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Tree Shade and Energy Savings: An Empirical Study

Ram Pandit
School of Agricultural and Resource Economics
University of Western Australia
35 Stirling Highway
Crawley, WA 6009, Australia
ram.pandit@uwa.edu.au

David N. Laband
School of Forestry & Wildlife Sciences
Auburn University
206 Duncan Drive
Auburn, AL 36849, USA
labandn@auburn.edu

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Abstract

Trees cast shade on homes and buildings, lowering the inside temperatures and thus reducing demand for power to cool these buildings during hot times of the year. Drawing from a large sample of residences in Auburn, Alabama, we develop a statistical model that produces specific estimates of the electricity savings generated by shade-producing trees in a suburban environment. This empirical model links residential energy consumption to hedonic characteristics of the structures, characteristics and behaviors of the occupants, and the extent, density, and timing of shade cast on the structures. Our estimates suggest that if an additional 10 percent of the 125 million home owners in America started using tree shade to reduce electricity consumption an average of 10 kwh/day for 100 days per year, the annual amount of electricity conserved would be approximately 12,500 thousand megawatts. At the 2007 average residential price of electricity ($0.1065/kwh), this would save each household an estimated $106/year and $1.3 billion in the aggregate. Moreover, the electricity saved would represent approximately one-third of the electricity produced annually in the U.S. by wind power.

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I. Introduction

Public discussion and policy initiatives related to energy tend to focus on supply-side aspects such as generation from non-fossil fuel sources (e.g., wind, solar, geothermal, tidal, nuclear). Yet more effective management of demand potentially would generate sizable benefits in the form of reduced energy consumption. One significant demand-side management option is the natural air conditioning provided by tree shade. Trees cast shade on homes and buildings, lowering the inside temperatures and thus reducing the demand for power to cool these buildings during hot times of the year. The savings may be sizable - - electricity usage for cooling houses in summer months is especially costly for those who live in hot climates as the energy used for air conditioning makes up a large fraction of the peak electrical utility loads during the warmest period of summer (Rudie and Dewers 1984).

Without knowing how valuable the natural air conditioning provided by tree shade is, individuals have little incentive to use trees strategically to reduce their electricity use during the hot summer months. Thus, a *sine qua non* for encouraging individuals to adopt management strategies that help conserve energy is to give them scientific data identifying the financial savings they personally can enjoy that result from strategic development/management of tree shade on their residential lots.

A simple way of thinking about how to assign a monetary value to the cooling services provided by tree shade is to think in terms of replacement cost. In the absence of the natural air conditioning provided by tree shade, we artificially cool our dwellings and commercial buildings and we can identify the costs of doing so. Thus, we can estimate the value of natural air conditioning provided by tree shade by calculating homeowners' savings from not having to provide the equivalent level of mechanical cooling. In this study, we aim to do just that by examining the tree shade characteristics in reducing daily electricity consumption at residences during peak summer months in Auburn, Alabama.

II. Literature Review

Most of the available analyses of empirical link between tree shade and residential energy usage are based on simulation exercises. For example, the simulation results of Simpson and McPherson (1996) indicated that two trees shading the west-facing exposure of a house and one tree shading the east-facing exposure reduced annual energy use for cooling by 10 to 50% and peak electrical use up to 23%. Huang et al. (1987) conducted a simulation study of the potential role of vegetation in reducing summer cooling energy in residential houses across 4 U.S. cities. Their results suggested that an additional 25% increase in tree cover would reduce annual cooling energy use by 40%, 25%, and 25% for an average house in Sacramento, Phoenix, and Lake Charles, respectively. However, the fourth city, Los Angeles, had minimal calculated savings. Similarly, another simulation study by McPherson et al. (1997) in Chicago indicated that three 7.6 m tall trees around a well-insulated new house would reduce annual heating and cooling costs by 8% as compared to otherwise identical houses without trees. However, conclusions drawn from these tightly controlled simulation exercises may not accurately reflect the savings realized by consumers, who lead lives that are considerably more complicated, in terms of energy consumption, than simulation exercises admit.

There are a few empirical studies of shade trees and residential energy consumption based on real-world data, but the usefulness of the findings generated by these studies (Akbari et al. 1992; Akbari et al. 1997; Carver, Unger, and Parks 2004) is limited due to small samples or the absence of rigorous controls for confounding effects (Clark and Berry 1995; Laverne and Lewis 1996). For example, Akbari et al. (1997) analyzed the impact of shade trees on peak power and cooling energy use in 2 houses in Sacramento, CA and found a 30% reduction in energy use and 0.6 to 0.8 kilowatt peak demand savings due to shade trees. In their tightly controlled experiment, Laband and Sophocleus (2009) found that the amount of electricity used exclusively to cool 2 buildings located in Beauregard, Alabama to 72 degrees F during April – September 2008 was 2.6 times greater for the building situated in full sun as compared to an otherwise identical building situated in dense shade.

There have been several large-scale empirical analyses of the linkage between tree shade and energy consumption in a residential context. Rudie and Dewers (1984) examined the impact of shade cast in different coverage categories on energy consumption by 113 residents in College Station, TX. Rudie and Dewers evaluated tree shade on roofs for 3 years (1977-1979) from June to September, using measured tree height to estimate the amount of shade cast based on hourly solar position on the 21st day of each month. They developed a shade score for each home ranging from 1 to 4 based on the shaded roof perimeter and wall space, and classified each homes into one of 4 shade categories (category 1 with 15 feet or greater depth of shade and category 4 homes with no shade/trees) to analyze energy savings as a result of tree shade. Their findings for different shade categories indicated that the amount of shade, roof color, and wall color were significant determinants of residential energy consumption.

Jenson et al. (2003) used remote sensing to measure Leaf Area Index (LAI) at 118 randomly selected points in Terre Haute, IN and regressed residential energy consumption against LAI values. The regression estimation produced statistically insignificant results, contradicting the strong and significant role of shade trees on residential energy consumption revealed by other studies.

Donovan and Butry (2009) estimated the effect of shade trees on the summertime electricity use of 460 single-family homes in Sacramento, California. Controlling for a modest number of structural characteristics (e.g., house age, square footage, the presence of a swimming pool), they conclude that tree shade on the west and south sides of a house reduces summertime electricity use. By contrast, tree shade on the north side of a house increases summertime electricity use.

III. Methods and Data

Drawing from a sample of 160 residences in Auburn, Alabama, we developed a statistical model that produces specific estimates of the electricity savings generated by shade-producing trees in a suburban environment. This empirical model links residential energy consumption to hedonic characteristics of the structures, characteristics/behaviors of the occupants, and the extent, density, and timing of shade cast on the structures.

Empirical Model

Our empirical model analyze the impacts of tree shade and shade density on daily electricity consumption for three summer months (July, August, and September), when daily electricity consumption peaks in residences. Equation (1) is the specific functional form of the models we estimated for summer months.

$$\text{DECS}_{ijk} = \alpha0 + \alpha1\ \text{FamilySize}_{ij} + \alpha2\ \text{LivingArea}_{ij} + \alpha3\ \text{Floors}_{ij} + \alpha4\ \text{Cook}_{ij} + \alpha5\ \text{WaterHeat}_{ij} + \alpha6\ \text{Laundry}_{ij} + \alpha7\ \text{Pool}_{ij} + \alpha8\ \text{Tempdiff}_{ij} + \alpha9\ \text{PercentShade}_{ijk} + \alpha10\ \text{ShadeDensity}_{ijk} + \varepsilon_{ijk} \quad (1)$$

where

DECS = average daily electricity consumption (kilowatt hours) at an individual house in a summer month
FamilySize = number of family members in residence
LivingArea = living area of the house in square feet
Floors = whether the house has multiple floors
Cook = whether the household uses any amount of electricity for cooking
WaterHeat = whether the house has one or more water heaters that use electricity
Laundry = average number of laundry loads run per week in the house
Pool = whether the house has a swimming pool
Tempdiff = the average daytime outside temperature minus the daytime thermostat setting for a given month (positive for summer months and negative for winter months)
PercentShade = the extent of the roof area covered by tree shade, in decile percentages
ShadeDensity = the intensity of tree shade cast on the dwelling, assigned one of four categories - no shade, light, moderate, or heavy[1]
ε_{ijk} = model error term for summer months, assumed to be normally distributed
i = sample households (i = 1 to 160)
j = electricity consumption period for each i, when j = July, August, and September
k = shade monitoring times in a day per month (k = 1 to 3; 1 for late a. m., 2 for early p.m., and 3 for late p. m.)

Data were collected from two sources - - (1) questionnaire survey of the residents and their submission of monthly electric bills, and (2) monthly monitoring of shade conditions on each residence in the sample. We deliberately selected specific neighborhoods for inclusion in our sample, to ensure substantial variation in tree shade conditions. However, within each neighborhood, the distribution of invitations was random - - every other home was contacted. In the invitation letter we explained the nature and scope of the study and provided relevant information for respondents to use to indicate their willingness to participate. Our final sample of homeowners reflects a complete range of shade conditions, in terms of both extent and density, on properties as well as the other explanatory variables in our model.

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[1] Our categorization of shade as light, moderate, or heavy was subjective, as we did not have instrumentation measuring light conditions (e.g., PAR values) on each structure. Heavy shade density was recorded for shade with little or no light reaching the structure. Light shade density was recorded for shade with a lot of light still reaching the structure. Moderate shade, then, was recorded when there was substantial shade, but also substantial light, reaching the structure.

We recorded monthly electricity usage data from each participating household from August 2007-August 2008. Specifically, we collected information on dates of current service, number of days in service period, and the amount of electricity consumed during the specified period. Because not all residences are on the same billing cycle, we divided kwh used per billing cycle by the number of days in the billing cycle. This standardized our variable of interest, kwh used per day, across participating households.

Data on characteristics of the dwelling and the occupants were collected at the onset of the study using the survey questionnaire. The building characteristics included: age of house (years), living space (sq. feet), number of stories, cooling system (central air or window unit), cooking/heating and hot-water systems (electricity, natural gas, or other), exterior construction materials, presence of a swimming pool, and presence of an additional freezer. The occupant(s) characteristics included: number of family members by age and gender, and average number of laundry loads run per week. In addition, we collected information on the daytime and nighttime inside house temperature maintained by the residents both in summer and winter months. In conjunction with information about exterior temperatures, this provided a measure of the intensity of the cooling (heating) regime at each residence across different seasons and months.

Monthly data on the extent and density of tree-cast shade was recorded through field visits conducted three different times on a sunny day as close as possible to the middle of each month. The extent of shade estimated in decile percentages three times a day -- morning (9:00-11:00 a.m.), early afternoon (noon-2:00 p.m.), and late afternoon (3:00-5:00 p.m.) -- was averaged to obtain a mean percentage of shade on each house. Shade density was recorded in one of four categories – heavy, moderate, light, and none. Heavy shade density refers to shade characterized by few-to-no patches of sunlight, light shade density refers to shade that allows most of the sunlight shine onto the structure, and moderate shade density is characterized by roughly equal amount of sunlight and shade hitting the dwelling. A single measure of shade density was constructed from the three density observations taken at different times of the day, using a weighted scheme reflecting the extent and density of shade. For example, if a house received 15% heavy shade in the late morning, 5% moderate shade in early afternoon, and 55% heavy shade in the late afternoon, then the mean shade extent for this house was assigned at 25% and shade density assigned was heavy. The same researcher monitored the extent and density of shade cast on each house every time to ensure consistency and uniformity with respect to the data.

In this analysis, we consider the 3 hottest summer months, consisting of July, August, and September. During the summer months electricity use per day peaks in August which coincides exactly with the maximum difference between the residents' desired thermostat setting and outdoor temperature, measured either as average daily temperature or average daily high/low temperature - - see Figure 1.

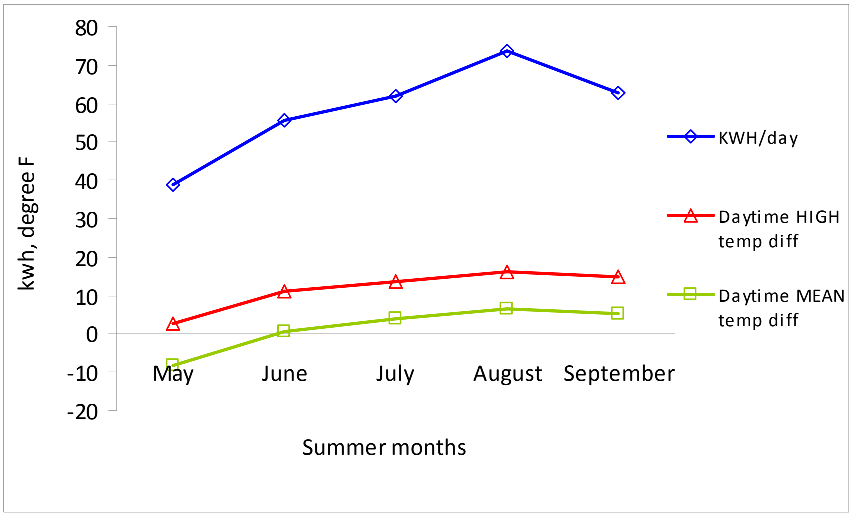

Figure 1. Electricity usage per day and temperature differential by month

We employed mixed modeling approach (SAS mixed procedure) to examine the impacts of predictor variables on daily electricity consumption at each residence mainly because of two reasons: 1) our data are from same observational units (residences) over time and represent some type of repeated measures, and 2) we included both time-variant and time-invariant predictor variables in the model. This modeling technique has relative advantage as it allows the flexibility to consider both fixed and random effects of the variables in the model. In particular, we employed random intercept model that allows intercept term to vary among residences around a fixed mean to capture unobserved variations in daily electricity consumption across the residences.

IV. Empirical Results and Discussion

In Table 1a, we report the descriptive statistics of time variant and invariant variables included in the model. We expect that the daily electricity consumption is positively related to model variables other than the variables related to tree shade conditions (e.g. shaded area in percent shade, density, and shade at different time of the day).

In Table 1b, we report the utility and structural types of the sample households related to the electricity consumption for various purposes. Out of 160 residences in the sample, a total of 107, 129, and 84 residences use electricity for heating, cooking, and hot water, respectively. In terms of the structural characteristics, 77 residences have single story houses and only 12 residences have swimming pool in their property.

Table 1a. Sample statistics for summer months– July to September (n = 906)

Attributes	Mean	Std. Dev	Min.	Max.
Time-variant attributes:				
Kwh/day	66.04	27.04	0.02	192.97
Inside temp – day	76.35	2.73	70.00	85.00
Inside temp – night	75.66	3.15	65.00	85.00
Outside high temp	91.21	2.31	86.35	95.61
Outside mean temp	81.44	1.81	77.57	85.03
Outside min. temp	71.18	1.52	68.20	73.94
Daytime temp diff (mean)	5.09	3.30	-7.34	15.03
Nighttime temp diff (mean)	5.78	3.66	-5.40	18.79
Percentage of house area under tree shade	19.30	21.10	0.00	88.00
Late a.m. (9-11 a.m.) percent house area under tree shade	22.88	27.08	0.00	100.00
Early p.m. (12-2 p.m.) percent house area under tree shade	11.84	16.77	0.00	90.00
Late p.m. (3-5 p.m.) percent house area under tree shade	32.04	33.06	0.00	100.00
Time-invariant attributes:				
Family Size	2.49	1.12	1.00	7.00
Living Area (sq. feet)	2694.33	855.55	1170.00	6100.00
No. of floors	1.52	0.50	1.00	2.00
Laundry loads/wk	5.51	3.08	1.00	21.00

Table 1b. Sample statistics for categorical variables by utility or structural types (out of 160 residences)

Variables	Utility / structural types	# of sample households
Heating	Partially or fully electric	107
	Others (Natural gas, propane etc.)	53
Cooking	Partially or fully electric	129
	Natural gas	31
Water heater	Partially or fully electric	84
	Natural gas	76
House floors	Single	77
	Multiple	83
Swimming pool	Yes	12
	No	148

Electricity consumption is affected strongly by the intensity of the cooling/heating effort in a residence. In part, this effort is determined by home size (which reflects the sheer volume of air that needs to be cooled); in part this effort is determined by the occupants' thermostat setting. As the distance between the desired temperature and the actual temperature increases, so does the intensity of the cooling/heating effort, depending on season.

Shade conditions on a property have a significant effect on energy consumption throughout the year, with strong seasonal, shade density, and time-of-day components. In Table 2, we report estimated regression coefficients for models containing different configurations of the tree shade variables. Among different configurations, model 1 and 2, respectively, represent the impact of average extent and density of shade on daily electricity usage. Model 3 incorporates both the extent and density simultaneously, while model 4 incorporates the time dimension of shade in the analysis.

Table 2. Regression results for peak summer months: Dependent variable = kwh/day

Explanatory Variables	Model 1	Model 2	Model 3	Model 4
Fixed Effects:				
Intercept	19.803**	19.825**	21.427***	19.442**
	(7.826)	(7.824)	(7.842)	(7.849)
Family size	3.622***	3.859***	3.602***	3.674***
	(1.289)	(1.283)	(1.286)	(1.290)
Living area	0.0148***	0.0153***	0.015***	0.015***
	(0.0018)	(0.0018)	(0.0018)	(0.0018)
# floors	2.001	1.425	1.943	1.999
	(3.001)	(2.995)	(2.996)	(3.003)
Elec. Cooking	0.694	0.203	0.905	0.789
	(3.542)	(3.533)	(3.539)	(3.547)
Elec. H_2O Heat	2.909	3.362	3.173	2.851
	(2.735)	(2.744)	(2.732)	(2.736)
Laundry loads/wk	1.140**	1.176**	1.174**	1.157**
	(0.475)	(0.477)	(0.474)	(0.475)
Swimming pool	21.099***	21.373***	20.867***	20.959***
	(4.919)	(4.925)	(4.909)	(4.923)
Daytime temp. diff. (mean)	3.025***	2.849***	2.910***	3.018***
	(0.176)	(0.176)	(0.179)	(0.177)
Percent shade	-0.119***		-0.083*	
	(0.044)		(0.049)	
Light shade		-5.106***	-4.219**	
		(1.633)	(1.712)	
Moderate shade		-3.892**	-2.412	
		(1.725)	(1.931)	
Heavy shade		-6.365***	-4.992**	
		(1.845)	(2.015)	
Late a.m. shade percent				-0.030
				(0.033)
Early p.m. shade percent				-0.005
				(0.067)
Late p.m. shade percent				-0.055**
				(0.027)
Random Effects (variance components):				
Intercept	241.23***	242.96***	240.29***	240.92***
	(29.816)	(31.199)	(29.869)	(29.837)
Residual	101.21***	100.23***	100.19***	101.50***
	(5.244)	(5.208)	(5.207)	(5.267)
-2 Log likelihood:	7165.6	7145.5	7146.8	7176.1
AIC:	7169.6	7149.5	7150.8	7180.1
N:	906	906	906	906

*** significant at 0.01 level ** significant at 0.05 level * significant at 0.10 level
The DF for fixed effect intercept is 153 and rest of the explanatory variables is 743.

The random intercept regression results in Table 2 suggests that, as predicted, family size, living area, and number of laundry loads per week significantly and positively impacts the daily electricity consumption during peak summer months. However, number of floors in the house, electric mode of cooking, and hot water system are not statistically significant across the models in contrary to the expectation. This likely reflects the fact that people tend to cook less frequently and/or intensively in the summer, as they leave home on holiday, go out to restaurants or on picnics, and more frequently eat cold meals when at home. Also, electric hot water may not be in use during summer months.

During the 3 hottest summer months (July, August, September), the mean shade coverage in our sample was 19.3 percent. As compared to a house with no shade, electricity use at an otherwise similar residence characterized by mean shade conditions was an estimated 3.5 percent lower.[2] Every additional 10 percentage points of shade cover reduces electricity consumption by 1.8 percent of the sample mean. Shade matters in terms of reducing daily electricity consumption, however, not all shade is created equal; dense shade provides significantly more cooling in the summer than does moderate or light shade. At a 'typical' house with mean shade coverage of 19.3 percent during the summer months, dense and light shade reduces daily electricity consumption by an estimated 16.37 percent.[3] Electricity consumption at a house characterized by just dense shade covering an average of 50 percent of the structure throughout the day is nearly (0.83 x 50 + 4.992 = 9.142 kwh) 13.84 percent lower than an otherwise identical house situated in full sun. The timing of shade also influences energy savings, with shade cast in the late afternoon being most beneficial. This is only to be expected, as late afternoon is when outside temperatures peak in the summertime. Our findings in this regard are consistent with those of Donovan and Butry (2009).

The dense shade cast by leafy deciduous trees planted on the west side of a structure provides maximum cooling benefits in the summer with minimal offsetting increases in the winter. Because the sun moves south (north) for those living in the northern (southern) hemisphere, deciduous trees located on the west side of a structure cast beneficial shade on the structure in the summer (i.e., in the afternoon when temperatures peak and shade thus exerts its maximum cooling influence - - see Table 2, Model 4). With sufficient shade coverage from the west, homeowners may see electricity savings of 15-20 percent or more during the hot summer months. On the other hand, homeowners disadvantage themselves with trees planted on northern or eastern exposures, for 2 reasons: (1) the beneficial shade impact during the summer months is minimized because the shade occurs during the morning before outside temperatures peak, and (2) as the sun shifts position in the winter, the structure is shaded during the morning hours when temperatures are at their coldest.

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[2] From Model 1, each percent of tree shade reduced daily electricity consumption by an estimated 0.119 kwh. So a residence with the mean tree shade coverage of 19.3 percent used an estimated 19.3 x 0.119 = 2.30 kwh less electricity per day than a residence with no tree shade. Compared to the average summertime consumption (66.04 kwh/day), this is a 3.50 percent reduction.

[3] From Model 3, each percent of tree shade reduced daily electricity consumption by an estimated 0.083 kwh. In addition, there is a fixed effect of dense and light shade of an estimated (4.219+4.992) 9.211 kwh/day reduction in electricity use. So a residence with 19.3 percent dense tree shade used an estimated 19.3 x 0.083 = 1.60 + 9.211 = 10.811 less electricity per day than a residence with no tree shade. Compared to the average summertime consumption (66.04 kwh/day), this is a 16.37 percent reduction.

The energy conservation benefits of shade trees may be quite sizable. For example, if an additional 10 percent of the 125 million home owners in America started using tree shade to reduce electricity consumption an average of 10 kwh/day for 100 days per year, the annual amount of electricity conserved would be approximately 12,500 thousand megawatts. At the 2007 average residential price of electricity ($0.1065/kwh), this would save each of these consumers an estimated $106/year and $1.3 billion in the aggregate. Moreover, the electricity saved would represent approximately one-third of the electricity produced annually in the U.S. by wind power.

V Conclusion

Human behavior is influenced strongly by personal incentives. In the absence of specific information about the personally-relevant economic benefits from tree shade, homeowners have little direct incentive to plant trees and/or leave trees near their homes. By extension, home builders have correspondingly little financial incentive to design and build homes that leave mature trees intact. Unless and until these directly-affected parties can be 'shown the money' they will continue to make completely rational and predictable decisions that, for the most part, ignore the energy conservation benefits from shade trees. In this study, we showed that shade trees produce a sizable benefit to home owners in reducing electric costs during peak summer months. The reduction in costs is directly associated with tree shade attributes (e.g. density and timing) and the home owner benefits the most from dense and late afternoon tree shades.

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