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The value of shade: Estimating the effect of urban trees on summertime electricity use

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ABSTRACT

We estimated the effect of shade trees on the summertime electricity use of 460 single-family homes in Sacramento, California. Results show that trees on the west and south sides of a house reduce summertime electricity use, whereas trees on the north side of a house increase summertime electricity use. The current level of tree cover on the west and south sides of houses in our sample reduced summertime electricity use by 185 kWh (5.2%), whereas north-side trees increased electricity use by 55 kWh (1.5%). Results also show that a London plane tree, planted on the west side of a house, can reduce carbon emissions from summertime electricity use by an average of 31% over 100 years.

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1. Introduction

Concern about carbon emissions and associated climate change, along with rising fuel costs, have made energy conservation a pressing public policy issue. Increased planting of urban shade trees has been suggested as one way of conserving energy by reducing the demand for heating and cooling [1–3].[2] Indeed, some utility companies offer customers free or reduced-cost trees [4]. However, no studies of utility billing data have shown that trees reduce energy consumption.

Previous studies that have looked at the effect of shade trees on energy use fall into two categories: (1) small-scale controlled experiments that examined the effect of trees on an individual house and (2) large-scale simulation modeling. Akbari et al. [1] quantified the effect of shade trees on the cooling costs of two similar houses in Sacramento, California. Sixteen trees in pots (eight were 6 m tall, and eight were 2.4 m tall) were placed along the exterior south and west walls. Inside, occupants kept windows closed, thermostats at the same temperature, and used lighting in a similar manner. Results showed that the trees reduced seasonal cooling costs by between 26% and 47%. Finally, Akbari et al. modeled the effect of the trees on both houses using the DOE-2.1E[3] simulation program. They concluded that the model underestimated the energy savings of the trees by as much as twofold. Akbari and Taha [5] used simulation modeling to study the effect of trees on energy use in four Canadian cities. They concluded that increasing the vegetative cover of a neighborhood by 30% and increasing the albedo of houses by 20% would decrease heating costs by 10–20% and decrease cooling costs 30–100%. Simpson and McPherson [3] used simulation modeling to evaluate the effect of trees on residential energy use in California. They found that trees shading the west side of houses had the biggest effect on cooling costs and that adding three shade trees to a house (two on the west side and one on the east side) reduced annual cooling costs by 10–50%. Akbari et al. [2] used simulation modeling to estimate the potential of urban trees to reduce cooling costs. They noted that peak urban electric demand rises 2–4% for every 1 °C increase in daily maximum temperature (above a threshold of 15–20 °C), and that urban areas are typically 0.5–3 °C warmer than surrounding rural ones. McPherson and Simpson [4] used simulation modeling and aerial photography to estimate the energy savings of existing urban trees and new plantings in California. Results suggest that existing trees reduce peak energy load by 10% resulting in annual savings of $779 million. McPherson and Simpson estimated that planting an additional 50 million trees on the east and west sides of houses would further reduce peak load by an average of 4.5% over

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[2] The U.S. Department of Energy estimates that heating and cooling account for 56% of energy use in a typical home. http://www.eere.energy.gov/consumer/your_home/space_heating_cooling/index.cfm/mytopic=12300.

[3] The DOE-2.1E model is used to calculate the energy use of buildings. Details on an updated version of the model, DOE-2.2, are available at http://www.doe2.com.

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the next 15 years, which would result in total savings for consumers of $3.6 billion or $71 per tree.

As Akbari et al. [2] noted, few studies have measured the energy savings of urban trees, and those that have did not use actual electricity billing data. The purpose of this study is to close this gap in the literature. Our research makes the following contributions: (1) demonstrates, through a large-scale empirical analysis, that properly positioned shade trees can reduce summertime electricity use; (2) shows that when the wholesale price of electricity varies by time of day, but the retail price does not, utilities and consumers derive different benefits from shade trees; and (3) quantifies the effect of trees on carbon emissions due to decreased electricity use and from direct sequestration.

2. Study area and data

Sacramento is located in California's central valley near the confluence of the Sacramento and American Rivers. It is the seventh largest city in California, with an estimated population of 475 743 in 2008.[4] Sacramento has a Mediterranean climate: mild winters and hot, dry summers. The mean high temperature in December/January is 12 °C and 34 °C in July. On average, Sacramento has 73 days a year over 32 °C. We focused our analysis on the Southland Park area of Sacramento (ZIP code 95822), because tree cover differs widely within this neighborhood.

Previous studies suggest that house size, heating and cooling systems, construction materials and methods, occupancy patterns, and trees can influence energy use. We obtained data on house size, lot size, house age, presence of a pool, and heating and cooling systems from Sacramento County assessor's office. Sacramento Municipal Utility District (SMUD) provided electricity billing data, and the City of Sacramento provided water use data. We obtained water use data, because we hypothesized that wintertime water use might be a good proxy for occupancy patterns, which is an important determinant of electricity use. Our sample was limited to the 460 houses in the 95822 ZIP code that had metered water.[5]

Using aerial photography, we collected data on the crown size of trees near each of the 460 houses in our sample. The shade a tree provides depends upon three factors: (1) crown area, (2) distance from a house, and (3) aspect relative to a house (north, east, etc.). Therefore, we measured the crown area of trees in 12 buffers around each house (Fig. 1). If a tree's crown spread over more than one buffer, we attributed the tree's entire crown to the buffer in which its stem was located. For example, in Fig. 1, the crown of the darker green tree would only be included in the N-1 buffer.

3. Methods

We regressed summertime (15 May–15 September) electricity use (E^s) against wintertime electricity (E^w) use, a vector of tree variables (**T**), and a vector of housing characteristics (**X**). The β's denote coefficients to be estimated in the regression step, and e is the normally distributed error term.

$$E_i^s = \beta_0 + \beta_1 E_i^w + \boldsymbol{\beta_T T_i} + \boldsymbol{\beta_X X_i} + e_i \quad (1)$$

Wintertime electricity use was included in the regression to capture variables that influence non-summer electricity use, as was wintertime water use. In particular, wintertime electricity use may capture the effect of house age, which may be correlated with tree cover: newer homes typically have less mature landscaping but are more energy efficient because of improved construction techniques and changes in the building code.[6] Housing characteristics included house size, lot size, garage size, presence of a pool and pool size, number of bathrooms and bedrooms, and the presence of air conditioning.

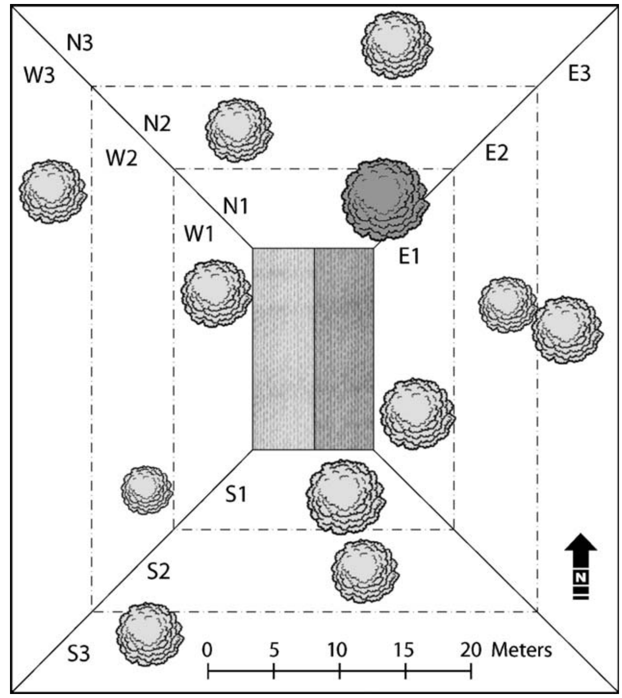

Fig. 1. Average tree cover for each of the 12 buffers.

Tree variables included combinations of the crown area in each buffer. For example, the three tree variables created for the north quadrant were the crown area falling within 6.1 m (20 ft) of the house (N-1), the crown area falling within 12.2 m (40 ft) of the house (N-1,2), and finally, the crown area falling within 18.3 m (60 ft) of the house (N-1,2,3).

4. Results

Table 1 provides summary statistics for all tree variables and other independent variables and shows that there is significant variation among the 460 houses in the sample. We found that shade trees significantly affected summertime electricity use, but that the magnitude of the effect depended on the tree's location. Because properly placed shade trees reduce electricity use, our results demonstrated that shade trees reduce carbon emissions from electricity generation. In addition, we found that shade trees benefited SMUD, but in a different manner than consumers, because of differences in the retail and wholesale pricing of electricity.

4.1. Consumer perspective

Table 2 shows the results of regressing summertime electricity use on wintertime energy use, house and lot characteristics, and tree-cover variables. A forward stepwise procedure was used for model selection: variables with p-values greater than 0.2 were excluded. Model coefficients were estimated using ordinary least squares.

[4] California Department of Finance.

[5] The City of Sacramento is in the process of metering all residential and commercial water users to comply with a mandate from the State of California to bill all water customers based on use by 2025.

[6] Although, on aggregate, wintertime electricity use may be a good indicator of summertime electricity use, for a particular house the relationship will depend on a number of factors including the type of heating used.

Table 1
Descriptive statistics for selected independent variables.

Variable[a]	Mean[b]	Minimum	Maximum
House area (square meters)	184	74	392
Lot area (square meters)	803	256	6274
Garage area (square meters)	41/43	0	90
Pool area (square meters)	7/37	0	67
Number of bedrooms	3.4	1	6
Number of bathrooms	2.2	1	5
Heating system (%)	99	n/a	n/a
Cooling system (%)	93	n/a	n/a
House age (years)	30	1	80
Summer power use (kWh)	3574	105	18,745
N-1 (square meters)	35/62	0	1104
N-2 (square meters)	21/58	0	370
N-3 (square meters)	23/70	0	543
S-1 (square meters)	30/52	0	404
S-2 (square meters)	20/53	0	463
S-3 (square meters)	22/65	0	342
W-1 (square meters)	24/51	0	327
W-2 (square meters)	12/45	0	401
W-3 (square meters)	22/68	0	408
E-1 (square meters)	27/53	0	389
E-2 (square meters)	17/52	0	322
E-3 (square meters)	23/68	0	493

[a] See Figure 1 for location of the 12 crown area variables.
[b] Where two values appear in a cell, the first is for all houses, and the second is for only those houses that have the attribute in question. For example, the average garage size for the sample is 41 m^2. However, if we exclude houses without a garage, then the average garage size is 43 m^2.

Table 2
Summertime energy use (kWh) regression results.

Variable	Coefficient	S.E.	*p*-Value
Intercept	−84.4	313	0.788
March	3.86	0.160	0.000
Pool	369	167	0.028
Cooling	550	239	0.022
House area	1.90	1.31	0.151
Lot area	0.223	0.161	0.166
W-1,2,3	−1.71	0.779	0.029
S-1,2	−1.68	0.848	0.049
N-1	1.59	0.762	0.038
R-Squared	0.656		

S.E. = standard error.

Of all the winter months, we found that electricity use from 15 February to 15 March had the greatest explanatory power on summertime demand (SMUD uses a mid-month billing cycle; for convenience, we call this period March in Table 2). As one would expect, March electricity use was positively correlated with summertime electricity use. Not surprisingly, air conditioning and the presence of a pool also increased summertime electricity use. Increases in house and lot area increased summertime electricity use, but the significances of these two variables were marginal, probably because March electricity use captured much of the effect of house and lot size.

Table 2 also shows that tree cover affected electricity use. However, the magnitude and direction of the effect depends upon the relative position of the trees. In the west quadrant, tree cover in all three buffers reduced electricity use, whereas in the south quadrant only trees in the S-1 and S-2 affected electricity use. Tree cover in the east quadrant has no effect, and tree cover in the north-quadrant N-1 buffer increased electricity use.

To help explain these results, Fig. 2 shows the length and angle of shadows cast by a 9.1-m (30-ft) tree at different times of day in Sacramento on 15 July 2007 (the midpoint of the study period), as well as mean air temperature, color-coded by hour, for the period 15 May–15 September 2007.[7] Fig. 2 demonstrates that east-quadrant trees cast house-shading shadows during the cool morning hours, when most people would not require air conditioning. It is not surprising, then, that we found east-quadrant tree cover had no effect on summertime electricity use. By the time average air temperature climbs into the 20 s (°C), shadows are shortening and turning to the north, which is consistent with our result that south-quadrant trees reduce electricity use, but only those trees within 12.2 m of the house. By the time shadows point to the east, they are lengthening and temperatures are peaking, which explains why trees in all three west-quadrant buffers reduce electricity use. In addition, this is the time of day when many people return home and turn on their air conditioners. Finally, Fig. 2 shows that north-quadrant trees do not cast house-shading shadows. Therefore, it is not surprising that they do not reduce summertime electricity use. However, our results found that not only do north-quadrant trees fail to provide energy savings, but also that those in the 6.1 m buffer were correlated with increased summertime electricity use. Perhaps trees close to a house reduce the cooling effect of wind, slow the release of heat at night, or cause more lighting to be used in the house. This may be true of trees in all four quadrants, but in the east quadrant the positive and negative effects of trees on energy use cancel out, and in the south and west quadrants the energy saving effects of trees predominate.

To validate the summertime model, we estimated the effect of trees on wintertime (15 November through 15 December) electricity use. We found that summertime results did not persist into the winter, which is consistent with previous studies (results not shown).[8] If they had, this would raise concern that we were not capturing the effect of trees on electricity use, but rather we were seeing the effect of an omitted collinear variable.

Setting the tree cover variables at their means (see Table 1), we calculated how much mean tree cover reduces summertime electricity use. Combined, west-quadrant and south-quadrant trees reduce summertime electricity use by 185 kWh (5.2%), whereas north-quadrant trees increase summertime electricity by 55 kWh (1.5%). Fig. 1, which is to scale, shows what the average amount of tree cover would look like for a 139 m^2 (1500 ft^2) single-story house.

Residential customers in Sacramento face a three-tiered pricing tariff[9]: (1) 9.2 cents per kWh for the first 700 kWh in a billing period, (2) 15.7 cents per kWh for 701 to 1000 kWh, (3) 17.6 cents per kWh for 1001+ kWh. In our sample, the mean price was 11.7 cents per kWh, and the mean price at the margin was 13.6 cents per kWh. In addition, the City of Sacramento levies a 7% tax on electricity use. Therefore, west-quadrant and south-quadrant tree cover combined reduced summertime electricity bills by an average of $25.16, and north-quadrant tree cover increased bills by an average of $7.48.

4.2. Compatibility with previous studies

To provide some context for our results, we compared them to two previous studies of the effects of shade trees on electricity use in California: one that used simulation modeling ([3]) and one that used an experimental approach ([1]).

[7] We used average temperatures from 15 May to 15 September rather than just 15 July, because 1 day's temperature might not well represent typical daily temperature variation.

[8] Beyond validating the summertime model, the wintertime model is of limited interest because the majority of houses in Sacramento are heated with natural gas (we were unable to get natural gas billing records), whereas air-conditioning is almost exclusively electric.

[9] Prices are lower in the winter but are based on the same three tiers. Prices were current in August 2008.

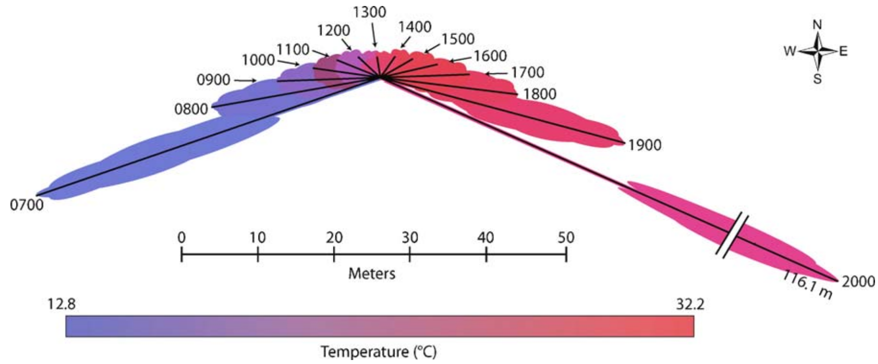

Fig. 2. Average hourly temperatures (15 May to 15 September 2007) and the length and direction of shadows cast by a 9.1-m (30-ft) tree on July 15th, 2007, in Sacramento, California.

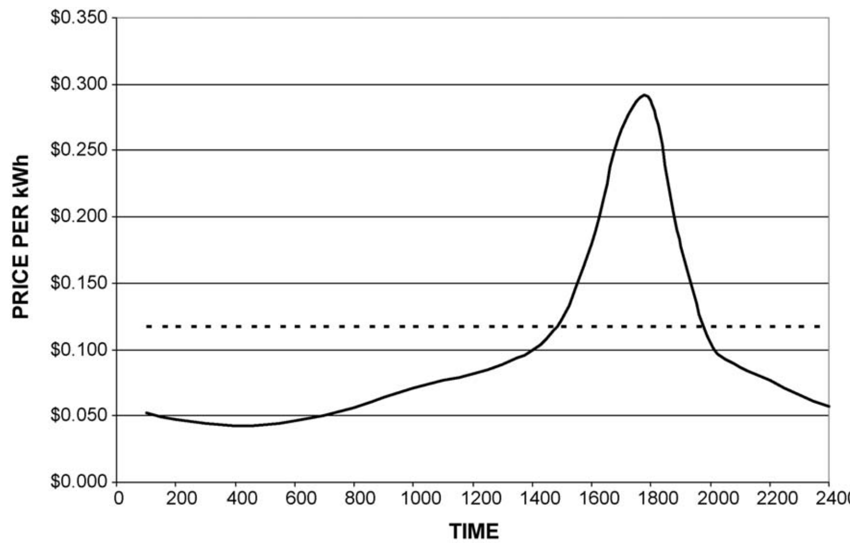

Fig. 3. The average electricity price paid by residential customers (dotted line) in our sample and the average price paid by SMUD (solid line) to purchase electricity by hour for the period 15 May to 15 September 2007, 2007.

Simpson and McPherson estimated that a tree with a 7.3-m (24-ft) diameter crown on the west side of a house would reduce annual electricity use by 180 kWh. Our results suggest that the same tree would reduce summertime electricity use by 82 kWh. This result is fairly consistent with our study especially given the different time horizons (12 months versus 4 months).

Akbari et al. placed 16 trees (eight were 6 m tall and eight were 2.4 m tall) on the west and south walls of two houses in Sacramento. They found that the trees reduced summertime electricity use of the two houses by 439 and 586 kWh. The authors did not provide information on the size of the trees' crowns. However, if we assume that tree height and crown diameter are equal (an assumption used by Simpson and McPherson), then our results suggest that the same-sized trees would reduce summertime electricity use by 457 kWh. The consistency of our findings, which were based on a statistical approach, with past experimental and modeling studies strengthens the evidence that shade trees reduce summertime electricity use.

4.3. Utility perspective

Residential customers in Sacramento face a tiered electricity pricing system, but it is based on total usage, and not on time of day. By contrast, the wholesale price of electricity varies widely depending on the time of day (Fig. 3). Fig. 3 shows that the wholesale price of electricity varies between 4.3 cents per kWh at 4 a.m. and 28.8 cents per kWh at 6 p.m. Between approximately 3 p.m. and 7 p.m., SMUD sells electricity at a per-unit loss. For reference, in 2007, 25% of all the electricity sold by SMUD was supplied between 3 p.m. and 7 p.m.

For each week of the study period, we calculated the time the sun was in the west quadrant (225–315°, see Fig. 2) and the south quadrant (135–225°). We then calculated the average wholesale electricity price for these hours[10]: 10.2 cents per kWh for hours with south-quadrant shading and 19.1 cents for hours with west-quadrant shading. Therefore, for every kWh conserved by south-quadrant trees, SMUD loses 1.5 cents, whereas each kWh conserved by west-quadrant trees saves SMUD 7.4 cents.

To illustrate how trees affect the demand faced by SMUD, Fig. 4 shows how the average tree cover for our sample affects hourly demand for electricity. Data on the hourly variation in demand were provided by SMUD; we used a total daily demand of 31.4 kWh (the average for our sample); we assumed that trees only had an effect when the sun was in the south or west quadrants[11]; we used sun angles from 15 July 2007.

[10] For each hour, we weighted the price depending on how long the sun was in the west or south quadrant.

[11] We did not include the effect of north-quadrant trees in Fig. 4, as we had no reasonable way of ascribing their effect to a particular time of day.

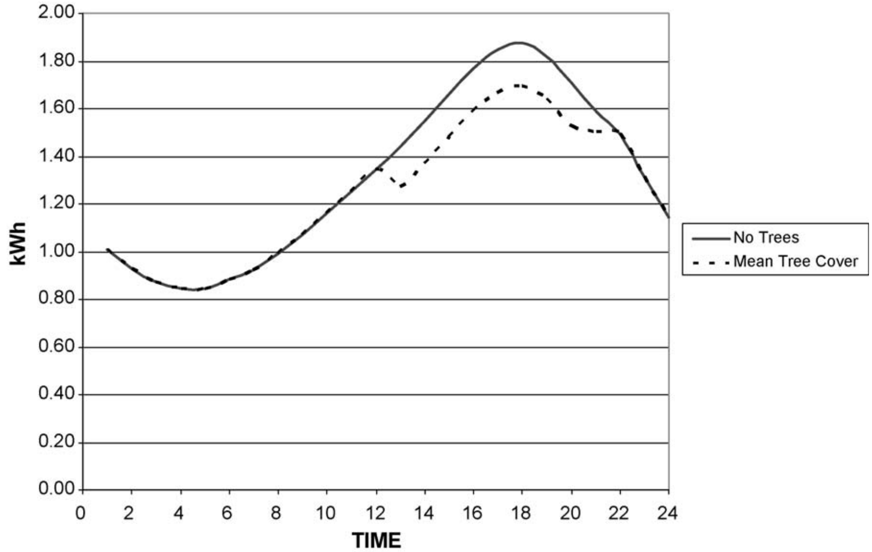

Fig. 4. Hourly demand for electricity for the average house in our sample without trees and with the average amount of tree cover in the south and west quadrants. Sun angles from 15 July 2007, were used to calculate the hourly reductions in demand.

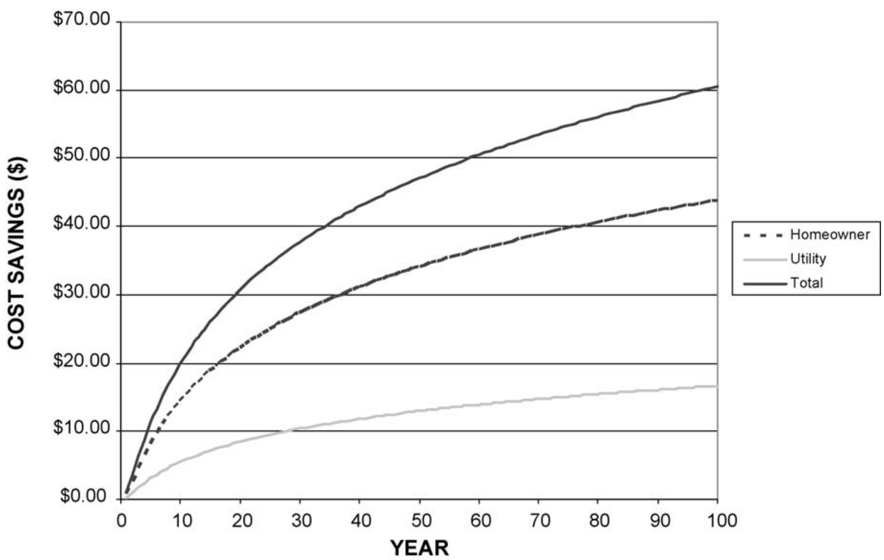

Fig. 5. Total annual benefits, benefits to the homeowner, and benefits to the utility of a west-quadrant London plane tree planted in year zero, in nominal dollars.

4.4. Planting shade trees

Our results so far have been for existing tree cover. However, we can also explore the benefits of planting new trees. Fig. 5 shows the total annual benefits of a west-quadrant London plane tree,[12] the benefits to the homeowner, and the benefits to the utility in nominal dollars. Tree growth was simulated using an established model of urban tree growth [6]. Table 3 provides the net present value of the west-quadrant London plane tree from the perspective of the homeowner and the utility for three time horizons (20, 50, 100 years).

In 2007, SMUD provided customers with approximately 16,000 trees at a cost of $1.4 million ($85 per tree). Our results show that SMUD would recoup this investment in 26 years, provided the tree was planted on the west side of a house (assuming a 4% discount rate). In fact, SMUD offers shade trees for all homes with an eastern, western, or southern exposure.[13]

Even if customers receive a tree at no cost, trees require maintenance. Maintenance costs vary widely, and we could find no widely agreed on figures. One expert suggested a range of $2–20 per year, which includes pruning, watering, and leaf removal.[14] Over a 50-year time horizon, annualized consumer energy-reduction benefits are $15.50 (4% discount rate). Therefore, in most cases, the consumer energy benefits of a west- or south-quadrant tree outweigh its maintenance costs. Furthermore, urban trees have been shown to have a range of benefits beyond energy conservation [7,8].

4.5. Carbon footprint

As well as financial savings, shade trees can reduce a home's carbon footprint in two ways. First, tree growth directly sequesters carbon. Second, energy savings from shade trees reduces carbon emissions from electricity generation. In California, generating

[12] The London Plane tree is the most common tree in Sacramento.
[13] http://www.smud.org/en/residential/trees/Pages/index.aspx.
[14] Greg McPherson (USDA Forest Service, PSW Research Station), personal communication 16 September 2008.

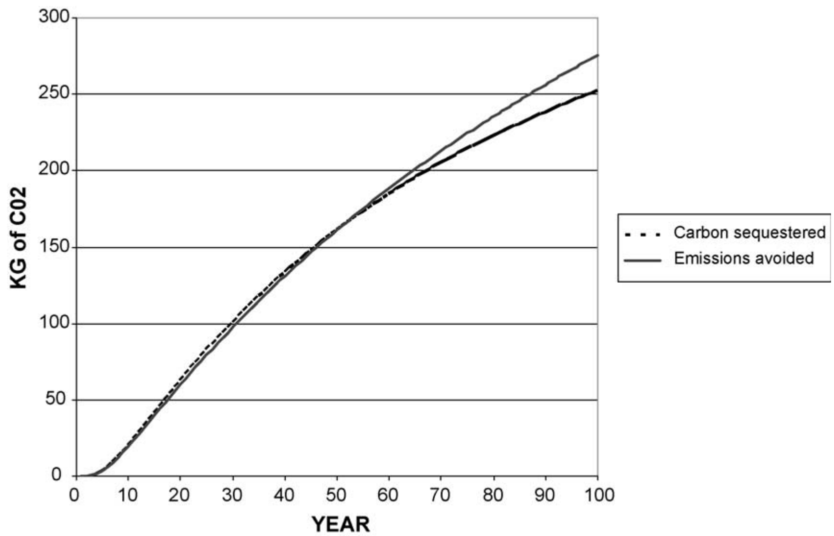

Fig. 6. Kilograms of carbon dioxide annually sequestered by a west-quadrant London plane tree and annual reductions in carbon dioxide emissions from energy conservation.

Table 3
Discounted benefits (4% discount rate) of west-quadrant shade trees to the consumer, to the utility, and total benefits for 20-, 50-, and 100-year time horizons.

Year	Consumer	Utility	Total
20	$167	$63	$230
50	$388	$147	$535
100	$503	$191	$694

1 kWh of electricity produces, on average, 0.274 kg of carbon dioxide.[15] Fig. 6 demonstrates that the amount of carbon dioxide a London plane tree directly sequesters throughout its lifetime is similar to the amount of carbon dioxide emissions that are avoided through energy conservation (this result may not hold for other species of trees or other locations). Over 100 years, these two effects reduce net carbon dioxide emissions by 29.8 Mg. Average summertime electricity use for our sample is 3574 kWh. Generating this amount of electricity in California would produce on average 0.98 Mg of carbon dioxide annually. Therefore, a west-quadrant London plane tree would, over 100 years, reduce the net carbon emissions from summertime electricity use by 31%.[16]

5. Discussion

The assertion that shade trees can reduce energy consumption is intuitively appealing and has been supported by modeling and experimental studies. However, ours is the first study that has analyzed electricity billing data. Results show that tree cover on the west and south sides of a house reduce summertime electricity use, whereas trees on the north side of a house increase summertime electricity use.

Our results support the use of shade trees to reduce electricity use, but they also demonstrate that the location of the trees is important. Furthermore, because residential electricity customers in Sacramento, and most of the country, do not face time of day pricing, optimal tree placement is different for homeowners and utilities. A tree within 12.2 m (40 ft) of the south side of a house and the same tree within 18.3 m (60 ft) of the west side of a house generate approximately the same benefits for the homeowner. By contrast, only west-quadrant trees generate cost savings for the utility. It may, however, be difficult for a utility to only subsidize trees planted on the west side of a house.

Trees can also provide significant carbon benefits both directly (sequestration by the growing tree) and indirectly (reductions in carbon emissions from electricity conservation). Because homeowners experience virtually none of the carbon benefits of tree planting, a subsidy to encourage tree planting may be warranted. Indeed, many of the benefits of urban trees have been shown to spill over to others in the community. Donovan and Butry[17] showed that urban street trees can increase the property value of houses within 100 feet. McPherson et al. showed that trees can reduce storm water runoff [8]. Several studies have shown that trees can increase physical and mental well-being [9,10]. Therefore, it may be appropriate to view urban trees as community assets (whether on private or public land) and to provide incentives for their provision accordingly.

Despite the benefits of urban trees, many homeowners face space constraints, and they are either unable to plant trees or are at least unable to do so in the optimal locations. This is especially true in a community such as Sacramento with high land prices. Many of the houses in our sample were as little as 2 m from the neighboring house. If such a house is aligned north–south, then planting trees to the west of the house may not be possible. Setting aside space for shade trees is something that should be considered when planning residential development, not simply something that is done as an afterthought.

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[16] If the tree subsequently died, and the carbon stored in the tree were released (by burning or decay, for example), then the carbon benefits of the tree would be reduced. However, the fraction of these benefits attributable to energy conservation would not be lost if the tree released some or all of its stored carbon.

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