

Peper PJ, McPherson EG & Mori SM (2001b) Predictive equations for dimensions and leaf area of coastal Southern California street trees. Journal of Arboriculture 27: 169–180

Simpson JR (1998) Urban forest impacts on regional space conditioning energy use: Sacramento County case study. Journal of Arboriculture 24: 201–214

Simpson JR & McPherson EG (1996) Potential of tree shade for reducing residential energy use in California. Journal of Arboriculture 22: 10–18

Simpson JR, McPherson GE & Rowntree RA (1994) Potential of tree shade for reducing building energy use in the Pacific Gas & Electric service area, final report to Energy Efficiency Services. Pacific Gas & Electric, San Rafael

Thompson RP & Ahern JJ (2000) The state of urban and community forestry in California. Urban Forest Ecosystem Institute, San Luis Obispo, CA

US Census Bureau (1996) Land area, population, and density for places in California. U.S. Census Bureau, Washington, DC

USDA Forest Service (1997) Urban forest canopy cover in California: Analysis of 21 cities and towns. California Department of Forestry and Fire Protection, Riverside, CA

US Energy Information Administration (1993a) Household energy consumption and expenditure tables. US Department of Energy/Energy Informaiton Administration, Washington, DC

US Energy Information Administration (1993b) Household energy consumption and expenditures 1990, Supplement: Regional. US Department of Energy, Energy Information Administration, Washington, DC