URBAN FOREST IMPACTS ON REGIONAL COOLING AND HEATING ENERGY USE: SACRAMENTO COUNTY CASE STUDY

by James R. Simpson

Abstract. Urban forests impact energy use for cooling and heating as a result of their moderating influence on climate. To evaluate the regional magnitude of these impacts, a large-scale analysis framework was developed and applied to Sacramento County, California, as a case study. Heating, cooling, and peak electrical energy use changes resulting from modification of solar radiation, air temperature, and wind speed by the existing urban forest were estimated for representative residential and commercial buildings. This is combined with building age and size, canopy and tree cover, and tree density (trees/ha) for 71 county subdivisions. Annual cooling savings are approximately 157 GWh (US$18.5 million) per year—12% of total air conditioning in the county. Net effects on heating are small, with 145 TJ (US$1.3 million) saved annually. Peak energy-use reductions result in avoided costs of US$6 million. The resulting large-scale analysis incorporates a manageable level of detail not previously available. Sensitivity of results to selected input data is demonstrated.

The moderating influence of climate on energy used for cooling and heating buildings (referred to subsequently as space-conditioning energy use) has been demonstrated primarily at the scale of individual buildings (Heisler 1990; Huang et al. 1990; Meier 1990/91; McPherson 1994; Simpson and McPherson 1996). Substantial energy savings on the scale a city can result (Akbari et al. 1990; Rosenfeld et al. 1996). For example, Akbari et al. (1990) made national estimates based on increases of 1.5 trees per unit, 15% canopy cover, and 19% urban albedo. Savings from trees were approximately 11%, based on their observation that trees and reduced urban albedo produced similar savings. Regional-scale air temperature and wind-speed reductions were responsible for 7% savings; the remaining 4% was due primarily to tree shade, and to a lesser degree wind-speed reduction. Energy savings, together with the other benefits of urban green space, have generally been shown to outweigh the associated costs, such as those for irrigation, disposition of green waste, and tree removal (McPherson 1995; Hildebrandt et al. 1996).

The objective of this paper is to extend results from studies of tree impacts on space conditioning of single buildings (Simpson and McPherson 1995, 1996, 1998) to a regional scale. Sacramento County, California, was used as a case study. The resulting estimates incorporate a level of detail in model elements previously unavailable, without being unmanageably complex. Multidimensional "what-if" sensitivity analysis of the model to uncertainties in selected input values is demonstrated. This methodology, applied to existing trees, is suitable for assessment of energy benefits of current or planned urban tree planting programs. It is one part of the Sacramento Urban Forest Ecosystem Study (SUFES), whose goal is to determine relationships between urban forest structure and function and the associated benefits and costs (McPherson 1998). Together with ongoing research on urban tree growth and health, and impacts on climate, hydrology, and air quality, SUFES findings will aid in development of management strategies for sustainable urban forest ecosystems and in making these concepts of greater use to arborists, managers, policy makers, and local governments.

Methods

For a description of the study area and sampling units, see McPherson 1998 (pp. 175–177 of this issue).

Tree impacts were estimated by summing energy use calculated for representative residential and commercial buildings of different types over the total number of units of each type in the county. First, heating and cooling energy use per unit of conditioned floor area (CFA), referred to subsequently as unit energy density (UED), were determined for single-family, 2- to 4-unit, and 5+ -unit residential structures (referred to as low, medium, and high density) as a function of age of construction (vintage), or as a function of size for commercial structures. Residential density and size of commercial structures are referred to collectively as "building type." Second, UED changes due to modification of solar radiation, air temperature, and wind speed by trees were estimated and adjusted based on equipment and diversity factors. Third, energy-use data are combined with numbers of buildings and their vintage/size distribution, tree cover, and tree density (trees/ha) for each SubRAD (Sub-Regional Assessment District) (McPherson and Simpson 1995) to estimate space-conditioning impacts. Benefits were assessed based on retail costs of energy to residential and commercial customers. Unless otherwise stated, all future reference to UEDs are to adjusted values. Details are given in the appendix to this article.

Tree and building data. Data from the Sacramento Area Council of Governments' 1994 Housing Module (SACOG 1995) were used to define the population of residential units and obtain a current inventory of units by SubRAD and density. Their inventory, which was divided into pre-1980, 1980–1984, and post-1984 vintages for each SubRAD, is based on 1990 census data updated with building permit completion data. As of January 1994, the population of residential units in Sacramento County was 441,071. Sixty-five percent (287,551) were single-family detached, 3% (15,027) mobile homes, 10% (43,608) structures with 2 to 4 units, and 22% (95,757) structures with 5 or more units. Building energy-use data based on pre-1978, 1978–1983, and post-1983 vintage definitions were applied to pre-1980, 1980–1984, and post-1984 building numbers, respectively.

Tree density (trees/ha) for each SubRAD, numbers of existing trees per unit (trees on the property within 20 m [66 ft] of the structure), and land cover are based on McPherson and Simpson (1995) and McPherson (1998). Tree canopy and building cover, defined as percentage of surface area covered by buildings or vertical projection of tree crowns, were determined for each SubRAD by dividing cover area found for each land use (low and high density, residential and commercial/industrial) by the total area for that land use.

Energy costs. Residential electric and gas rates have a 2-tiered structure; higher (peak) rates are charged for usage over a fixed threshold in a billing period (approximately 1 month duration). Based on analyses of typical buildings, changes in residential energy use were found to occur primarily at peak rates for cooling (electricity; $0.12695/kWh) and average rates for natural gas (mean of peak, $0.711/therm and off-peak, $0.527/therm, or $0.62/therm). Average rates were used for calculation of total energy use ($0.104/kWh and $0.62/therm). Commercial electric rates of $0.068 and $0.081 were used for large and small/medium commercial and industrial buildings, respectively (Hildebrandt, personal communication 4/24/96). Residential heating costs are based on equipment saturation data for natural gas, heat pump, and electric resistance heat (Sarkovich, personal communication 9/5/96). Annual space-heating energy use for commercial buildings was estimated from UEDs taken from EIA (1994) for climate zone 4 and conditioned floor areas supplied by the Sacramento Municipal Utility District (SMUD) (Hildebrandt, personal communication 4/24/96). Commercial gas rates were $0.991 and $0.442 per therm for small/medium and large users, respectively. Based on total consumption by fuel source for EIA climate zone 4, it is estimated that 8% of commercial space heating is electric. Other small or indeterminate heating sources (e.g., fuel oil and district heat) are treated as if gas heat is being used.

After a brief summary of tree and building cover for the county, energy use and changes due to climate modifications are presented in both energy and dollar units. Effects of solar radiation, air temperature, and wind-speed reductions on cooling and heating are treated. Results are presented for the entire county, as well as by sector, vintage, and building type; impacts on high- versus low-density residential building types, residential versus commercial buildings, and old versus new vintages are presented as well.

Results

Approximately 3.5 million (Table 1) of Sacramento County's estimated 6 million trees (McPherson 1998), or 59%, are located in residential and commercial land areas. Of these, 32% (1.1 million, 2.4 trees/unit) have shading potential (i.e., are located within 20 m [66 ft] of residential and commercial structures). Most trees (2.97 million, 84%) are located in low- and medium-density residential land areas, where they have the greatest potential to influence space-conditioning energy use. Existing tree cover averaged by land use ranged from 17% for low- and medium-density residential to 4% for large commercial land uses. Average building cover was greatest in high-density residential (37%), 26% in medium- to low-density residential, and lowest in commercial/industrial land areas (22%).

Total space-conditioning energy use estimated for the county without trees is 1,439 GWh, 2,037 MW, and 20,277 TJ (terajoules) for annual cooling, peak cooling, and annual heating, respectively (Table 2). Trees reduce these by 157 GWh (10.9%), 124 MW (6.1%), and 145 TJ (0.7%) for annual cooling, peak cooling, and annual heating, respectively. Annual energy use for the county agreed closely with utility data because diversity factors (see appendix) were based on utility estimates of county average energy use per unit. For example, residential cooling load of 526 GWh compares with SMUD estimates of 479 GWh used for residential cooling in 1995 (Hildebrandt, personal communication 4/24/96). Some of the difference is due to the addition here of approximately 15,000 mobile homes found in the county and not included in SMUD data (approximately 14 GWh annually). Residential peak capacity was 605 MW, which agrees closely with the SMUD-estimated total for 1994 of 600 MW (SMUD 1994).

Residential structures account for 41%, 60%, and 62% of total (residential plus commercial/industrial) annual cooling, peak cooling, and annual heating, respectively, but 88%, 87%, and 59% of the respective savings (Table 2). Approximately 79% of total annual savings are due to low-density residential structures

Table 1. Tree, building, land cover, and climate effects data by building type and vintage/size. Average trees per unit are weighted by number of units, and mean climate effects are weighted by area covered by trees, for all SubRADs. Land use, land cover totals, and tree number data are from McPherson and Simpson (1995).

Building Type:	Residential									Commercial/Industrial		
	Low density: SF detached/attached, mobile homes			Medium density: two to four units/structure			High density: Five or more units/structure			Small	Medium	Large
Vintage	pre-80	80-84	post-84	pre-80	80-84	post-84	pre-80	80-84	post-84			
Number of units	197,503	32,705	72,370	33,633	3,771	6,204	69,058	10,068	16,631			
Units by building type			302,578			43,608			95,757	48,818	6,463	1,325
% units by type			68%			10%			22%	86%	11%	2%
CFA adjustment		0.94			0.62			0.43			1.00	
Average CFA (m²)	130	156	157	87	104	105	60	72	72	92	1,138	13,808
Tree density (trees/ha) City		138			138			117			42	
Suburb		83			83			44			27	
Rural		33			33			0			29	
Adjustment factor for trees/unit City	1.00	1.00	1.00	1.00	1.00	1.00	0.85	0.85	0.85	0.30	0.30	0.30
Suburb	1.00	1.00	1.00	1.00	1.00	1.00	0.53	0.53	0.53	0.33	0.33	0.33
Rural	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.88	0.88	0.88
Trees/Unit	2.9	2.3	1.7	3.0	2.3	1.8	2.0	1.7	1.2	1.3	1.1	0.8
Land Area (ha)	35,775						2,680			8,850		3,465
Tree cover (ha)	5,948						350			467		134
(%)	17%						13%			5%		4%
Building cover (ha)	9,286						995			1,944		768
(%)	26%						37%			22%		22%
Climate Effects ΔT(°C)	2.3						1.9			1.5		0.4
(ΔU/U)	15%						9%			21%		3%
Number of trees	2,967,134						184,098			279,283		120,062
Trees within 20 m	575,337	75,114	120,001	99,958	8,798	11,255	139,016	16,857	20,001	63,243	7,394	1,013

alone. The large proportion of energy savings found for residential structures largely results from the fact that about 90% of the trees are found in residential land uses (Table 1). Also, lower-density housing has greater potential to be shaded (see appendix), and input data for commercial buildings were conservatively assigned.

Tree shade is estimated to reduce residential and commercial cooling load by 12% (78 GWh) and 1.3% (10 GWh) and to increase heating load by 3.9% (477 TJ) and 0.4% (33 TJ), respectively. Total reduction in cooling is 6.0% (88 GWh), and net increase in heating of 2.5% (510 TJ) is due to reduced solar radiation (Table 2). Shade by itself results in air-conditioning savings of $10.7 million and heating losses of $5.6 million.

Average maximum air-temperature reductions from existing trees, weighted by area covered by tree canopy in each SubRAD and land use, were 2.3°C [36.1°F] for low-density residential areas, 1.9°C [35.4°F] for high-density residential and small commercial, and 0.4°C [32.7°F] for large commercial land uses (Table 1). Resulting cooling energy-use reductions were similar to those for direct shade (Table 2). For high-density residential, reductions were more than twice those due to shade, primarily because of more limited shading opportunities found for multi-unit structures (see appendix).

Wind-speed reductions act to increase overall cooling load 3.1% and 0.7% for residential and commercial properties, respectively, for a combined increase of 1.8% (Table 2). Respective heating loads are reduced 4.4% and 1.5%, for a combined reduction of 3.2%. Heating penalty due to shade (–510 TJ) is approximately offset by heating savings from wind-speed reduction (655 TJ), for a net savings of 145 TJ ($1.3 million). Increased cooling load of 1.8% (26 GWh) due to reduced wind speed is less than 30% of the air-conditioning savings from either shade or air-temperature reductions, and less than 15% of total savings. An alternative view is that, for wind speed, negative effects on cooling (–$3.0 million) are more than offset by savings for heating ($7.2 million).

Sacramento County's existing urban forest saves a total of approximately $20 million through combined shade, air-temperature, and wind-speed effects on annual heating and cooling (Table 2). Most of these savings ($18.5 million, 93%) are for air conditioning; the remainder are for heating. Total annual residential and commercial space-conditioning costs are approximately $100 million for cooling and $180 million for heating. Total peak savings from reduced solar radiation, air temperature, and wind speed were 6% (124 MW), or $6.2 million, based on an avoided cost from deferred investment in new generation capacity of $50 per kW. Peak savings may be somewhat less if based on avoided incremental costs of new electric supply; they accrue to individual consumers through deferment of future power plant construction and accompanying rate increases.

Annual residential savings are $17 million (86% of total annual savings) for the county, $39 per residence and $8 to $16 per tree (Table 3). Savings per tree for shade are referenced to the approximately 1.1 million trees estimated to be within shading range (i.e., < 20 m [66 ft] distant and not on north side) of residential structures. The effect of tree-to-structure distance on the relative contribution of individual trees to air-temperature and wind-speed reduction is not well understood. Consequently, savings per tree from air-temperature and wind-speed reduction are referenced both to total number of trees within shading range and to the total number of trees found in residential land uses (~3.2 million, Table 1); hence, the range of net annual savings per tree (Table 3).

Table 2. Annual energy use and energy-use changes due to existing trees from reduced insolation, air temperature, and wind speed by land use for Sacramento County.

Annual air conditioning

	Electricity cost		Total cooling energy use			% Change, existing trees				Change in energy use			Total savings (M$'s)
Building Type	$/kWh Average	$/kWh Peak	Existing Trees (GWh)	No Trees (GWh)	No Trees (M$)	Direct Shade	Air Temp	Wind Speed	Net change	Shade (GWh)	Temp/Wind (GWh)	Total (GWh)	
1-4 Family Res	0.104	0.127	438	556	58	13.3%	11.3%	-3.3%	21.3%	74	44	118	15.0
5+ Family Res	0.104	0.127	88	99	10	3.9%	8.8%	-2.0%	10.7%	4	7	11	1.3
Small-Med C/I	0.081	0.081	297	314	25	3.1%	3.0%	-0.8%	5.4%	10	7	17	1.4
Large C/I	0.068	0.068	459	470	32	0.0%	3.1%	-0.7%	2.4%	0	11	11	0.8
TOTALS, air conditioning			1,283	1,439	$125	6.1%	6.6%	-1.8%	10.9%	88	69	157	$18.5

Annual heating

	Heating equipment saturation			Total heating energy use			% Change, existing trees			Change in energy use			Total savings (M$'s)
Building Type	Heat Pump	Electric Resist.	Natural Gas	Existing trees (TJ)	No Trees (TJ)	No Trees (M$)	Direct Shade	Wind Speed	Net change	Shade (TJ)	Wind Speed (TJ)	Total (TJ)	
1-4 Family Res	23%	14%	63%	11,367	11,416	116	-4.1%	4.5%	0.4%	-464	513	49	0.53
5+ Family Res	34%	26%	40%	1,059	1,074	14	-1.2%	2.7%	1.5%	-13	29	16	0.21
Small C/I [4]	0%	8%	92%	3,032	3,048	20	-1.1%	1.6%	0.5%	-33	49	16	0.18
Large C/I [4]	0%	8%	92%	4,675	4,739	30	0.0%	1.3%	1.3%	0	64	64	0.35
TOTALS, heating				20,132	20,277	$180	-2.5%	3.2%	0.7%	-510	655	145	$1.3

Peak air conditioning

		Total energy demand		% Change, existing trees				Change in demand			Total avoided costs (M$'s)
Building Type	$/kW Avoided	Existing trees (MW)	No Trees (MW)	Direct Shade	Air Temp	Wind Speed	Net change	Shade (MW)	Temp/Wind (MW)	Total (MW)	
1-4 Family Res	50.00	510	585	5.3%	5.1%	2.4%	12.9%	31	44	75	3.8
5+ Family Res	50.00	95	102	1.6%	3.9%	1.4%	6.9%	2	5	7	0.4
Small-Med C/I	50.00	491	511	1.0%	1.9%	0.9%	3.8%	5	14	19	1.0
Large C/I	50.00	817	839	0.0%	1.8%	0.8%	2.6%	0	22	22	1.1
TOTALS, peak cooling		1,914	2,037	1.9%	2.9%	1.3%	6.1%	38	86	124	$6.2

Table 3. Total, per unit and per tree, residential energy-use savings for Sacramento County. There are a total of 441,943 residential living units.

	Existing Tree Shade		Air Temperature		Wind Speed		Total		Heating + Cooling
	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	
Total Energy use							655 GWh	12,490 TJ	
Change for county	78 GWh	-477 TJ	72 GWh	0 TJ	-21 GWh	542 TJ	129 GWh	65 TJ	
Percent change	11.9%	-3.8%	10.9%	0.0%	-3.1%	4.3%	19.7%	0.52%	
Change for county (M$)	10	-5	9	0	-3	6	16	1	17
Change/unit	176 kWh	-1,079 MJ	162 kWh	0 MJ	-47 kWh	1,226 MJ	292 kWh	147 MJ	
Change/unit ($)	22	-12	21	0	-6	13	37	2	39
Change/tree §	73 kWh	-447 MJ	67 kWh	0 MJ	-19.3 kWh	508 MJ	121 kWh	61 MJ	
Change/tree ($)	9.3	-4.9	8.5	0	-2.4	5.6	15.3	0.7	16
Change/tree ¶	73 kWh	-447 MJ	23 kWh	0 MJ	-6.5 kWh	172 MJ	89 kWh	-275 MJ	
Change/tree ($)	9.3	-4.9	2.9	0	-0.8	1.9	11.3	-3.	8

§ Trees found < 20 m from residences (1,066,338) used to compute air temperature and wind speed values

¶ All 3,152,232 residential trees used to compute air temperature and wind speed values

Table 4. Annual cooling savings by sector and building type from existing trees for Sacramento County.

	Energy Use by Sector (percent)			Savings by Sector								
				City			Suburb			Rural		
Building Type	City	Suburb	Rural	GWh	$(millions)	(%)	GWh	$(millions)	(%)	GWh	$(millions)	(%)
Residential Low	34%	54%	12%	47	6.0	40%	61	7.8	52%	10	1.3	8%
Residential High	40%	55%	5%	5	0.7	52%	5	0.6	46%	0	0.0	3%
Small/Medium C/I	30%	32%	39%	6	0.5	35%	5	0.4	28%	6	0.5	37%
Large C/I	55%	36%	8%	10	0.7	85%	2	0.1	15%	0	0.0	0%
TOTALS	40%	44%	16%	68	$7.8	43%	72	$8.9	46%	16	$1.8	10%

City and suburban sectors account for 40% and 44% of total energy use, respectively, compared to 16% for the rural sector (Table 4). Savings were a slightly greater percentage in city and suburban sectors (44% and 46%), with rural savings being somewhat smaller (10%). These overall energy-use and savings distributions were found for all building types except small- to medium-sized commercial/industrial, where distributions were approximately uniform across building type, reflective of the somewhat more even distribution of commercial/industrial land uses across sectors (McPherson 1998).

Annual space-conditioning savings due to existing trees are greatest for residential areas surrounding the urban core and within the U.S. 50 and Interstate 80 corridor, as illustrated for residential air conditioning (Figure 1). Geographic distribution of savings generally correspond to tree density distributions (McPherson 1998). Because net annual heating impacts are small compared to annual cooling (Table 2), distribution of cooling savings in the figure can be interpreted as total savings with little error.

Discussion

In this section, sensitivity analyses are used to demonstrate the model's "what-if" capability and to make preliminary estimates of effects of selected uncertainties in key model inputs on resulting energy use. This is followed by discussion of other model components which can impact savings estimates.

The range of annual cooling savings (Figure 2) depends on canopy air temperature ($0.5 < \Delta T^{CC} < 2.5$°C/10%$\Delta$C) and UED temperature ($5 < \Delta UED^{T} < 12$%/°C) coefficients (see appendix; ΔC = change in canopy cover). Maximum temperature reduction computed for each SubRAD ($\Delta T = \Delta T^{CC} \times \Delta C$) is limited to 3.5°C, the largest value found by Huang et al. (1987) for Sacramento (25%ΔC). This limits computed savings for larger values of ΔT^{CC} in Figure 1 but has no impact at the lower value used here of ΔT^{CC} = 1.0°C/10%ΔC.

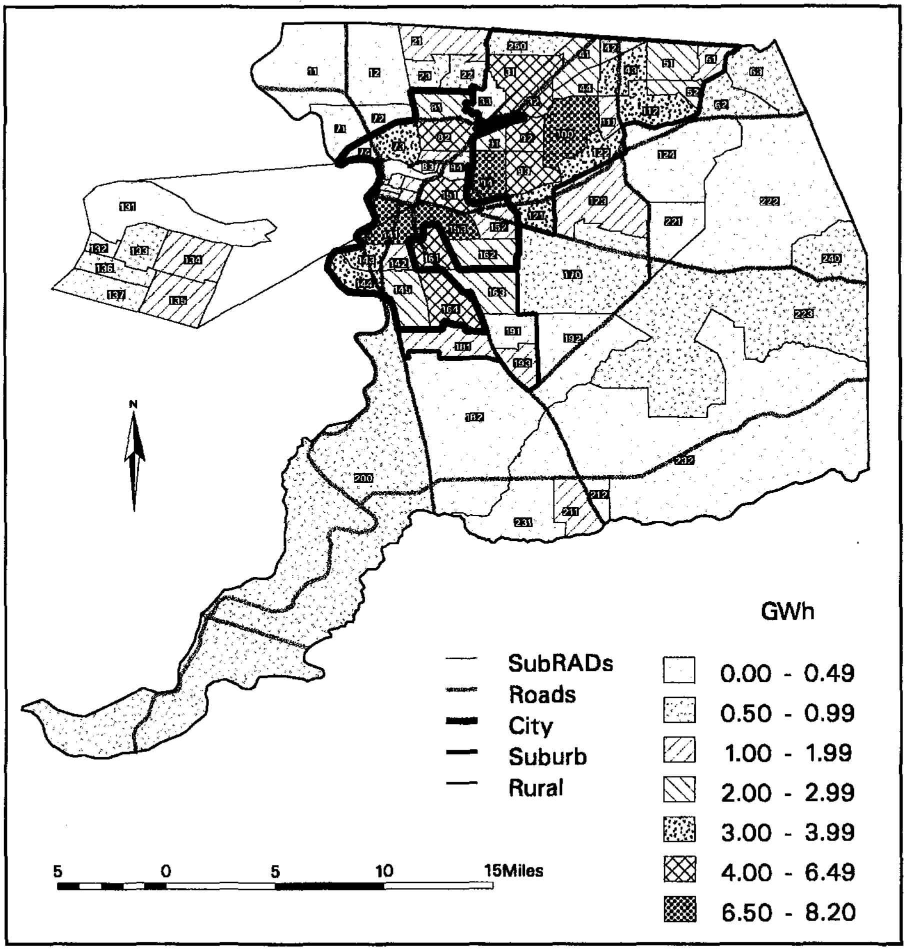

Figure 1. Annual air-conditioning energy savings from existing trees in Sacramento County by SubRAD.

Air-temperature-related savings found in the detailed analysis (6.6%, or 95 GWh) are indicated in the figure, as well as savings from shade (88 GWh). Savings of 95 GWh are nearer the low end of the possible range (low of 40 GWh; high of 350 GWh).

Annual cooling savings from shade are related to uncertainty in the number of trees per property (~ ± 5%, McPherson and Simpson 1995) and savings per tree (ΔUED^{tree}, range based on Huang et al. 1987; Huang et al. 1990; McPherson 1994; Simpson and McPherson 1998) (Figure 3). Savings found in the detailed analysis are indicated in the figure, as well as savings from reduced air temperature (95 GWh), which are represented as constant with changing number of trees per property because it is assumed that reference is to an individual building—not to large-scale changes in tree numbers for many properties. The number of trees per property and ΔUED^{tree} in the figure are averages for the county; in the actual analysis, percentage changes were applied to these variables as a function of vintage, size, or SubRAD, as appropriate.

Complete analysis of upper and lower bounds for energy savings is beyond the scope of the present paper due to the many variables and relationships involved, and lack of definitive information concerning key processes. Methods presented provide a basis for evaluating sensitivity of energy savings to tree, building, and climate characteristics, and identifying areas for improvement. For example, Sacramento results (Table 2) suggest that: 1) shade and wind effects on heating approximately balance each other, so need not be considered; 2) air-conditioning savings from direct shade (88 GWh, \$10.7 million) may be as little as 68 GWh (\$8.3 million, Figure 3), which suggest a range of approximately \$10 ± 2 million; and 3) heat gain due to reduced wind speed is probably overestimated because shade is not accounted for in estimates of wind-speed effects employed here. Any refinement would likely increase benefits, so the loss due to wind-speed reduction is fixed at –\$3 million (Table 2). 4) Minimum expected savings from air-temperature reduction (Figure 2) are 42 kWh (~\$5 million).

Combining results suggests approximate bounds on savings of \$17 ± 7 million. This is considered a worst-case scenario for the processes considered, given the disparate data sources used to determine the range of input parameters. More precise information, especially related to air temperature, is needed to refine these estimates. In addition, a number of other areas related to climate and energy use, building characteristics, and urban forest structure should be considered in a comprehensive sensitivity analysis. In many cases, limited data are available. It should be noted that greater overall savings could be expected

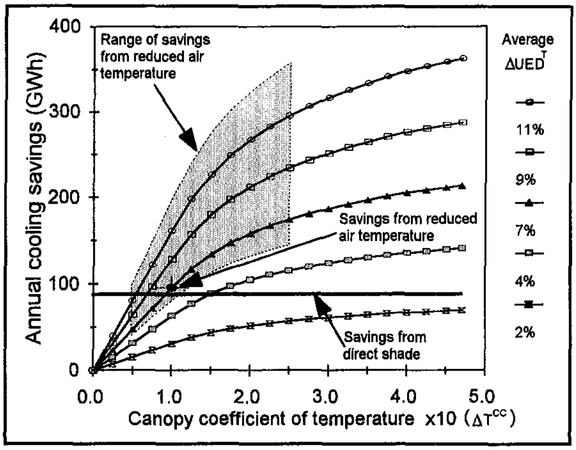

Figure 2. Effect of canopy air temperature coefficient ΔT^{CC} and UED temperature coefficient (ΔUED^{T}) on cooling savings.

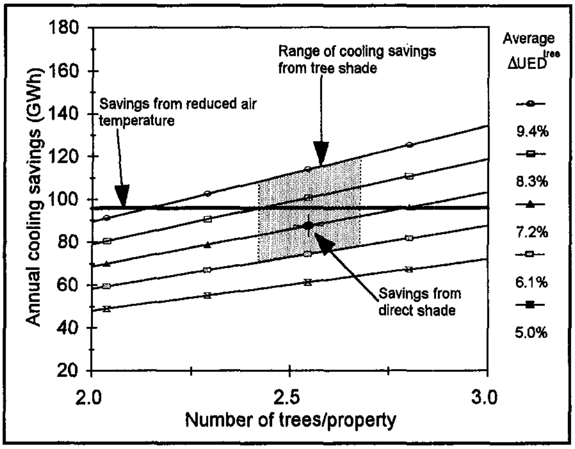

Figure 3. Effect of changes in numbers of trees per property and UED per tree (ΔUED^{tree}).

for a tree planting program designed to produce beneficial results such as reduced energy use. For example, it is estimated that existing trees on south sides of buildings in Sacramento account for approximately one-third of the increase in winter heating costs from shade found here (~\$2 million) and 15% of summer air-conditioning savings (~\$1.5 million). A design that maximized these benefits while minimizing the costs would increase overall program savings.

Effects of trees on climate, and climate on energy savings, are largely based on simulation results. The magnitude of simulated shade effects has been confirmed for cooling based on actual measurements of energy-use changes for individual buildings in Sacramento (e.g., Akbari et al. 1993). Measured data for larger numbers of buildings as functions of shade, air temperature, and wind speed are not available for cooling or heating impacts. Total energy-use results here are scaled to actual utility data, minimizing overestimates of savings or costs computed as percentage changes. For tree effects on air temperature in particular, it has been pointed out (e.g., Huang et al. 1987) that inflated estimates of cooling effects may result by assuming that water is always freely available for transpiration. As a result, conservative values for defining parameters (e.g., ΔT^{CC}, ΔUED^{T}) were used; results from southern California indicating that a large proportion of residential landscapes are well-watered (Kiefer and Dziegielewski 1991) indicate that this may not be a concern.

The magnitude of results also relies on approximately offsetting impacts of wind reduction and shade on heating and the fact that net heat gain from changes in infiltration of outside air, natural ventilation, and convective heat gain (or possibly loss) from wind reduction are no larger than estimated. In the latter case, it is likely that convective gain in the summer is overestimated because the method used here does not account for the possibility that gain will be smaller, and possibly even a heat loss, for surfaces shaded by trees. Such a reduction in heat gain would not be as pronounced in winter due to reduced shading from deciduous trees. Other potential climate impacts from increased tree canopy cover, such as increased relative humidity or long-wave radiation, are likely smaller than those in the present treatment and so are not considered here.

Residential energy use and changes in energy use per unit (total energy use divided by number of units) reported here reflect energy use for the average structure by incorporation of adjustments for diversity and equipment saturation. Consequently, an individual residential customer with central space conditioning that is normally left on with summer/winter thermostat setpoints of 26°C/20°C (78°F/68°F) can expect energy-use changes ranging from 50% to 150% larger for cooling, and 5% to 50% larger for heating, than those in Table 3, with greater energy use and energy-use changes for older vintages and lower densities, and smaller values for newer vintages and higher densities.

Simplifying assumptions are made for high-density residential and commercial/industrial buildings, such as extrapolation of single-family residential building parameters to describe them, and reductions to building shade for higher-density and commercial structures. Potential errors introduced by these effects are minimized by conservative choice of parameters, and the fact that most (~80%) heating and cooling savings are for low-density residential buildings. Uncertainty in number of trees was approximately ± 5%

(McPherson and Simpson 1995); in any event, tree numbers are likely underestimated due to inventory methods used (Sacamano et al. 1995).

Conclusions

Sacramento County's existing urban forest is responsible for annual air-conditioning savings of approximately 157 GWh ($18.5 million) per year of electricity. This is 12% of total air conditioning and 1.5% of total electrical use. Savings from shading, air-temperature, and wind-speed reduction are 6.1%, 6.6%, and −1.8%, respectively. Beneficial effects of wind-speed reduction are somewhat greater than detrimental effects of shading for space heating, resulting in 145 TJ ($1.3 million) savings annually. Net annual heating and cooling savings for the county are $20 million. Peak energy reductions result in avoided costs of $6 million.

A number of areas for further study and improvement are suggested. Better functional relationships between urban forest structure, climate, and building energy use are necessary to reduce the level of uncertainty from current estimates. This would include better methods for determining tree sizes and shading coefficients for diverse urban populations, more detailed studies of the effects of changing forest structure on microclimate, and better information on the magnitude of climate effects on building energy use based on measured data.

In terms of current and possible future urban forestry programs, results suggest that ample tree planting opportunities exist or will exist for both newer and older residential buildings in Sacramento. The methodology presented can be applied to estimate benefits of these programs. Potential energy savings per unit area (ΔUEDs) are smaller for newer, more energy-efficient buildings, and lot sizes may be smaller. However, newer residences tend to be larger and have fewer existing trees, providing more potential planting opportunities. The large number of older residences, because of their large UEDs, will become increasingly important candidates for tree planting as existing trees age and need replacement. Commercial/industrial areas represent another potentially important planting opportunity. The large proportion of energy use there (about 60% of total annual cooling) (Table 2) and small amount of saving (20%) suggest that even a small percentage change in savings would be appreciable if applied to a large segment of the population. In addition, better information on tree impacts in these areas may reveal savings larger than the conservative results reported here.

Literature Cited

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

Akbari, H., S.E. Bretz, J.W. Hanford, D.M. Kurn, B.L. Fishman, H.G. Taha, and W. Bos. 1993. Monitoring peak power and cooling energy savings of shade trees and white surfaces in the Sacramento Municipal Utility District (SMUD) service area. Report LBL-34411, Energy and Environment Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA.

EIA. 1993. Household energy consumption and expenditures 1990, Supplement: Regional. Energy Information Administration, Office of Energy Markets and End Use, US Department of Energy, Washington, DC. DOE/EIA-0321(90)/S, 359 pp.

EIA. 1994. Energy end-use intensities in commercial buildings. Energy Information Administration, Office of Energy Markets and End Use, US Department of Energy, Washington, DC. DOE/EIA-0555(94)/2. 135 pp.

Heisler, G.M. 1990. *Mean wind speed below building height in residential neighborhoods with different tree densities.* ASHRAE Transactions 96(1):1389–1396.

Hildebrandt, E., R. Kallett, M. Sarkovich, and R. Sequest. 1996. Maximizing the energy benefits of urban forestation. Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings. ACEEE, Washington, DC.

Huang, J., H. Akbari, H. Taha, and A. Rosenfeld. 1987. *The potential of vegetation in reducing summer cooling loads in residential buildings.* J. Climate Appl. Meteorol. 26:1103–1106.

Huang, J., H. Akbari, and H. Taha. 1990. *The wind-shielding and shading effects of trees on residential heating and cooling requirements.* ASHRAE Trans. 96 (1):1403–1411.

Kiefer, J.C., and B. Dziegielewski. 1991. Analysis of residential landscape irrigation in southern California. Report to Planning Division, Metropolitan Water District of Southern California, Los Angeles, CA.

Lowry, W.P. 1988. Atmospheric Ecology for Designers and Planners. Peavine Publications, McMinnville, OR. 435 pp.

McPherson, E.G. 1994. Energy-saving potential of trees in Chicago, pp 95–114. **In** McPherson, E.G., D.J. Nowak, and R.A. Rowntree (Eds.). Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. USDA For. Serv. Northeast For. Exp. Sta. Gen. Tech. Rpt. NE-GTR-186. Radnor, PA.

McPherson, E.G. 1995. Net benefits of healthy and productive urban forests, pp 188–194. **In** Bradley, G.A. (Ed.). Urban Forest Landscapes, Integrating Multidisciplinary Perspectives. University of Washington Press, Seattle, WA.

McPherson, E.G. 1998. *Structure and sustainability of Sacramento's urban forest.* J. Arboric. 24(4):174–190.

McPherson, E.G., and J.R. Simpson. 1995. Technical potential for shade tree planting in Sacramento County. Final report, USDA For. Serv. West. Ctr. for Urban For. Res. & Educ., Davis, CA.

Meier, A.K. 1990/91. *Strategic landscaping and air-conditioning savings: A literature review.* Energy and Buildings 15–16:479–486.

Myrup, L.O., C.E. McGinn, and R.G. Flocchini. 1993. *An analysis of microclimatic variation in a suburban environment.* Atmos. Environ. 27B:129–156.

Rosenfeld, A., J. Romm, H. Akbari, M. Pomerantz, and H. Taha. 1996. Policies to reduce heat islands: Magnitudes of benefits and incentives to achieve them. **In** Proc. 1996 ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC. Also Lawrence Berkeley National Laboratory Report No. LBL-36587, Berkeley, CA. 1996.

Sacamano, P.L., E.G. McPherson, R.J. Myhre, M. Stankovich, and R.C. Weih. 1995. *Describing urban forest cover: An evaluation of airborne videography.* J. For. 93:43–48.

Sacramento Area Council of Governments. 1995. SACOG 1994 Housing Module, Sacramento Area Council of Governments, Sacramento, CA.

Sailor, D.J., L. Rainer, and H. Akbari. 1992. Measured impact of neighborhood tree cover on microclimate, pp 9.149–9.157. **In** Proc. 1992 ACEEE Summer Study on Energy Efficiency in Buildings, Vol 9. American Council for an Energy-Efficient Economy, Washington, DC.

Simpson, J.R., and E.G. McPherson. 1995. Impact evaluation of the Sacramento Municipal Utility District's shade tree program, Sacramento Municipal Utility District, Monitoring and Evaluation, Sacramento, CA.

Simpson, J.R., and E.G. McPherson. 1996. *Potential of tree shade for reducing residential energy use in California.* J. Arboric. 22(1):10–18.

Simpson, J.R., and E.G. McPherson. 1998. *Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento.* Atmos. Environ.: Urban Atmos. 32:69–74.

Sacramento Municipal Utility District. 1994. Demand-Side Management Resource Plan, Vol. 1: Executive Summary. SMUD, Resource Planning and Evaluation Department, Sacramento, CA.

Sacramento Municipal Utility District. 1995. Shade Tree Program Impact Evaluation. SMUD, Monitoring and Evaluation Department, Sacramento, CA.

Taha, H., H. Akbari, and A.H. Rosenfeld. 1991. *Heat island and oasis effects of vegetative canopies: Micro-meteorological field-measurements.* Theor. Appl. Climatol. 44:123–138.

Wilkin, D., and H. K. Jo. 1993. Landscape carbon budgets and planning guidelines for greenspaces in urban residential lands. Tech. Res. Rep. School of Renewable Natural Resources, University of Arizona, Tucson, AZ. 205 pp.

Appendix: Calculation of Climate Effects on UEDs

Unit energy densities (UEDs) and total energy use. UEDs were estimated for residential structures following methods from Simpson and McPherson (1995, 1998). They performed detailed simulations of residential energy use for a sample of 254 single-family residences in Sacramento County divided into pre-1978, 1978–1983, and post-1983 vintages. Vintage is used here as a surrogate for building energy efficiency, reflecting increasingly stringent standards in California over time to reduce building energy use. Vintage differences are reflected mainly in insulation levels, HVAC equipment efficiency, CFA, and window construction. Multifamily structure UEDs (UED_{mf}) were estimated as the product of single-family UEDs (UED_{sf}), and energy adjustment ratios UED_{mf}/UED_{sf} (Table 6 on page 213) reported for similar structures and climate (zone 4) from a national survey of residential energy consumption (EIA 1993). Similar adjustment ratios were used to account for UED differences between single-family detached and attached residences and mobile homes.

Residential UEDs were adjusted by equipment and diversity factors (Table 6) to estimate energy use for the county from individual building data. Equipment factors are average estimated reductions in energy consumption for alternative cooling methods compared to central air conditioning (SMUD 1995), weighted by the occurrence of each type of equipment in the county based on data from a 1993 SMUD residential appliance saturation survey (Sarkovich, personal communication 9/5/96). It is assumed that all residences are heated. Diversity factors result from operational differences within a population that reduce average consumption per unit, that is, some space-conditioning units being turned off and thermostat setpoints being much higher or lower than normal. Diversity factors are estimated from ratios of average energy use per unit for the entire population from SMUD data (Sarkovich, personal communication 4/5/96) to that from Simpson and McPherson (1998) for each vintage. Single-family values were assumed for multifamily dwellings. Unless stated otherwise, reference to UEDs are to adjusted values, products of single-family UEDs and energy adjustment ratios, equipment, and diversity factors (Table 6).

Each of the 12 building types in Table 6 is associated with 4 separate tables in the computer model, representing total energy use and changes in energy use due to solar radiation, air-temperature, and wind-speed reduction. The resulting 48 tables contain tree cover, building cover, trees per unit, and number of units appropriate for each building type for each of the 71 SubRADs. Results by SubRAD from these tables are then combined to produce results for each sector and the county.

Commercial/industrial UEDs for annual and peak cooling are quotients of total energy use and CFAs for each of 3 building sizes for the county supplied by SMUD, reduced by system distribution efficiency of 94% (Hildebrandt, personal communication 4/24/96), so adjustments associated with scaling-up are already accounted for. UEDs for commercial/industrial heating are taken from EIA (1994) for climate zone 4. Heating values for natural gas are expressed in SI units (1.0 kBtu/ft^2 = 11.35 MJ/m^2); residential annual fuel utilization efficiencies of 0.75 to 0.78 were assumed.

Total energy use for the county (E_c) for annual cooling (GWh), peak cooling (MW), or annual heating (TJ) is found as the summed products of individual building effects,

$$E_c = \sum_{i=1}^{4}\sum_{j=1}^{3}\sum_{k=1}^{71}\left[UED_{i,j} \times CFA_{i,j} \times n_{i,j,k}\right] \qquad \text{(A1)}$$

where $UED_{i,j}$ is adjusted UED (Table 6), $CFA_{i,j}$ is conditioned floor area, and $n_{i,j,k}$ is number of units for building type i, vintage (residential) or size (commercial) j, and SubRAD k. Average UEDs and CFAs for each vintage or size were assumed to apply to the entire county.

UED changes and tree shade. Energy savings from tree shade are based on previous studies (Simpson and McPherson 1995, 1998) that simulated effects of existing trees, adjacent buildings, and trees recently planted by a local tree planting program on single-family residential space-conditioning energy use in Sacramento County. Attenuation of solar radiation by trees and adjacent buildings was simulated using the Shadow Pattern Simulator program (SPS), which accounts for tree size, location, canopy density, and time to calculate shade on building surfaces. Space-conditioning energy use was determined with Micropas 4.01 (Enercomp, Inc., Sacramento), which accounts for building, shading, and weather effects. Savings from shade were reduced by 25% to remove effects of adjacent buildings. Current results are relatively insensitive to this percentage, with net annual savings from cooling and heating varying less than ± 5% for a building shade range of 25% ± 15%.

UED changes for higher-density residential and commercial structures were calculated from single family residential UEDs adjusted by average potential shade factors (APSF) to account for reduced shade resulting from common walls and multi-story construction. APSFs are estimated from potential shade factors (PSF), defined as ratios of exposed wall or roof (ceiling) surface area to total surface area, where total surface area includes common walls and ceilings between attached units in addition to exposed surfaces. PSF = 1 indicates that all exterior walls and roof are exposed and could be shaded by a tree, while PSF = 0 indicates that no shading is possible (e.g., the common wall between duplex units). PSFs are estimated separately for walls (PSF_w) and roofs (PSF_r) for both single and multi-story structures (Table 5 on page 212). For example, a 3- to 4-unit multifamily structure is estimated to have 3 exposed walls with $PSF_w = 3/4 = 0.75$ for a 2-story structure, and 2 exposed walls with $PSF_w = 2/4 = 0.50$ for 1 story. $PSF_r = 0.5$ for 2 stories and 1.0 for 1 story.

One- and 2-story unit fractions (f_u) are defined as proportions of units that have 1 or 2 stories; a multi-story (> 2 stories) shade-reduction factor (s_r) accounts for reduced shading of upper stories extending above the height of most trees. Average PSF is then $APSF = f_u \times (PSF_{w1} + PSF_{r1})/2 + (1 - f_u) \times s_r \times (PSF_{wn} + PSF_{rn})/2$, where subscripts 1 and n refer to 1 to 2 and > 2 stories, respectively. An APSF of 0.6, the approximate mean value for low- and medium-density residential structures (Table 5), was used for small commercial structures, which have similar CFAs (Table 6); APSF for high-density residential was used for medium and large commercial structures (Table 5). No energy impacts (APSF = 0) were ascribed to large commercial/industrial structures due to shading because these structures are expected to have surface-to-volume ratios an order of magnitude larger than smaller buildings and less extensive glazed area. Fewer numbers of trees expected near commercial structures are accounted for in a subsequent section.

Trees per unit ranged from 2.5 to 3.4 for pre-1978 to post-1983 vintages, respectively (Simpson and McPherson 1998). These values were adjusted by relative tree density with respect to low-density residential properties (adjustment factor for trees per unit, Table 1) for high-density residential and commercial properties. They accounted for effects of tree size, distance to building, and orientation by averaging results for 254 properties. Change in energy use from shade for the county (ΔE_{cs}) was found as

$$\Delta E_{cs} = \sum_{i=1}^{4}\sum_{j=1}^{3}\sum_{k=1}^{71}\left[\Delta UED_{i,j}^{tree} \times n_{i,j,k}^{tree} \times CFA_{i,j} \times n_{i,j,k}\right] \qquad \text{(A2)}$$

where $\Delta UED_{i,j}^{tree}$ is adjusted change in UED per tree (UED shade coefficient, Table 6), $n_{i,j,k}^{tree}$ is number of trees, $CFA_{i,j}$ is conditioned floor area, and $n_{i,j,k}$ is number of units for building type i, vintage (residential) or size (commercial) j, and SubRAD k.

UED changes and air temperature. Increases in urban tree cover over neighborhood or larger scales can have a cooling effect due to transpiration, which reduces summer air-conditioning demand. Individual trees are unlikely to have a significant effect on air temperature beyond their immediate vicinity because atmospheric mixing rapidly dilutes cooler air near the tree with air at ambient temperature (Lowry 1988), but larger groupings of trees can measurably reduce summer air temperatures. Evaporation is largely driven by net (incoming minus reflected) solar radiation, so that resulting temperature reductions typically reach a maximum in early to mid-afternoon. Temperature reductions at other times are approximately proportional to the amplitude of the diurnal temperature cycle, approaching zero in morning and evening (Huang et al. 1987). Temperature reductions in this paper refer to the afternoon maximum.

Countywide tree impact on space-conditioning energy use from air-temperature modification (ΔE_{cT}) is the summed product of UED temperature coefficient ($\Delta UED^{T}_{i,j}$, change in UED per °C), canopy air-temperature coefficient ($\Delta T^{CC}_{i,j,k}$ change in air temperature per percentage change in canopy cover), percentage of canopy cover (CC_k), conditioned floor area ($CFA_{i,j}$), and number of units ($n_{i,j,k}$) for building type *i*, vintage (residential) or size (commercial) *j*, and SubRAD *k*, given as

$$\Delta E_{cT} = \sum_{i=1}^{4}\sum_{j=1}^{3}\sum_{k=1}^{71}\left[\Delta UED^{T}_{i,j} \times \Delta T^{CC}_{i,j,k} \times CC_k \times CFA_{i,j} \times n_{i,j,k}\right] \quad \text{(A3)}$$

ΔUED^T is the product of change in energy use due to change in air temperature estimated from the literature $(\Delta UED/UED)/\Delta T$, and adjusted UED (both from Table 6), or $(\Delta UED/UED)/\Delta T \times UED = \Delta UED/\Delta T = \Delta UED^T$. Reductions of 14% and 17% in annual residential air-conditioning energy use (kWh) were simulated for a 1.2°C air-temperature reduction (12% and 14% $°C^{-1}$) for pre-1973 and 1980s construction, respectively, in Sacramento (Huang et al. 1987). Sailor et al. (1992) estimated a 13% $°C^{-1}$ reduction in cooling degree days for Sacramento, which are closely related to annual kWh consumption. McPherson (1994) found kWh savings of 5.1% to 7.0% $°C^{-1}$ for various construction types in Chicago. Capacity (kW) savings of 6.4% and 2.0% $°C^{-1}$ were simulated by Huang et al. (1987) for 1980s and pre-1973 homes in Sacramento, respectively. Results of a similar magnitude (4.9% $°C^{-1}$) were found in Dade County, Florida, based on measured central air-conditioner energy use and outside air temperature for a sample of approximately 50 properties (Parker, personal communication 1994). McPherson (1994) found average kW savings ranging from 2.7% to 25% $°C^{-1}$ for various construction types in Chicago. Based on these data, cooling energy and capacity reductions for Sacramento are estimated to be 6% and 7% $°C^{-1}$ for kWh, and 2% and 6% $°C^{-1}$ (kW) for pre-1978 and post-1983 vintages, respectively (Table 6). Evaporative cooling effects on heating are assumed to be negligible because solar radiation is at a minimum during the heating season, and most plants are dormant and not actively transpiring. Values for single-family residential buildings were used as estimates for higher-density residential and commercial/industrial buildings, because data for the latter were not available.

For each SubRAD, maximum temperature deficit for each percentage increase in canopy cover (canopy coefficient of air temperature, ΔT^{CC}) is estimated to be 0.1°C. This is based on reported reductions of maximum midday air temperature ranging from 0.04°C to 0.2°C per percentage increase in canopy cover, where temperature reductions reflect the aggregate effect of all the trees in the local area (Huang et al. 1987; Taha et al. 1991; Sailor et al. 1992; Myrup et al. 1993; Wilkin and Jo 1993). For Sacramento in particular, Huang et al. (1987) simulated a 1.2°C decrease for a 10% citywide canopy cover increase. Sailor et al. (1992) estimated a decrease of 0.36°C per 10% cover increase based on regression analysis of measurements at 15 residential locations scattered throughout Sacramento. Cover was determined for approximately 40-ha (100-ac) areas surrounding each measurement location; substantial scatter was observed in the data. Taha et al. (1991) consistently found midday air temperature reductions of approximately 1°C per 10% cover difference for an orchard compared to a dry field in nearby Davis, California; reductions occasionally reached 2.4°C per 10% cover difference.

UED changes and wind speed. Reduced wind speed can have a number of effects on building heat gain (Huang et al. 1990). Convective heat gain may increase for sunlit surfaces but decline for those in shade. The former increases cooling load in summer but reduces heating load in winter; the latter has just the opposite effect. In addition, infiltration of outside air is reduced, which reduces demand for both heating and cooling. Effectiveness of natural ventilation for cooling will be diminished.

Countywide energy impact from wind-speed reduction (ΔE_{cU}) is the summed product of UED wind coefficient ($\Delta UED^{U}_{i,j}$, UED change per percentage change in wind speed), canopy wind speed coefficient ($\Delta U^{CC}_{i,j,k}$, percentage change in wind speed per percentage change in canopy cover), percentage of canopy cover (CC_k), conditioned floor area ($CFA_{i,j}$), and number of units ($n_{i,j,k}$) for building type *i*, vintage (residential) or size (commercial) *j*, and SubRAD *k* as

$$\Delta E_{cU} = \sum_{i=1}^{4}\sum_{j=1}^{3}\sum_{k=1}^{71}\left[\Delta UED^{U}_{i,j} \times \Delta U^{CC}_{i,j,k} \times CC_k \times CFA_{i,j} \times n_{i,j,k}\right] \quad \text{(A4)}$$

ΔUED^U is the product of change in energy use due to change in wind speed $(\Delta UED/UED)/(\Delta U/U)$, and adjusted UED (both from Table 6), or $(\Delta UED/UED)/(\Delta U/U) \times UED = \Delta UED/(\Delta U/U) = \Delta UED^U$. Values for ΔUED^U are based on simulated wind-reduction effects on building heating and cooling loads for typical pre-1973 and 1980s houses in Sacramento (Huang et al. 1990) using wind reductions from Heisler (1990). Their base case was no trees and approximately 25% ground coverage due to buildings. Wind-speed reductions were simulated for 10%, 20%, and 30% canopy cover increases (equivalent to 1, 2, and 3 trees/property). Resulting UED wind coefficients are used for all residential building types of the sam e vintage; average values are used for commercial buildings due to lack of better data.

Fractional change in wind speed ($\Delta U/U$) for each percentage increase in canopy cover (wind-speed coefficient ΔU^{CC}) is estimated for each SubRAD as $\Delta U^{CC} = (TC + BC)/(24 + 1.1 \times (TC + BC)) - BC/(24 + 1.1 \times BC)$, where TC and BC are percentages of tree canopy and building cover, respectively (Heisler 1990). Results apply to aggregate effects of trees and buildings in the local area. Reductions range from 3% to 8% for a 10% increase in canopy cover, depending upon antecedent canopy and building cover (Figure 4).

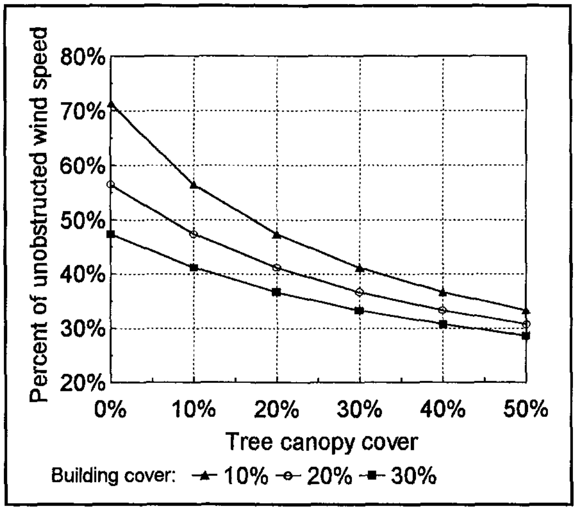

Figure 4. Decrease in wind speed from increase in canopy and building cover (from Heisler 1990).

Acknowledgements. Thanks to Greg McPherson for his comments and suggestions, as well as his leadership of the Sacramento Urban Forest Ecosystem Project, from which this work arose. In-depth reviews of early versions of the manuscript by Peggy Sand and Eric Hildebrandt are greatly appreciated, as was data provided by the Sacramento Utility District and the Sacramento Tree Foundation. Funding for this work was provided by the USDA Forest Service Western Center for Urban Forest Research and Education.

James R. Simpson
Forest Meteorologist
Pacific Southwest Research Station
USDA Forest Service
c/o Department of Environmental Horticulture
University of California
Davis, CA 95616
(916) 752-9534

Table 5. Residential shade adjustments (PSF: potential shade factor; APSF: average PSF).

	Low density			Medium density		High density
Unit Types:	Single family detached	Mobile Home	Single family Attached	Duplex	Multi- family (3-4 units)	Multi- family (5 or more units)
Building distribution (1990 census)	59%	4%	7%	3%	6%	21%
Wall PSF: 1 story	1.00	1.00	0.75	0.75	0.50	0.38
>2 story	1.00	1.00	0.75	0.75	0.75	0.38
Roof PSF: 1 story	1.00	1.00	1.00	1.00	1.00	1.00
>2 story	1.00	1.00	1.00	1.00	0.75	0.50
1 and 2 story unit fraction	1.00	1.00	1.00	1.00	0.60	0.40
Multistory (>2) shade reduction	1.00	1.00	1.00	1.00	0.75	0.50
APSF	1.00	1.00	0.88	0.88	0.68	0.41
APSF by density class		0.99		0.74		0.41

Table 6. Energy-use data summary by building type and vintage/size. Floor areas are in square meters (m^2).

Building Type:		Residential									Commercial/Industrial		
		Low density: SF detached/attached, mobile homes			Medium density: Two to four units/structure			High density: Five or more units/structure			Small	Medium	Large
Vintage:		pre-80	80-84	post-84	pre-80	80-84	post-84	pre-80	80-84	post-84			
Unit Energy Densities (UED's)													
Energy adjustment ratio	annual cooling	1.11	1.11	1.11	1.29	1.29	1.29	1.49	1.49	1.49			
	peak cooling	1.11	1.11	1.11	1.29	1.29	1.29	1.49	1.49	1.49			
	Gas heat (GJ)	1.04	1.04	1.04	0.86	0.86	0.86	0.72	0.72	0.72			
	Elec heat (GJ)	0.95	0.95	0.95	1.00	1.00	1.00	0.63	0.63	0.63			
Diversity factors	annual cooling	0.56	0.77	0.85	0.56	0.77	0.85	0.56	0.77	0.85			
	peak cooling	0.45	0.57	0.77	0.45	0.57	0.77	0.45	0.57	0.77			
	Heating (GJ)	0.65	0.84	0.98	0.65	0.84	0.98	0.65	0.84	0.98			
Equipment factors	annual cooling	0.70	0.95	0.95	0.70	0.95	0.95	0.71	0.82	0.91			
	peak cooling	0.70	0.95	0.95	0.70	0.95	0.95	0.70	0.95	0.95			
	Heating (GJ)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00			
Adjusted UED's	A/C kWh/m^2	12.6	12.8	11.9	14.5	14.9	13.7	17.1	14.9	15.3	24.3	25.5	25.1
	W/m^2	12.2	13.5	13.5	14.2	15.7	15.7	16.4	18.2	18.1	5.1	63.7	44.7
	Gas (MJ/m^2)	287	206	174	237	171	144	198	143	120	256	256	256
	Elec (MJ/m^2)	262	188	159	276	198	167	174	125	105	14.8	14.8	14.8
Changes to UED's from Solar Radiation, Air Temperature and Wind Speed modifications													
	Average potential shade fraction	0.99	0.99	0.99	0.74	0.74	0.74	0.41	0.41	0.41	0.60	0.40	0.00
	a/c %kWh Change/tree	6.6%	7.3%	7.6%	5.0%	5.4%	5.7%	2.7%	3.0%	3.1%	4.4%	2.9%	0.0%
	%kW Change/tree	2.7%	2.8%	3.5%	2.1%	2.1%	2.6%	1.1%	1.1%	1.4%	1.7%	1.1%	0.0%
	heat %GJ Change/tree	-2.0%	-2.5%	-2.8%	-1.5%	-1.9%	-2.1%	-0.8%	-1.0%	-1.2%	-1.5%	-1.0%	0.0%
UED shade coefficient	kWh/m^2/tree	0.83	0.93	0.90	0.73	0.81	0.79	0.47	0.44	0.48	1.12	0.77	0.00
	W/m^2/tree	0.33	0.38	0.47	0.29	0.33	0.41	0.18	0.21	0.26	0.09	0.73	0.00
	MJ/m^2/tree	-5.7	-5.2	-4.9	-3.5	-3.2	-3.1	-1.6	-1.5	-1.4	-3.88	-2.60	0.00
Air temperature													
	%kWh Change/°C	6.0%	6.5%	7.0%	6.0%	6.5%	7.0%	6.0%	6.5%	7.0%	6.7%	6.7%	6.7%
	%kW Change/°C	2.0%	4.0%	6.0%	2.0%	4.0%	6.0%	2.0%	4.0%	6.0%	4.1%	4.1%	4.1%
	%Heat Change/°C	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
UED temperature coefficient	kWh/m^2/°C	0.75	0.83	0.83	0.87	0.97	0.96	1.03	0.97	1.07	1.76	1.84	1.81
	W/m^2/°C	0.24	0.54	0.81	0.28	0.63	0.94	0.33	0.73	1.09	0.22	2.76	1.93
	MJ/m^2/°C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wind speed													
	%kWh Change/%U	-0.34%	-0.25%	-0.16%	-0.34%	-0.25%	-0.16%	-0.34%	-0.25%	-0.16%	-0.25%	-0.25%	-0.25%
	%kW Change/%U	0.16%	0.29%	0.42%	0.16%	0.29%	0.42%	0.16%	0.29%	0.42%	0.29%	0.29%	0.29%
	%Heat Change/%U	0.38%	0.48%	0.58%	0.38%	0.48%	0.58%	0.38%	0.48%	0.58%	0.48%	0.48%	0.48%
UED wind coefficient	kWh/m^2/%U	-0.04	-0.03	-0.02	-0.05	-0.04	-0.02	-0.06	-0.04	-0.02	-0.06	-0.06	-0.06
	kW/m^2/%U	0.02	0.04	0.06	0.02	0.05	0.07	0.03	0.05	0.08	0.01	0.19	0.13
	MJ/m^2/%U	1.09	0.99	1.01	0.90	0.82	0.83	0.75	0.69	0.70	1.23	1.23	1.23

Résumé. Les forêts urbaines affectent la consommation d'énergie pour la climatisation grâce à leur effet de modération sur le climat. Afin d'évaluer l'amplitude régionale de ces impacts, un système d'analyse à grande échelle a été développé et appliqué dans le comté de Sacramento en Californie. Les besoins en chauffage et climatisation, en périodes normales ou en périodes de pointe, résultant des modifications de la radiation solaire, de la température de l'air et de la vitesse du vent causées par la forêt urbaine environnante ont été estimés pour des édifices commerciaux et résidentiels. Ces données ont été combinées avec d'autres sur l'âge de l'édifice et ses dimensions, la surface d'ombrage créée par les arbres et la densité en arbres dans 71 quartiers différents. Les résultats ont été additionnés en terme de nombre d'unités pour ainsi obtenir une valeur totale pour le comté. Les économies annuelles en climatisation sont de 157 GWh (US$18,5 millions), soit 12% des besoins en climatisation du comté. Les effets nets sur le coût de chauffage des bâtiments sont faibles, soit 145 TJ annuellement (US$1,3 million). La diminution des besoins en périodes de pointe permet une économie de 6 millions de dollars (US). La finesse des résultats obtenus est prouvée avec des données type.

Zusammenfassung. Die Stadtforste wirken auf den Energieverbrauch als Ergebnis ihres moderaten Einflußes zu bewerten, wurde ein umfassendes Analysekonzept entwickelt und auf den Bezirk von Sacramento CA als Fallstrudie angewendet. Aufheizen, Abkühlen, die Änderungen der erreichbaren Grenzwerte, die aus der veränderlichen Sonneneinstrahlung herrühren, die Lufttemperatur und die Windgeschwindigkeit aus den existierden urbanen Forsten werden für private und gewerblich genutzte Gebäude geschätzt. Dieses wird verbunden mit dem Alter der Gebäude, der Größenverteilung, die Bedeckung des Bodens durch den Kronenbereich und die Baumdichte für 71 Unterbezirke. Die Ergebnisse sind inEinheiten zusammengerechnet, um ein Gesamtergebnis für den Bezirk zu erhalten. Die jährlichen Einsparungen durch Kühlung sind ca. 157 Gwh (GigaWattstunden) (US18,5 Millionen) pro Jahr, 12 % der gesamten Klimaanlagennutzung in dem Bezirk. Die Netto-effekte der Raumheizung sind gerind, mit 145 TJ (US$1,3 Millionen) jährliche Einsparung. Die Reduktion der Energie zu Spitzenzeiten verursachte Einsparungen von US$6 Millionen. Hier wird die Sensibilität der Ergebnisse gegenüber ausgewählter, eingegebener Daten demonstriert.

Resumen. El bosque urbano afecta el espacio condicionando el uso de energía como un resultado de su moderada influencia sobre el clima. Para evaluar la magnitud regional de estos impactos, se desarrolla y aplica un análisis estructural a gran escala al Condado de Sacramento, California, como un caso de estudio. Se estima para edificios residenciales y comerciales el calentamiento, el enfriamiento y los cambios de la capacidad pico, resultantes de la modificación de la radiación solar, la temperatura del aire y la velocidad del viento, por los bosques urbanos existentes. Esto se combina con la época y la distribución de tamaño de los edificios, el dosel y la cobertura de los árboles, y la densidad de árboles, para 71 subdivisiones del condado. Los resultados son resumidos en todas las unidades para obtener los totales. Los ahorros anuales por enfriamiento son aproximadamente 157 GWh (US$18.5 millones) por año, 12% del total de aire acondicionado en el condado. Los efectos netos sobre el espacio de calentamiento son pequeños, con 145 TJ (US$1.3 millones) ahorrados anualmente. Las reducciones de los picos de energía resultan en costos evitados de US$6 millones. Se demuestra la sensibilidad de los resultados para los datos de entrada seleccionados.