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Research paper

Long-term monitoring of Sacramento Shade program trees: Tree survival, growth and energy-saving performance

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HIGHLIGHTS

- We assessed tree survivorship, growth, and energy performance over 22 years.
- Survivorship was 42.4%, substantially lower than the initial projection.
- Annual cooling saving per property and per tree were 23% and 52% of the initial projection.
- Lower survivorship was the major factor affecting lower cooling savings.
- Planting medium stature trees and rapidly growing large trees achieve the greatest long-term energy savings.

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ABSTRACT

Long-term survival and growth of urban forests are critical to achieve the targeted benefits of urban tree planting programs, such as building energy savings from tree shade. However, little is known about how trees perform in the long-term, especially in residential areas. Given this gap in the literature, we monitored 22-years of post-planting survival, growth, and energy saving performance of shade trees in Sacramento, California. Using field surveys, aerial photo interpretation and survival analysis, we calculated cumulative survivorship and compared measured with projected tree growth. Using Shadow Pattern Simulator and Micropas (building energy simulation), combined with survival and growth observations, we modeled the current energy savings produced by the program trees and then compared this result with initial projections from the early years of the program. The 22-year post planting survivorship was 42.4%, considerably less than the initial projection. On average, measured growth rates were within expected ranges to provide shading benefits; 22-year old trees reached 74.6% and 68.8% of the projected 30-year mature size for tree heights and crown diameters, respectively. Annual energy savings were 107 kW h per property and 80 kW h per tree, which were 23% and 52% of the initial projection, respectively. Lower survivorship was the primary factor influencing lower cooling savings. Medium-sized trees had higher survivorship and growth attainment compared to other trees. This study contributes to more accurate quantification of urban greening performance, helping urban forest managers make data-driven decisions.

1. Introduction

Urban tree planting has received increasing attention over the past few decades, fueled by numerous studies that quantified and monetized the benefits of urban trees (McPherson et al., 1997; McPherson, Simpson, Xiao, & Wu, 2011; McPherson, Simpson, Peper, Maco, & Xiao, 2005; Roy, Byrne, & Pickering, 2012). These benefits encompass environmental, social, and economic aspects, including improving air quality (Brack, 2002; Morani, Nowak, Hirabayashi, & Calfapietra, 2011; Nowak, Crane, & Stevens, 2006; Scott, Simpson, & McPherson, 1998; Rowntree & Nowak, 1991; Scott, Simpson, & McPherson, 1999), improving water quality, reducing surface stormwater runoff (Bartens, Day, Harris, Dove, & Wynn, 2008; Xiao, McPherson, Simpson, & Ustin, 1998), mitigating the urban heat island (Armson, Stringer, & Ennos, 2012; McPherson, 1994; McPherson & Muchnick, 2005), reducing energy consumption (Akbari, 2002; Donovan & Butry, 2009; Huang, Akbari, Taha, & Rosenfeld, 1987; Ko, 2013; Ko & Radke, 2014; McPherson

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& Rowntree, 1993; McPherson & Simpson, 2003; Pandit & Laband, 2010a,b; Sawka, Millward, Mckay, & Sarkovich, 2013; Simpson & McPherson, 1998), sequestering carbon (Nowak & Crane, 2002), increasing property value (Anderson & Cordell, 1988; Sander, Polasky, & Haight, 2010; Tyrväinen, 1997), enhancing thermal comfort (Shashua-Bar & Hoffman, 2000; Shashua-Bar, Pearlmutter, & Erell, 2011), and improving mental and physical well-being (Donovan et al., 2013; Gidlöf-Gunnarsson & Öhrström, 2007; Maas, Van Dillen, Verheij, & Groenewegen, 2009; Schroeder & Anderson, 1984; Van den Berg, Maas, Verheij, & Groenewegen, 2010). Cities and metropolitan regions including Los Angeles, CA; Sacramento, CA; Denver, CO; New York City, NY; and Philadelphia, PA have initiated tree planting campaigns with ambitious goals for "planting one million trees" to capitalize on the reported benefits of urban forests and associated monetary values (Young & McPherson, 2013). Many of these claimed ecosystem services are derived from generalized models with numerous assumptions. There is need for locality-specific empirical evidence to more fully evaluate the performance of tree planting initiatives (Pataki et al., 2011; Setälä, Viippola, Rantalainen, Pennanen, & Yli-Pelkonen, 2013).

Tree survival, longevity and growth are major factors that can significantly affect the performance of urban forests, as well as projections of their population numbers and ecosystem services. For contemporary million tree campaigns, ecosystem services projections have been conducted for Los Angeles, CA with a 35–40 year time horizon (McPherson et al., 2011) and New York City, NY with a 100-year time horizon (Morani et al., 2011). Both studies concluded that long-term mortality is a major source of uncertainty in the models. For example, Morani et al. (2011) reported that doubling the annual mortality rate from 4 to 8% resulted in a 72.7% reduction in the total pollutant removal of newly planted trees through the MillionTreesNYC initiative. Indeed, since the massive urban planting campaigns are a relatively recent phenomena, performance data is only beginning to become available (McPherson, 2014). Urban-specific growth rates and allometric relationships are also important components of ecosystem services models that require new empirical evidence (McHale, Burke, Lefsky, Peper, & McPherson, 2009; Troxel, Piana, Ashton, & Murphy-Dunning, 2013). Given the importance of benefits projection to policy-makers and urban greening organizations, and the need for locality-specific performance data, our study re-visits early projections from a multi-decade tree planting initiative in Sacramento, CA. This program provides a compelling case study for the comparison of expected versus achieved benefits.

1.1. Sacramento Shade Tree Program

The Sacramento Shade Tree Program, referred to as Sacramento Shade, is the largest and the oldest utility-sponsored shade tree planting initiative in the United States that specifically targets plantings to reduce cooling energy use by buildings (Sarkovich, 2009). Begun in 1990 as a partnership between the Sacramento Tree Foundation (STF) and Sacramento Municipal Utility Districts (SMUD), the program has distributed 500,000 deciduous trees to homes, businesses, and public spaces for free throughout Sacramento County and a part of Placer County (SMUD, 2014). Residents are responsible for planting and maintenance of shade trees as advised by community foresters.

When the trees in our study were distributed, participating residents were required to attend a 40-min educational session about shade benefits, as well as tree planting and maintenance techniques. This was followed by a site visit to each residential property several weeks later, and residents then attended shade tree distribution events at a centralized neighborhood location after another several weeks (R. Tretheway and L. Leineke, pers. comm.). Notably, these operations differ from more recent program procedures, in which residents and community foresters primarily interact through a brief home visit followed by tree delivery directly to the property (Roman, Battles, & McBride, 2014); the educational workshops and neighborhood distribution events are no longer used.

1.2. Initial energy-saving simulations

In 1995, SMUD contracted with the USDA Forest Service to evaluate the cooling energy (kW h) and capacity (kW) provided by the Sacramento Shade Program. Computer simulations of tree shade and space conditioning energy use were completed for a random sample of 254 residential properties. The sample was found to be representative of the 20,123 Sacramento Shade participants for years 1991 to 1993. During site visits by SMUD staff, information on the species, sizes and locations of program trees was recorded. Diagrams of building footprints and tree locations were augmented with additional information on glazing, location of existing trees and adjacent buildings that shaded the target building (Hildebrandt and Sarkovich, 1998). The energy impacts of 787 trees planted at the 254 participating homes from 1991 to 1993 were analyzed using shade and building simulation models (Simpson & McPherson, 1998).

On average, 3.1 trees per property reduced annual cooling energy use by 153 kW h (7.1%) and peak demand by 0.08 kW (2.3%) per tree. Annual heating loads were projected to increase by 0.85 GJ (1.9%) per tree. Using 1998 energy rates ($0.10/kW h and $6.15/MMBtu), these energy impacts converted to $15.25 for annual cooling saving and $5.25 for annual heating penalty per tree. After deducting the heating penalty, the net annual energy savings was $10.00 per tree. Adjusting Simpson and McPherson's results (e.g., accounting for participants with no central air conditioning (AC) system and effects of shade trees on neighboring houses), Hildebrandt and Sarkovich (1998) calculated the average annual energy and demand savings and the monetary value of load impacts over 30 years. They assumed that 57.5% of the trees delivered were alive after 30 years (called "survivability" by the Sacramento Shade program; for survival terminology in the program, see Roman et al., 2014). The average annual energy and demand savings per tree was 106 kW h and 0.041 kW for homes with central AC system and 95 kW h and 0.038 kW for all homes, including those without central AC. The average annual value of cooling energy savings was $39 per tree. In their sensitivity analysis, they estimated that differences between rapid tree growth rates (achieving 100% of shade at maturity in 18 years) and slow growth rates (100% of shade at maturity in 24 years) resulted in energy savings that varied by ±8%. Differences between high and low survivability rates (72.5% vs. 57.5%) over 30 years resulted in energy savings that varied by ±9%. Roman et al. (2014)'s recent study of more recently planted Sacramento Shade trees reported that only 58.9% of delivered trees were alive after five years. Given these new findings, it is reasonable to expect that actual survival rates and cooling energy savings are less than projected by these early studies.

Our study helps fill the gap between early projections and actual results by measuring survival and growth rates for shade trees planted 22 years ago. These rates, as well as simulated energy effects of program trees, are compared with findings from the initial study (Simpson & McPherson, 1998). We addressed four questions: (1) how many of the shade trees planted between 1991 and 1993 were alive in 2013? (2) how large did they grow? (3) what are their effects on cooling and heating energy use? and (4) how do these current estimates differ from the initial simulations (Simpson & McPherson, 1998)? This study is unique because it documents survival, growth, and performance of residential shade trees over the long-term. With historic data in hand, planners, utilities and policy-makers can better evaluate potential return on investment from

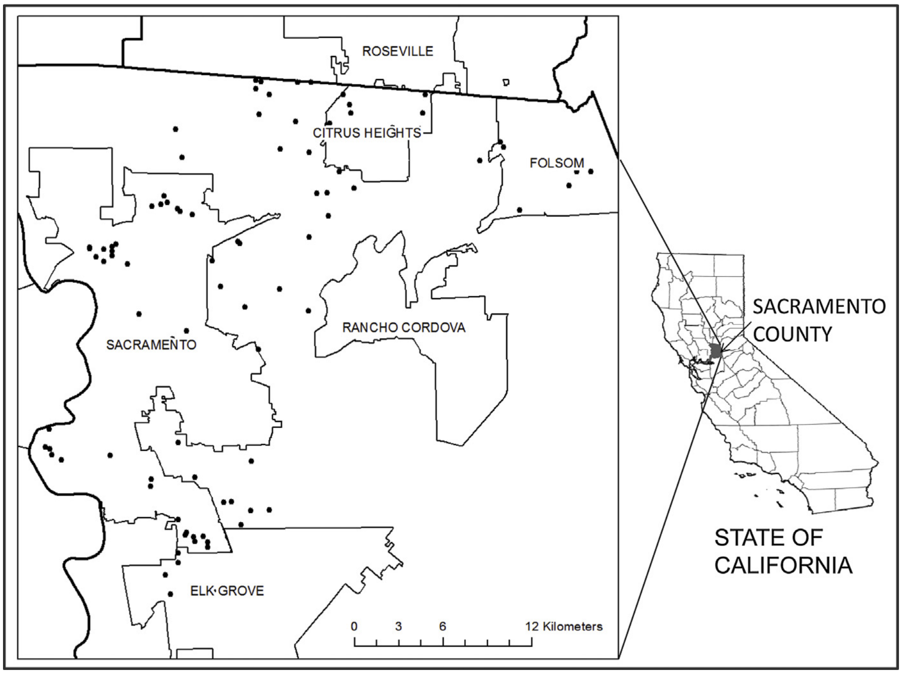

Fig. 1. Location of sample properties throughout Sacramento County, CA.

similar tree planting programs (Pataki et al., 2011; Young, 2010). Many massive tree planting initiatives are too new to have empirical evidence of performance as trees reach mature sizes, and the Sacramento program provides a distinct opportunity to validate model assumptions.

2. Methods

2.1. Study area

Sacramento County is located in Northern CA and has a Mediterranean climate characterized by wet, mild winters and hot, dry summers. On average, there are 74 days per year with maximum temperature equal to or above 32.2 °C, mostly distributed from June to September (National Oceanic and Atmospheric Administration, 2014).

2.2. Study sample

The original sample included 787 program shade trees that were planted from 1991 to 1993 on 254 randomly selected residential properties. Our current study's sample included 297 trees that were planted on 92 properties randomly sampled from the original sample of 254 properties (Fig. 1).

2.3. Data collection

2.3.1. Field surveys

The first field survey was conducted in 1994 to check young tree establishment (Simpson & McPherson, 1998). Field measurements included species, mature tree size (small, medium and large), condition (good, dead, missing, or container), orientation and distance to the building. Trees in containers were clearly not planted, while those observed missing may have been removed after planting or never planted. We conducted the second field survey from July to August in 2013 to monitor the survival and growth of program Trees 20 to 22 years after planting. We recorded survival (alive, replaced, dead, or missing), condition (good, fair, or poor), crown diameter (parallel and perpendicular to the street), bole height, and tree height. Prior to site visits, postcards were sent to describe the purpose and background of the study and request permission to access private property.

2.3.2. Aerial image interpretation

High resolution aerial images were obtained at approximately 4 year intervals to monitor survival and growth of the program trees between two field surveys (Table 1). All images were obtained from public sources. Most images were of sufficient resolution to enable detection of tree survival (15 to 30 cm pixel size). Resolution of

Table 1
Aerial imagery used for long-term tree monitoring in Sacramento, CA.

Image	Dates	Color	Resolution	Notes
DOQ NAPP 1998	Primary source date 1998/08/18	B/W	1 m	Difficult to recognize objects
Urban image 2002	Acquisition 2002/05/09–2002/05/14	RGB	30 cm	Very good, Survival and crown
Urban image 2006	Acquisition 2006/02/18–2006/04/19	RGB	15 cm	Good but leaf-off condition
Urban image 2009	Acquisition 2009/03/08–2009/03/11	RGB	15 cm	Good but leaf-off condition
Urban image 2011	Acquisition 2011/04/09 2006/04/28	RGB	15 cm, 30 cm	Very good but leaf-off condition

Sources: http://earthexplorer.usgs.gov.

Table 2
Projected sizes of trees 30 years after planting for each tree class, modified from Simpson and McPherson (1998).

Tree class		Code in the figure	Species: Scientific name (common name)	Bole height[1] (m)	Crown height (m)	Tree height[2] (m)	Crown width (m)
Size	Growth rate (Habit[3])						
Small	Moderate	SM	*Lagerstroemia hybrid* (Crape Myrtle) *Cercis canadensis* (Eastern Redbud) *Acer palmatum* (Japanese Maple) *Magnolia* × *soulangeana* (Saucer Magnolia) *Acer buergerianum* (Trident Maple)	2.1	5.5	7.6	7.6
Medium	Moderate (Upright)	MMU	*Triadica sebifera* (Chinese Tallow Tree) *Carpinus betulus* (European Hornbeam) *Nyssa sylvatica* (Tupelo/Sour Gum)	2.1	8.5	10.6	6.1
Medium	Moderate (Spread)	MMS	*Pistacia chinensis* (Chinese Pistache)	2.1	8.5	10.6	10.6
Large	Slow to medium	LSM	*Tilia americana* (American Linden) *Quercus macrocarpa* (Bur Oak) *Celtis sinensis* (Chinese Hackberry) *Ginkgo biloba* (Maidenhair Tree)	3.0	10.7	13.7	12.2
Large	Rapid	LR	*Platanus* × . *acerifolia* (London Plane) *Acer rubrum* (Red Maple) *Quercus rubra* (Red Oak) *Quercus coccinea* (Scarlet Oak) *Quercus lobata* (Valley Oak)	3.0	13.7	16.7	13.7

[1] Bole height is average height from ground to the bottom of crown.
[2] Tree height = bole height + crown height.
[3] Upright habit indicates that crown height is greater than diameter, spread habit indicates that crown diameter is greater than crown height.

the 1998 image (1 m pixel size) made it difficult to clearly identify tree crown boundaries, but knowledge of exact tree locations permitted identification of survival status. Image quality was deemed insufficient to accurately measure growth in most cases.

2.4. *Analysis*

2.4.1. *Survival analysis*

Survival analysis was performed using survival records obtained from two field visits and interpretation of five aerial images over the study period. Survival analysis techniques appropriate to interval-censored data were applied via the 'interval' package in R (Fay & Shaw, 2010; R CoreTeam, 2013; Roman et al., 2014). This technique resolves the fact that we did not know the exact date of death, but rather, had evidence that death occurred between two observations. Tree delivery date was considered time zero, assuming that the trees were planted close to delivery. This analysis included 297 program trees that were distributed and confirmed planted from 1991 to 1993. For example, the trees recorded as "dead" in the first field visit in 1994 were included; however, trees found to be "missing" in 1994 were not included in this survival analysis, because we could not distinguish between trees removed within 1 to 3 years after planting versus trees that were never planted. We also used weighted log-rank tests in 'interval' (Fay & Shaw, 2010) to assess relations between tree classes and survival outcomes (see growth description below). For more about long-term survival analysis and outcomes with the Sacramento Shade program, see Ko, Lee, McPherson, and Roman (2015).

We calculated overall survivorship, annual survival, and annual mortality over the study period (Roman & Scatena, 2011; Sheil, Burslem, & Alder, 1995). The overall survivorship (l_x) for the 22 year post-planting period was obtained from the output value of the survival curve at day 8036. This estimation takes into account different planting dates of each program trees over one to three years. Survivorship is cumulative from the time of planting to year *x*. Assuming that annual mortality was constant, annual survival rates (p_x) and annual mortality rates (q_x) were calculated using:

$$p_x = (l_x)^{1/x}$$

$$q_x = 1 - p_x$$

2.4.2. *Growth analysis*

We measured tree sizes during the 1993 and 2013 field surveys. Actual tree sizes measured in 2013 were compared to the projected tree sizes for Trees 30 years after planting from Simpson and McPherson (1998) (Table 2). Average annual tree height and crown diameter growth were calculated for the most abundant species and compared to similar data from other sources. One data source was growth equations developed from measurements on the same species of Sacramento street trees. Predicted average annual growth rates were calculated for 22-year old trees following procedures described by Peper, Alzate, McNeil, and Hashemi (2014). Measured data came from two long-term evaluation studies, 47-year old London planetrees (*Platanus* × *acerifolia*) ($n = 26$) growing in 3.7-m wide tree lawns in Toledo, Ohio and 14-year old Red Push pistache (*Pistacia* × *'Red Push'*) ($n = 4$) and Texas red oak (*Q. buckleyi*) growing in the Sacramento area (McPherson & Albers, 2014; Sydnor, Chatfield, Todd, & Balser, 1999). Our calculations assumed that trees were 1.5-m tall and 0.5-m crown diameter when planted from #5 containers (American Association of Nurserymen, 1997) and currently 22 years post-planting. Because the sample size was too small to conduct species-level analysis, we used five tree classes for survival and growth analysis (Table 2).

2.4.3. *Energy-saving performance simulation*

We estimated the effects of shade trees on cooling energy saving using SPS and Micropas, the same modeling programs used by Simpson and McPherson (1998). SPS computes the percentage of shade on each wall and roof caused by neighboring trees and buildings by accounting for locations, dimensions, and orientations of buildings and trees, as well as local time zone, latitude, longitude and time of year (McPherson, Brown, & Rowntree, 1985). In the initial study, shade from program trees was based on predicted size at 30 years after planting. Each tree species was assigned to one of five classes based on mature size and growth rate (Table 2). The mature dimensions for each tree class were taken from the literature (Dirr, 1977; Gerhold, Lacasse, & Wandell, 1993; Hogan, 1988; Johnson, 1978; PG&E, 1994). It was assumed that mortality and removal would be approximately balanced by tree growth and replacement (Simpson & McPherson, 1998).

Hourly cooling energy, capacity and heating energy were calculated with Micropas 4.01 (Enercomp, 1992). Inputs for Micropas include building footprints (e.g., building shape, conditioned floor area, and garage), building characteristics (e.g., *R*-values for wall roof and attic ducts, number of glazing panes, glazing shading coefficient, heating and cooling system efficiency) and hourly weather data for a typical year in Sacramento. In the Simpson and McPherson (1998) study, building footprint was simplified into rectangular shapes that are similar to actual building footprints while fixing conditioned floor area. Building conditions were determined based on building vintage: pre-1978, 1978–1983, and post-1983. This study calculated annual cooling energy use (kW h) and peak demand (kW for the peak cooling day of 7 August). Annual heating energy use (GJ) was estimated by assuming that shade from stems and trunks blocked 72.5% of irradiance during the in-leaf season (April through November) and 30% during the leaf-off season (December through March). Total annual energy savings were calculated by taking into account net effects of shading on cooling and heating energy use. Simulations were run for no shade, existing shade and existing plus program tree shade conditions. The effects of program trees were estimated by subtracting existing plus program tree shade runs from existing shade runs. To control for the various conditioned floor area (CFA) of each property, output values were normalized across the entire sample. Further details are given in Simpson and McPherson (1998).

In our current study, all inputs were the same as those from Simpson and McPherson (1998), except new shade files were generated using tree survival and size data measured in 2013. To insure that shading calculations were comparable, the same locations and sizes of existing trees reported by Simpson and McPherson (1998) were used. We intentionally used SPS and Micropas 4.01, the same versions that were used by Simpson and McPherson (1998) to control for any variations caused by different versions of the software. Also, building retrofits that may have occurred during intervening years were not included.

3. Results

3.1. Tree survival

The survival curve showed a steady decline over the study period after a steep drop in the first year (Fig. 2). The 22-year post-planting survivorship was 42.4%; annual survival rate was 96.2% and annual mortality rate was 3.8% (Ko et al., 2015). Survivorship was significantly different among tree classes ($p = 0.012$) (Fig. 3). Medium sized trees with spreading crowns (MMS) showed the highest survivorship over the study period; however, the survivorship dropped rapidly around year 2011–2013 and became similar to that of large sized trees with rapid growth rate (LR) and medium sized trees with upright crowns (MMU) at the end of the study period. Large sized trees with slow to moderate growth (LSM) constantly showed lower survivorship than that of large sized trees with rapid growth rate (LR). Smaller sized trees with moderate growth rate (SM) showed the lowest survivorship over the majority of the study period.

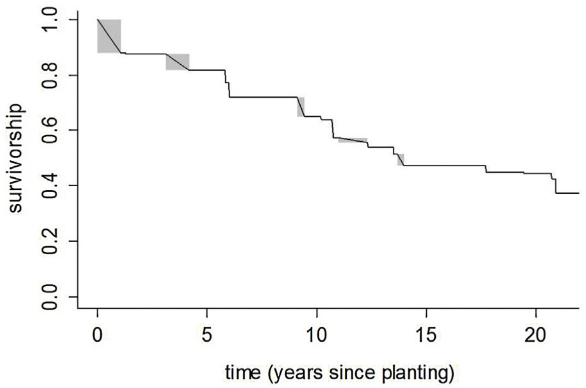

Fig. 2. Survival curve for all planted shade trees ($n = 297$) over 22 years. Survivorship was assessed from Kaplan–Meier survival analysis with Turnbull (1976) estimator for censored observations (Fay & Shaw, 2010). Gray rectangles indicate the range of possible values given censoring.

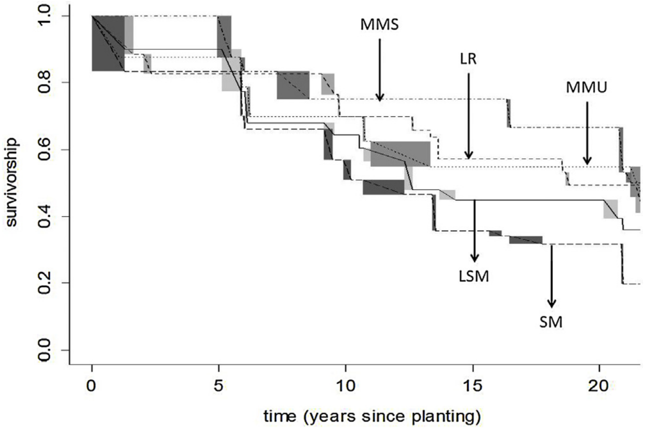

Fig. 3. Survival curves for planted shade trees ($n = 297$) by tree class (Table 2) over 22 years. Survivorship was assessed from Kaplan–Meier survival analysis with Turnbull (1976) estimator for censored observations (Fay & Shaw, 2010). Gray rectangles indicate the range of possible values given censoring.

3.2. Tree growth

Mean tree height and crown diameter after the 22-year period and average annual tree height and crown diameter growth rates varied by species and tree class (Table 3). The data in Table 3 include species with 6 or more trees and assume that trees were 1.5 m tall with 0.5 m crown diameter at the time of planting.

The ratio of tree size measured in 2013 to tree size predicted in 1998 was calculated for each tree class and indicates the extent to which trees are as large as anticipated. Across all tree classes these ratios average 74.6% and 68.8% for tree height and crown diameter, respectively (Table 4). The ratios are largest for medium trees with upright crowns and lowest for small trees. Given that tree sizes

Table 3
Mean tree height and crown diameter in 2013 and annual growth rates for each tree class by most common species.

Tree class	Species	Count	Mean tree height (m)	Standard deviation (m)	Avg. tree height/year (m/yr)	Mean crown diameter (m)	Standard deviation (m)	Avg. crown diameter/year (m/yr)
SM	*Acer palmatum* (Japanese Maple)	7	3.00	1.09	0.07	3.21	1.47	0.13
MMU	*Triadica sebifera* (Chinese Tallow Tree)	14	9.73	1.73	0.39	7.08	1.13	0.31
MMS	*Pistacia chinensis* (Chinese Pistache)	16	8.85	1.87	0.35	7.66	2.09	0.34
LSM	*Celtis sinensis* (Chinese Hackberry)	14	9.79	1.77	0.40	8.79	1.60	0.40
LR	*Platanus* × *acerifolia* (London Plane)	7	11.43	2.37	0.47	9.00	1.98	0.40
LR	*Acer rubrum* (Red Maple)	12	10.23	2.53	0.42	7.54	2.52	0.34
LR	*Quercus rubra* (Red Oak)	11	13.37	3.03	0.57	10.41	2.64	0.48

Table 4
22 year survivorship and comparison of tree growth between projected (30 years) and measured (20–22 years) dimensions by tree class.

Tree class	Count	Survivorship (%)	Tree height			Crown width		
			Projected (m)	Measured (m)	Attainment (%)	Projected (m)	Measured (m)	Attainment (%)
SM	21	19.9	7.62	4.82	63.3	7.62	4.40	57.7
MMU	19	55.0	10.67	9.27	86.9	6.10	6.55	107.4
MMS	16	53.3	10.67	8.85	83.0	10.67	7.66	71.8
LSM	23	36.0	13.72	9.57	69.8	12.19	7.75	63.6
LR	37	41.1	16.76	12.33	73.6	13.72	8.95	65.2
Total	116	41.1	12.65	9.44	74.6	10.64	7.32	68.8

Table 5
Mean annual tree height and crown diameter growth rates from 20 to 22 year old Sacramento Shade trees measured in 2013, predicted from growth equations for Sacramento street trees and measured in long-term evaluation studies.

Species	Tree height (m/yr)			Crown diameter (m/yr)		
	Measured Sacto. Shade trees in 2013	Predicted for Sacto. street trees	Measured by other studies	Measured Sacto. Shade trees in 2013	Predicted for Sacto. street trees	Measured by other studies
Pistache[1] (16)	0.33	0.45	0.30	0.33	0.50	0.47
Chinese hackberry (14)	0.38	0.36		0.38	0.34	
London planetree[2] (7)	0.45	0.53	0.30	0.39	0.39	0.32
Red oak[3] (11)	0.54	0.61	0.44	0.45	0.55	0.42

[1] 2013 and predicted data for Chinese pistache, measured data for 14-year old. Red Push pistache in Sacramento area (McPherson & Albers, 2014).
[2] Measured data for 37-year old street trees in Ohio (Sydnor et al., 1999).
[3] 2013 and predicted data for red oak, measured data for 14-year old Texas red oak (*Quercus buckleyi*) in Sacramento area (McPherson & Albers, 2014).

Table 6
Comparison of energy savings for all planted trees (shade effect only) between projected saving (30 years, Simpson & McPherson, 1998) and simulated saving (20–22 years). The percentage reported below each energy value indicates that percentage saved per year compared to unshaded base case.

	Initially projected for 2023 30 year post planting		Simulated for 2013 20–22 year post planting	
	Per property[1]	Per tree	Per property[1]	Per tree
Mean annual cooling energy	471 kW h	153 kW h	107 kW h	80 kW h
	22.0%	7.1%	4.9%	3.7%
Peak demand	0.23 kW	0.08 kW	0.05 kW	0.04 kW
	7.1%	2.3%	1.6%	1.2%
Mean annual heating energy	−2.6 MMBtu	−0.85 MMBtu	−0.5 MMBtu	−0.38 MMBtu
	−5.9%	−1.9%	−1.2%	−0.9%

[1] Average number of program trees observed per property: 3.1 (1994) vs. 1.3 (2013).

predicted in 1998 were for 30-year old trees and the measured trees were 20 to 22 years old (66.7% to 73.3% of mature age), these results suggest that actual and predicted growth rates are consistent.

Average annual tree height and growth rates for the four species of Sacramento Shade trees measured in 2013 were similar to their respective predicted rates (Table 5). The exception was Chinese hackberry, where measured rates exceeded predicted rates for both height and crown diameter. Lower mean growth rates for the Sacramento Shade trees are partially due to the effect of young replacements on mean sizes.

3.3. *Energy performance*

Simulated annual cooling energy savings per property was 107 kW h (4.9%), less than one-quarter of the initially projected savings (471 kW h, 22.0%) (Table 6). The percentage reported with each kW h value indicates percentage saved per year, compared to unshaded base case. Reduced tree survivorship is primarily responsible for lower cooling energy savings based on 2013 data. Of course, the trees measured in 2013 (20–22 year old) had not attained their 30-year old stature, and savings may increase as they grow to shade more building surface area. Energy savings per tree was 80 kW h (3.7%) compared to 153 kW h (7.1%), the projected energy saving. Peak demand savings was 0.05 (1.6%) per property and 0.04 (1.2%) per tree, both were reduced from the initial projection. The heating penalty from winter shade decreased from the original projection to −0.50 (−1.2%) per property and −0.38 (−0.9%) per tree.

As expected, reduced energy savings were accompanied by reduced monetary savings for energy. Applying the 1998 energy rates ($0.10/kW h and $6.15/MMBtu), the annual dollar savings per tree decreased from $10.00 in the 1998 study to $5.73 in this study (Table 7). The gap between projected values and monitored values was slightly reduced when applying the 2013 energy rates ($0.12/kW h and $10.31/MMBtu): the annual dollar savings per tree were $9.60 in the 1998 study and $5.78 in this study. The increased dollar savings for cooling due to higher electricity rates was largely offset by increased costs from the heating penalty caused by higher gas rates.

Table 7
Comparison of dollar savings for all planted trees (shade effect only) between projected saving (30 years) and simulated saving (20–22 years).

	Initially projected for 2023[1]	Simulated based on the 2013 survey[1]
Mean annual savings from cooling per tree	$15.25	$8.05
Mean annual penalty from heating per tree	$5.25	$2.31
Mean net annual savings per tree	$10.00	$5.74

[1] Energy rates used: $0.10/kW h and $6.15/MMBtu (Simpson & McPherson, 1998). For reference, 2013 energy rates for Sacramento, CA, are $0.12/kW h (SMUD, 2014) and $10.31/MMBtu (PG&E, 2014).

Table 8
Comparable studies on the cooling energy savings by tree shade for Sacramento, CA.

Authors (study year) [method]	Assumptions		Energy Savings (per property)		Energy savings (per tree)	
	Conditioned floor area	Trees	kW h	kW	kW h	kW
Our study [Simulation]	146 m^2 (1573 ft^2)	Average 1.3 "program" trees/property, 20–22 years post planting in all orientations	107 (4.9%)	0.05 (1.6%)	80 (3.7%)	0.04 (1.2%)
Donovan and Butry (2009) [regression]	139 m^2 (1500 ft^2)	Current average tree cover on the south and the west of a house	185 (5.2%)	N/A	82 (2.3%)	N/A
Simpson and McPherson (1998)[1] [simulation]	146 m^2 (1573 ft^2)	Average 3.1 trees/property, 20–30 years post planting in all orientations	471 (22.0%)	0.23 (7.1%)	153 (7.1%)	0.08 (2.3%)
Akbari et al. (1997) [experiment]	135 m^2 (1453 ft^2)	16 trees (eight were 6 m tall and eight were 2.4 m tall)/property on the west and south walls of a house	396 (29.0%)	0.8 (22.0%)	N/A	N/A
Simpson and McPherson (1996) [simulation]	139 m^2 (1500 ft^2)	Three trees with 7.3-m (24-ft) crown diameter/property; two on the west, one on the east	513 (34.0%)	0.74 (23.0%)	180 (11.9%)	N/A

[1] Initial projection of the study sample.

4. Discussion

This study reports survival, growth and energy saving performance of Sacramento Shade trees at 22-years post planting. Annual cooling energy savings per property at 22-year post planting attained only 22.7% of the 30-year projection from the initial studies (Hildebrandt & Sarkovich, 1998; Simpson & McPherson, 1998). We found that this lower energy performance compared to the 1998 projections was primarily due to lower survival rates. Only 34% of the trees delivered in 1991 to 1993 were surviving in 2013. Considering only trees confirmed planted, 42.5% survived to 2013 according to the survival analysis, which took into account variation in planting dates and observation dates (Ko et al., 2015). The average number of program trees per property dropped from 3.1 in 1994 to 1.3 in 2013. The initial assumption (Simpson & McPherson, 1998) that removed trees would be promptly replaced without a reduction in tree shade was faulty. In our 2013 field survey, we found that only 39 trees out of 145 dead or removed trees (26.9%) were replaced in the same location as planted; and replacements were much smaller than their projected mature size. Largely because of unanticipated mortality, it is not surprising that our simulated annual cooling energy savings was substantially lower than those simulated in the initial study.

Among the surviving trees, medium-sized trees had the highest survival rates compared to large or small sized trees. Also, medium trees were closest to reaching their projected mature sizes. Small-sized trees had the slowest annual growth rates, while large trees grew most rapidly. Planting medium stature trees and rapidly growing large trees appears to achieve the greatest energy savings over the long-term. Small stature trees are least effective because of their small shade area, slow growth and relatively high mortality rate. Higher mortality of small sized trees agrees with recent energy-saving models used by SMUD (Sarkovich, pers. comm.).

Measured growth rates for the Sacramento Shade trees were comparable with measured rates for similar species in the Sacramento area and Toledo, Ohio with the exception of Chinese pistache (Table 5). The mean crown diameter growth rate for Chinese pistache (0.33 m/yr) was considerably less than measured for 14-year old Red Push pistache (0.47 m/yr). This difference may be because Red Push pistache is a hybrid between *P. atlantica* and *P. integerrima* and develops a broadly oval crown with a height and width of 9 to 12 m. The more upright Chinese pistache can reach a height of 20 m. Given the relatively strong annual growth rates documented here, along with the observed attainment of mature tree height and crown diameter (Table 4), it appears that among the surviving trees, growth was within expected targets to produce shading benefits.

The difference between the simulated annual cooling energy savings per tree at the 22-year post planting (80 kW h) and the originally projected savings for a 30 year old tree (153 kW h) (Simpson & McPherson, 1998) was mainly due to the time difference between our growth measurement at 22-year post planting and that of the 30-year initial projection. In another early simulation study using the same software, 180 kW h of average annual cooling savings per tree was found assuming two trees on the west and one on the east (Simpson & McPherson, 1996) (Table 8). Although not reporting per-tree savings, Akbari, Kurn, Bretz, and Hanford (1997)experimental study found more conservative annual cooling energy per property than other simulation-based studies assuming 16 trees on the west and south walls of a house. Our 80 kW h saving per tree is similar to the 82 kW h (2.3%) per tree reported by Donovan and Butry (2009), which was based on observed energy savings from tree cover. Unlike our analysis, which focused on program trees, the Donovan and Butry (2009) analysis included all trees on single-family residential properties in Sacramento, CA. Although our study did not focus on strategic locations of program trees, it is worth noting that the 1994 field survey found 21.6% of the surviving trees were planted in locations that provided minimal summer shade to buildings (i.e., north, northeast, or northwest). Roman et al. (2014) found that 25.4% of Sacramento Shade trees were not planted in the correct location (e.g., the location agreed upon by the community foresters and residents). Stronger encouragement and education regarding planting in optimal locations could enhance program performance. Some residential tree giveaway programs have contractors plant the trees, which eliminate the problems of failure to plant and incorrect locations (e.g., Asian Longhorn Beetle Reforestation Program in Massachusetts, M. Cahill, pers. comm.).

Assuming 1998 energy prices, annual energy savings for heating and cooling totaled $5.73 for this study compared to $10 for the 1998 study. Using current energy prices the respective values are $5.78 and $9.60. Future savings are likely to be constrained by building energy efficiency improvements to new and existing structures. SMUD estimated that the average summer cooling load for a single family detached home in Sacramento is 1336 kW h (M. Sarkovich, pers. comm.) compared to 2164 kW h used in the 1998 study. As base cooling loads decrease in the future, the marginal energy conservation benefit of summer tree shade may diminish.

To improve tree survival and energy performance it is critical to understand how different factors influence the survival and growth of urban trees, especially in residential areas. For Sacramento Shade program, homeowner stability was important to establishment survival (Roman et al., 2014) and long-term survival (Ko et al., 2015) in residential areas. Homeowner stability was also strongly associated with observed maintenance (Roman et al., 2014). New residents may be unaware of the fact that their trees were planted specifically to conserve cooling energy, and may not assume responsibility for tree care. Changes in home ownership often result in landscape changes, including tree death from neglect or removal that reflects different horticultural preferences (Kirkpatrick, Davison, & Daniels, 2013). During our 2013 field survey, it was apparent that very few residents knew about the Sacramento Shade Program. Maintaining contact with the stream of different residents who live at the same residence and inherit program trees planted 20 plus years ago is a challenge that needs to be addressed to increase future survival and performance.

Because trees planted today yield their full benefits decades into the future, long-term performance evaluations like our study are essential to the transition from speculative modeling to empirically-based analyses. Other authors have called for more locality-specific empirical data (Pataki, 2013; Setälä et al., 2013). Our study responds to that call with two decades of data. Findings indicate that original energy savings projections were overly optimistic, primarily because they did not account for tree mortality and replacement.

This study contains several limitations and uncertainties to consider when interpreting results. Survival and growth estimates may include errors in distinguishing original program trees from replacement trees when the original tree was replaced within 5 years of planting with the same species. For energy simulation, although this study used field-measured tree survival and growth data to estimate energy effects, careful interpretation is required. Simulation results are highly sensitive to assumptions related to building characteristics and occupant behaviors. For consistency with the 1998 study we adopted the same assumption for building characteristics and occupant behaviors. Our results are not directly applicable to current conditions to the extent that these factors have changed over the past 20 years. Because of these and other simplifying assumptions, the uncertainty associated with modeling effects of tree shade on building energy use exists; simulated energy effects may be accurate within ±25% (California Air Resources Board, 2011; Hildebrandt & Sarkovich, 1998). Nevertheless, by using the same simulations employed in the initial projections (Simpson & McPherson, 1998) and comparing results to other studies in the same system (Table 8), our assessment documents the impact of tree performance on projected energy effects.

5. Conclusion

This study demonstrates the importance of tree survival to achieving expected energy savings in the long-term. Our findings have implications for the realization of ecosystem services that tree planting initiatives strive to achieve (Young, 2010). Without concomitant investments in tree monitoring and long-term stewardship, such planting programs are unlikely to achieve their potential or projected level of performance. Although our study results confirm the findings from other empirical studies that strategically planted shade trees do reduce energy demand (Donovan & Butry, 2009; Ko & Radke, 2014; Pandit & Laband, 2010a,b), the magnitude of savings were highly dependent on tree survival rates. By taking a longitudinal approach to evaluating tree performance, we demonstrate that the time lapse between planting and mature tree performance is a critical factor. As trees age and grow, their potential to produce ecosystem services increases. But this gain is offset by attrition due to death and purposeful removal. Studies that fail to incorporate these realistic survival and growth outcomes provide a very limited perspective on tree performance and delivery of benefits.

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