Measured Impact of Neighborhood Tree Cover on Microclimate

David J. Sailor, Leo Rainer[1] and Hashem Akbari
Lawrence Berkeley Laboratory

In this paper we present results of our investigation into the relationship between urban microclimate and the local density of tree cover as measured in Sacramento California. These results were obtained through analysis of data collected in a two-month long monitoring program with automatic weather stations installed at 15 residential locations throughout the city. Measured wind speeds showed a highly negative correlation with respect to tree cover. Daily peak air temperatures showed significant variation often differing from site to site by 2 to 4°C (~3.5 to 7°F). A complex interaction between several competing factors is discussed leading to the conclusion that additional tree cover may actually increase urban air temperatures on synoptically cool days. It is suggested that this does not have a significant adverse affect in terms of overall summer urban cooling load. This is supported by an integrated analysis of the temperature data which yielded preliminary estimates indicating that residential cooling load (as measured by cooling degree days) may decrease by 5 to 10% per 10% increase in tree cover. Shortcomings of this experiment are briefly discussed and suggestions are provided for future experiments.

Introduction

It has been well documented (Changnon 1976; Landsberg 1981) that urban neighborhoods are often warmer than their suburban and rural counterparts. This phenomenon, referred to as the urban heat island, is caused by differences in vegetative cover, albedo, substrate properties, and rates of anthropogenic heat release between urban and rural areas. The urban heat island is typically largest in winter, and during the early evening hours as the rural environment cools at a higher rate than does the city. The magnitude of the heat island may also be large in the summer when it adversely affects urban air-conditioning requirements. This poses a significant problem in mid-latitude climates where it is estimated that the heat island effect is responsible for 5-10% of the total urban electricity demand (Taha et al. 1990).

Researchers are currently studying two methods of mitigating the negative microclimatic effects caused by urbanization. Increasing the city's reflectance to solar energy (albedo) and increasing the vegetative cover of the city are both thought to hold great promise (Akbari et al. 1990; Akbari and Taha 1991). In order to further evaluate the potential of these mitigation schemes, data must be collected to validate current simulation efforts and to improve the understanding of the relationship among albedo, tree cover, and the urban microclimate. The research discussed in this paper focuses on the impact of neighborhood tree cover on urban temperatures and wind speeds as measured in Sacramento California during the summer of 1987.

Method

The research approach involved several distinct elements. First, we selected a city for the study and identified 15 residential sites scattered throughout that city. We then characterized the sites with respect to local and neighborhood tree cover. We assembled, calibrated, and then installed weather stations in the backyards of these sites, and collected data for over 50 days. Finally, we applied calibrations to the data and conducted a detailed statistical analysis. These steps are discussed in further detail below.

Site Selection

Sacramento was chosen as the city for this measurement study for a number of reasons. First, Sacramento is relatively void of topographical features which could seriously affect local meteorology. Secondly, Sacramento has a variety of neighborhood types, including some heavily treed neighborhoods, and other, newer neighborhoods with virtually no tree cover. Thirdly, Sacramento typically experiences warm summers with a number of days having peak air temperatures exceeding 38°C (100°F). Finally, the proximity of Sacramento to our laboratory enhanced our ability to conduct in-field equipment tests and investigate site problems and data anomalies.

Although in many respects Sacramento is ideal for the study of surface-induced microclimate variations and the structure of the heat island, there are two features of the city which complicate such an analysis. The first complication is that the urban core is fairly small comprising roughly five square kilometers (2 square miles) out of the 260 square kilometers (100 square miles) which make up the greater Sacramento metropolitan area. The other complication is that much of the core urban area is heavily treed. These two features tend to decrease the magnitude of the heat island effect with respect to typical urban heat island situations in which the urban core is large and relatively void of vegetation. In addition, the presence of several large rivers and their grassy flood channels may be responsible for localized oasis effects.

Table 1 provides a summary of the climatology for Sacramento, listing typical summertime and annual data.

In order to assess the impact of trees on local microclimate we required numerous residential sites with varied tree cover. In a study such as this it is very important that biases from other variables, such as neighborhood albedo, building density, substrate properties, and anthropogenic heat release be minimized. We accomplished this as much as possible by obtaining sites in many different communities with a relatively equal geographical distribution. Initial requests for sites were sent out using lists of people who we thought might be personally interested in the research objectives including employees of organizations who had been involved with our research programs in the past. Further sites were obtained using referrals from respondents and personal contacts. The final distribution of sites (see Figure 1) lacked coverage in the South East and downtown sections of Sacramento which have little or no residential housing.

Although these sites were scattered throughout Sacramento, they had the common characteristic of being in moderately dense suburban communities. Much of the tree cover difference was due primarily to the relative ages of the particular communities involved. Otherwise, these communities had fairly similar characteristics.

Table 1. Climatological Data for Sacramento[1]

	July	August	September	Annual
Temperature (°C)				
average monthly	23.2	22.7	20.9	15.3
average daily (max/min)	34/14	33/15	30/14	22/9
extreme (max/min)	41/11	38/12	38/9	41/-3
Days with max above 32°C (90°F)	22	22	10	69
Degree Days				
heating (base 65°F)	0	5	5	2771
cooling (base 65°F)	325	324	208	1166
Wind				
mean speed (m/s)	4.3	4.0	3.4	3.5
prevailing direction	SSW	SW	SW	SW
Relative Humidity (%)				
4AM	76	77	76	81
10AM	50	52	50	61
4PM	30	28	32	45
10PM	62	64	62	71

1 Taken from Typical Meteorological Year (TMY) weather data tape for Sacramento (latitude 38°31', longitude: 121°30').

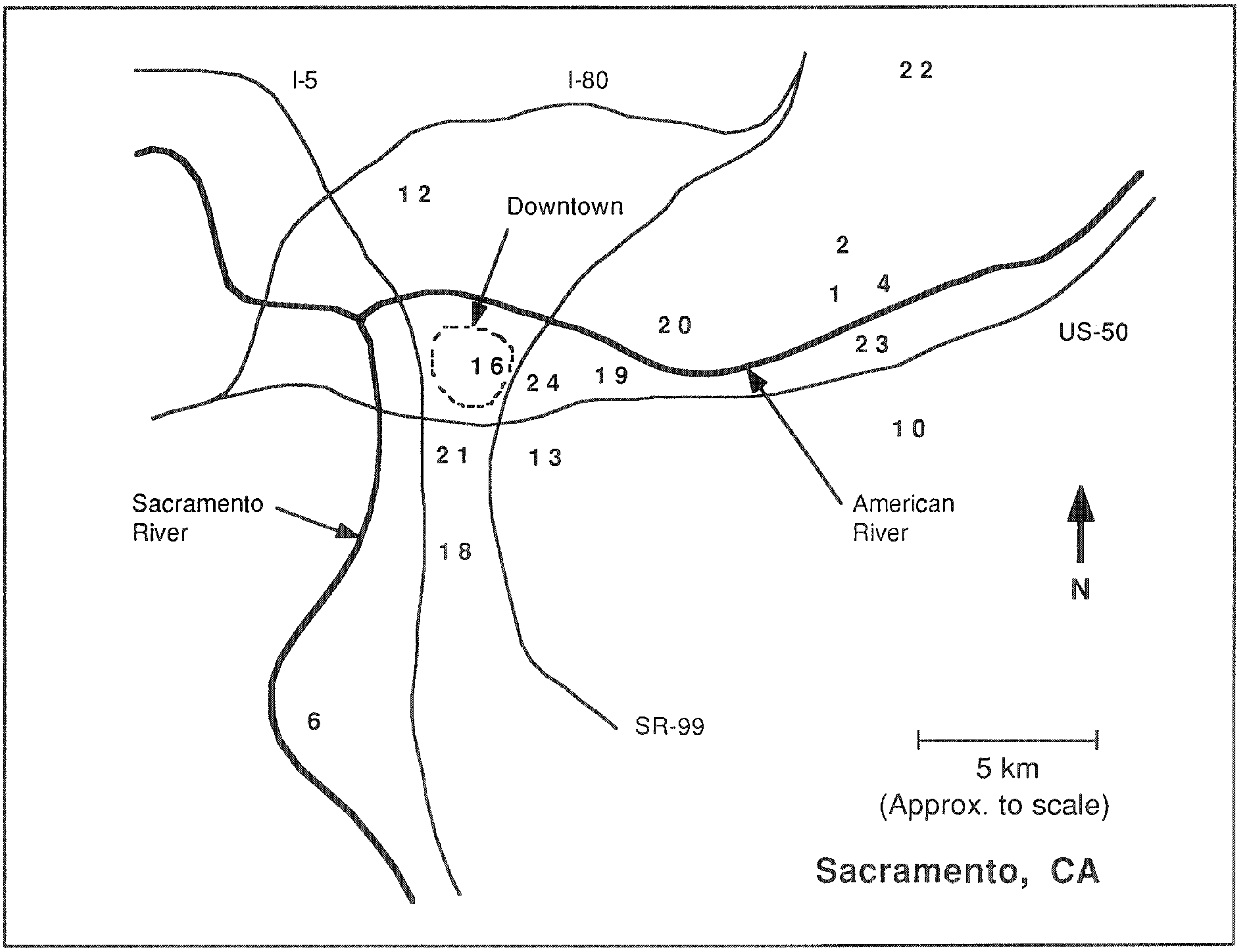

Figure 1. Distribution of Monitoring Sites Within Sacramento, California. Bold numbers (1..24) indicate site numbers.

Characterization

In order to characterize the tree cover of the residential sites we obtained high resolution aerial photographs of the relevant neighborhoods in Sacramento. These photographs have a scale of 8400 to 1. We superimposed a grid over these photographs and determined the number of individual grid cells that contained greater than 50% tree canopy. We then divided this number by the total number of grid cells in the region of interest. The resulting value indicated the percent tree cover. At each site we measured tree cover on two scales. Local tree cover was defined as the percent tree cover measured in a 213 m by 213 m (700 ft. by 700 ft.) square area centered at the residential site. Neighborhood tree cover was defined using a matrix of nine of these local grids. The measured tree cover spanned a wide range of values from 0% to roughly 50%. At the time of this study we were interested in isolating the effects of vegetative cover. The importance of measuring other characteristics such as albedo and substrate properties was not yet understood. Due to resource limitations we were unable to return to the residential sites to conduct a post-experiment evaluation of these other site characteristics. Thus, the only site characteristic available for analysis was tree cover.

Equipment

Each weather station consisted of a wind speed sensor, a wind direction sensor, and a dry bulb temperature sensor. The wind sensors were mounted at a height of just over 1.5 meters (4 1/2 ft). The air-temperature sensors were mounted at a height of roughly 1 meter (3 ft). Each station also consisted of a signal conditioning box and a microprocessor controlled data logger which could gather up to 16 channels of data and record up to 24 kbytes of data on a removable memory storage module. The sensors were sampled at each minute and averaged and recorded at half hour intervals. With this schedule, each memory module could store data for up to 30 days before having to be replaced.

Prior to the data acquisition phase of this project, all of the monitoring equipment was taken to an expansive outdoor test facility for pre-calibration. In addition, several weeks after the data collection phase of the study, all of the stations were dismantled and returned to the test facility for post-calibration. The calibrations were actually performed using one of the weather stations as a control unit. Thus, these *calibrations* are actually equipment intercomparisons. The temperature sensor electronics, however, were adjusted prior to calibration using a mercury thermometer until they indicated good agreement with a set point. Furthermore, the subsequent calibration data for the temperature sensors produced very good linear curve fits (all R^2 values were above 0.98) both before and after the data collection phase, indicating that the temperature network as a whole was self-consistent and had not drifted.

Data Collection

All of the monitoring equipment was brought to Sacramento on July 15 and installed over the next two days. The weather stations were all installed in the backyards of the residential sites, as removed as possible from obstructions such as fences and the houses themselves.

Each site was visited and inspected every other day for the first week and then once or twice a week for the remainder of the study. During each inspection the operation of the data logger and each sensor was verified and the data stored on the memory module since the last inspection were checked to ensure that the equipment was operating properly.

Data Analysis

After the data collection phase the raw data were downloaded onto a mainframe computer. These data were adjusted by applying the calibrations obtained in the pre-calibration phase of the study and scatter plots were produced to help identify trends in the data.

At this point the temporal domain for the analysis was defined. Although the first station began operating on July 15, it wasn't until July 23 that all sites were up and running. The end of the monitoring period was signaled by the dismantling of the stations which began on September 13. Thus, the temporal domain for the analysis is from midnight of July 23 through midnight of September 12. These dates correspond to Julian days 205 through 255.

The data were processed to produce two additional types of data files. First, the half-hourly data were aggregated into an hourly format and saved. Daily data were also produced. The peak, average, and minimum temperature, as well as the average wind speed for each site on each day were found. Since we were interested in the daytime heat island which develops during the course of the day, a daytime average wind speed was also useful. This wind speed was defined as the average wind speed between the hours of 10:00 a.m. and 3:00 p.m. This daytime average wind speed was calculated for each site for each day of the study.

A statistical software package was then used to produce correlative information regarding the role of tree cover in the urban microclimate. All correlation coefficients presented in this paper are the Pearson correlation coefficients defined as the covariance of two variables divided by the product of their standard deviations. Since local tree cover was highly correlated with neighborhood tree cover (with a correlation coefficient of 0.95), only the neighborhood value was used in the analysis.

Results and Discussion

The impact of local tree cover on urban microclimate was investigated using a variety of measures. Air temperature, being of particular interest with regard to the air-conditioning load impacts of urban heat islands, was studied in depth. Peak daytime temperatures and noontime temperatures are discussed below. In the following section, the relationship between tree cover and local wind speeds is also presented. This is followed by an investigation of the potential impact of tree cover on air-conditioning energy use.

For easy reference, Table 2 summarizes some of the more significant calculations from the following sections. This table lists the neighborhood tree cover and presents average peak temperatures and daytime average wind speeds for each site.

Peak Temperatures

The following analysis focuses on daily peak temperatures at all of the sites. It is important to note that the peak temperatures at two sites generally do not occur at the same time of day. The peak temperature, in fact, may

Table 2. Average Site Peak Temperatures and Wind Speeds

Site #	Tree Cover (Neighborhood %)	Peak Temperatures: Mean (°C)	Peak Temperatures: Standard Deviation	Wind Speed (m sec^{-1})
01	23	25.9	3.8	0.170
02	47	26.4	4.2	0.394
04	12	31.3	5.1	0.473
06	0	26.9	4.5	1.790
10	4	27.8	4.0	1.310
12	0	26.8	3.8	1.045
13	41	27.4	3.9	0.283
16	48	28.5	3.7	0.004
18	20	26.5	3.9	0.523
19	26	26.9	4.2	0.449
20	3	26.7	4.5	1.798
21	42	27.3	3.7	0.073
22	15	28.2	3.3	0.390
23	16	29.2	4.4	0.342
24	41	29.4	3.8	0.158

occur any time in the mid to late afternoon. Thus, when comparing the peak daily temperatures at two sites we may be comparing datum points which occurred several hours apart. We repeated much of the analysis which follows using time-specific temperature data. Results for the noon-time temperatures are presented in the next section.

Figure 2 presents the average of the peak temperatures for each site plotted against the neighborhood tree cover percent at those sites. Vertical lines through datum points indicate standard deviations. A solid line best linear fit through the data is also plotted.

There is essentially no correlation between peak air temperatures and local tree cover; the correlation coefficient is only 0.004. Application of various filters to peak temperature data also failed to produce a significant correlation. A number of factors help to explain this surprising result. In fact, several points need to be discussed in detail before drawing conclusions from this data.

First, as pointed out earlier, peak temperatures may be measured at different times depending upon conditions at each site. Also, these peak temperatures generally occur in the late afternoon when differential shading at the sites may be responsible for local temperature depressions.

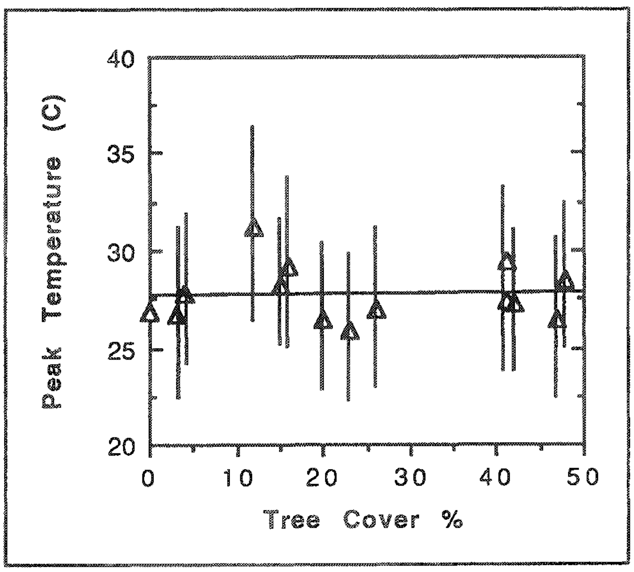

Figure 2. Average Peak Temperatures Plotted Against Neighborhood Tree Cover Percent

The large standard deviations in the data are simply representative of the highly variable synoptic weather conditions during the study. The scatter in the mean data, however, is indicative of the effect of numerous unmeasured site characteristics. Previous research has shown that substrate properties, vegetative cover, local moisture availability, and albedo are among the most important site characteristics which influence local meteorology (Atwater 1972). Since we have only measured one of these characteristics the scatter present in Figure 2 is to be expected. If the unmeasured characteristics of our study sites had fairly uniform distributions, then any significant trend in the data would be indicative of the impact of tree cover alone. Due to the small number of sites, however, it is unlikely that these unmeasured characteristics would manifest themselves as uniform noise in the data. Instead, certain sites which are unexplicably warm or cold will have a large impact on the correlative behavior of the data.

Finally, the correlation between tree cover and peak air temperatures depends upon other factors such as solar insolation, cloud cover, and synoptic wind speeds. In addition, this correlation may itself be a function of peak temperature. In other words, tree cover may have very different effects depending upon whether a given day is hot or cold; windy or calm; and cloudy or clear.

Noon-Time Temperatures

In order to address several of the points discussed above, we repeated the analysis for air temperatures measured at specific times. The noon-time temperatures are of particular interest since at noon the sun is relatively near its zenith and differential shading is less likely to affect the local temperatures. Additionally, time-specific temperature measurements add to our confidence that we are comparing similar measurements from all of the sites.

When peak temperatures were replaced with noon-time temperatures in the above analysis a slight negative correlation between tree cover and temperature of -0.08 was obtained. This correlation was encouraging yet still relatively insignificant. In order to address the point that the impact of tree cover on cool days is not important in terms of air-conditioning load we filtered the data to remove days in which the city-wide peak temperature average was below 28°C (82°F). Figure 3 presents the noon-time air temperature of this filtered data plotted against tree cover. The straight line in this figure is a best linear fit through the data. The slope of this line indicates that in general noon-time temperatures decrease by 0.36°C (0.65°F) per 10% increase in tree cover for warm days. Furthermore, the correlation between tree cover and the filtered noon-time temperature is -0.20.

Wind Speeds

The magnitude of the local wind speed is important since it is directly related to local advection, vertical mixing of warm air with cool air, and convection of heat away from warm surfaces. The local wind speeds can vary significantly from site to site and from day to day. Variability between sites is indicative of differences in site wind-shielding and topographical channeling effects. The day to day variation in wind speeds is due primarily to changes in the synoptic weather patterns. Because of the connection between tree cover and local wind shielding we expect some negative correlation between wind speed and percent tree cover. In fact, this correlation coefficient was found to have a moderately large value of - 0.79. In Figure 4 the average of the daily wind speed is plotted versus percent tree cover for each site. The trend in this figure is similar to that found by previous researchers (Heisler 1989). Increasing levels of tree cover are indeed associated with measurably decreased wind speeds. This relationship, in fact, appears to be exponential, indicating that significant wind shielding may occur when trees are added to a barren neighborhood, but the addition of trees to a moderately treed neighborhood will have little impact on wind shielding.

As mentioned earlier, local winds can greatly influence low level air temperatures. On a calm day near surface air temperatures are generally higher than for an otherwise similar windy day. This is demonstrated in Figure 5 which

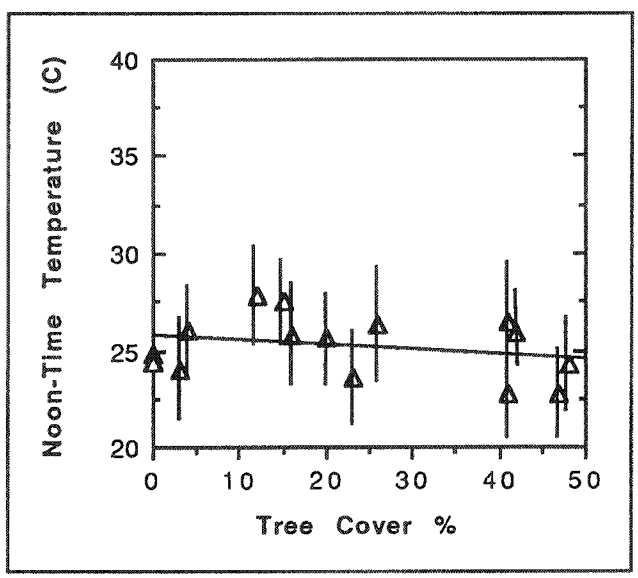

Figure 3. Average Noon-time Temperatures Plotted Against Neighborhood Tree Cover Percent. A filter has been applied to exclude data for which the site peak temperature does not exceed 28°C.

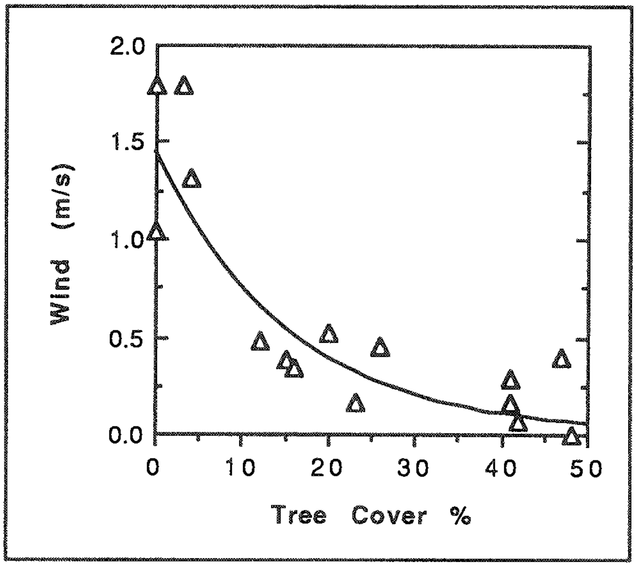

Figure 4. Average Daily Wind Speed Plotted Versus Neighborhood Tree Cover Percent. Solid Line is best exponential fit through data.

plots peak daily temperature at all sites versus the corresponding daily average wind speeds at these sites. The straight line in this figure is a best linear fit through the data. Similar results were obtained for time-specific temperatures. Thus, the mixing produced by local winds mitigates the heat island effect by reducing the low level air temperatures.

Trees and other vegetation play a similar role in mitigating the heat island effect through evapotranspiration and shading. Trees may, however, also have a negative impact resulting in increased urban temperatures. The wind-shielding of trees is a negative effect in that it reduces the ability of local winds to moderate the near-surface air temperatures. It is possible that the air-temperature impact of the positive and negative effects of tree cover may be of the same order of magnitude. Thus, on windy days, trees may be a burden on the urban heat island, and on calm days they may be a net benefit.

To test this hypothesis we divided our data set into two categories: high wind speed days, and low wind speed days. The average daily wind speeds at the 15 sites were averaged to arrive at a city-wide average wind speed for each day of the study. The data were then aggregated into high and low wind speed days using a somewhat arbitrary cutoff value of 0.25 m sec^{-1} (0.82 ft sec^{-1}) applied to the city-wide average wind speed values. Associated with each datum point was a value of the site neighborhood tree cover and the city-wide daily wind speed for that day. The correlations between tree cover and peak temperatures for calm and windy days were -0.031 and +0.036 respectively. Although these correlations are relatively weak, their differing signs help to strengthen the above-stated hypothesis.

Wind direction was also measured at each site. It was difficult, however, to interpret these data as they pertain to this study. Furthermore, the wind direction sensors proved to be unreliable at low wind speeds. These data are therefore absent from this analysis.

Energy Use Implications

The data have shown that the addition of trees has the potential to increase peak air temperature on windy days, yet decrease peak air temperatures on calm days. This conclusion is illustrated in Figures 6 and 7 which depict the diurnal temperature profiles at representative high and low tree cover sites for calm and windy days respectively.

Note that the peak temperatures in Figure 6 are roughly 5°C (9°F) higher than in Figure 7. This demonstrates the point made earlier that calm days tend to be warmer.

We might expect that the negative effects of trees which manifest themselves on synoptically windy and relatively cool days may not be significant relative to the positive effects which are present on the calm and warm days. For this reason a final measure was investigated in order to determine the possible impact of trees on air-conditioning loads. For the 50 days of the study the total number of cooling degree days was calculated for each site, using a

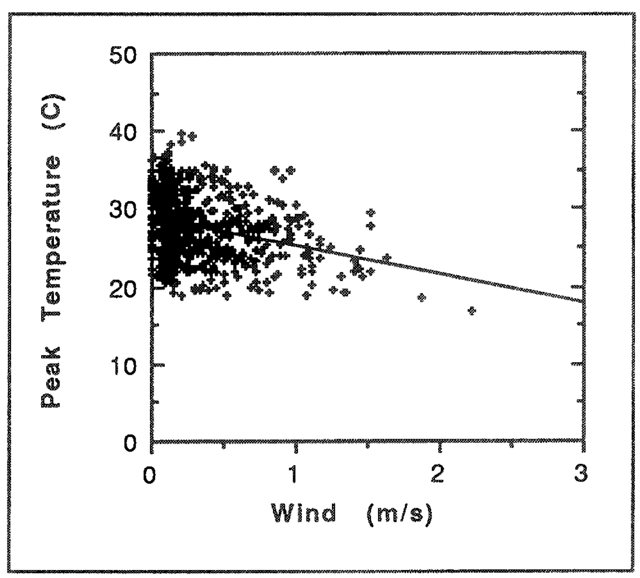

Figure 5. Peak Temperatures Plotted Versus Site Daily Average Wind Speed

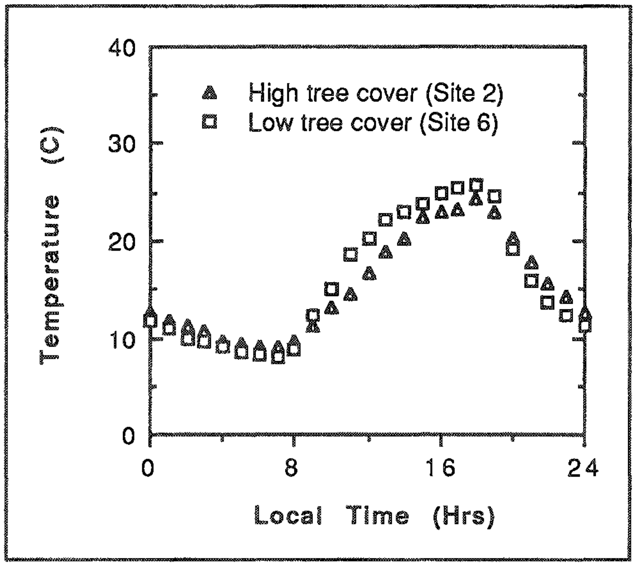

Figure 6. Diurnal Temperature Profiles at High and Low Tree Coverage Sites for a Typical Low Wind Speed Day

base temperature of 28°C (82°F). The results are plotted in Figure 8 versus percent tree cover. The solid line is a best linear fit through the data. This line indicates a 5% reduction in cooling degree days for each 10% increase in tree cover. Similar results were obtained using base temperatures ranging from 24 to 30°C (75 to 86°F).

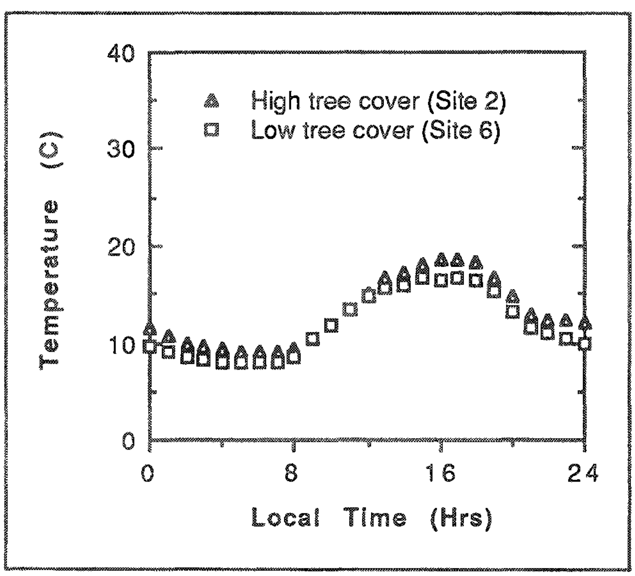

Figure 7. Diurnal Temperature Profiles at High and Low Tree Coverage Sites for a Typical High Wind Speed Day

Due to factors discussed previously the conclusions to be drawn from this figure must be only tentative, pending further examination in future studies. As a first order estimate, however, we expect small reductions in cooling degree days to be roughly proportional to air-conditioning savings in a given neighborhood. Furthermore, nearby neighborhoods will benefit to some extent from lower air temperatures resulting from tree planting in one neighborhood. It is therefore reasonable to expect a total air-conditioning energy savings of 5 to 10% for each 10% increase in residential tree cover. This estimate is for the indirect effects only and does not include the direct effects of shading buildings and air conditioner condenser units.

Conclusions

The measured data in this study show no correlation between peak air temperatures and local tree cover. When the data were filtered to exclude cool days (average peak temperature of less than 28°C) a slight negative correlation of -0.20 was evident in the noon-time air temperature data. As a result the noon-time air temperature was shown to decrease by approximately 0.36°C (0.65°F) per 10% increase in tree cover, on warm days.

Analysis of site-measured wind speed data provided much more conclusive results. A negative correlation of -0.79 exists between wind speed and neighborhood tree cover. It was hypothesized and subsequent analysis showed that additional tree cover may indeed increase local urban temperatures on synoptically windy days. This was

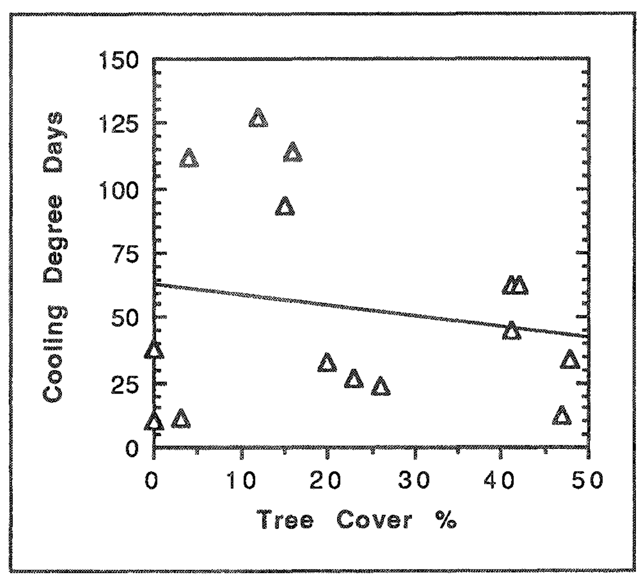

Figure 8. Total Cooling Degree Days Plotted Versus Neighborhood Percent Tree Cover. Solid line is best linear fit through data.

explained as the result of several competing factors; wind-shielding, evapotranspiration, and shading.

A preliminary analysis of the implications of tree cover on air-conditioning energy use indicated a possible savings of 5 to 10% per 10% increase in tree cover. These results seem to indicate that the indirect (air cooling) effects of tree planting programs may have significant impacts on air-conditioning loads. It must be emphasized, however, that these results are only preliminary based on results from a limited monitoring project. Some of the shortcomings of the design of this project have already been addressed. A short summary of these design flaws and possible solutions are now presented.

First, we recorded measurements at only one location for each neighborhood, assuming that these measurements were representative of the entire neighborhood. This assumption may result in large errors due to spatial variations in microclimate within a neighborhood. Furthermore, the small number of sites studied resulted in a low level of statistical significance for our conclusions. To address these problems, future studies should monitor as many sites as possible including multiple sites in each neighborhood.

Also, we were only capable of characterizing these sites in terms of tree coverage. The characterization of additional site parameters would greatly enhance the ability to fit statistical models to the data. Specifically we suggest measuring neighborhood values of albedo, building height and density, and substrate properties. Percent impervious surface area may be a useful surrogate for substrate properties as the latter may be difficult to measure accurately.

Finally, our estimate of the impact of tree cover on air-conditioning energy use was very crude and preliminary. A connection needs to be made relating the air-temperature depressions from vegetation to subsequent reductions in air-conditioning load. One obvious approach is to actually measure the air-conditioning energy use at the test sites. If this approach is to be successfully applied, the researchers will need to maintain strict control over important variables such as thermostat settings. Another, more easily managed approach is to use building energy simulation programs with modified weather tapes to simulate the impact of the air-temperature depressions on air-conditioning energy use.

Once we can reliably relate residential tree cover to air-conditioner energy use we will be able to compare the direct effects of tree cover to the indirect effects. Such comparisons are necessary in order to guide tree planting efforts. The results will help determine whether city planners should focus on shade trees alone, or simply try to increase the overall tree cover of their cities.

Acknowledgments

This work was supported by the University-Wide Energy Research Group (UERG) of the University of California and by the Department of Energy under contract No. DE-AC0376SF00098. Professor Arthur Rosenfeld of U.C. Berkeley provided useful guidance for this project and Dr. Haider Taha and Phil Martien provided assistance in experiment design and implementation.

Endnotes

1. Current address is Davis Energy Group, Davis, California.

References

Akbari, H., A.H. Rosenfeld, and H. Taha 1990. "Summer Heat Islands, Urban Trees, and White Surfaces." Presented at ASHRAE January 1990 Meeting, Atlanta, Georgia. Also Lawrence Berkeley Laboratory report # LBL-28308.

Akbari, H. and H. Taha 1991. "The Impact of Trees and White Surfaces on Residential Heating and Cooling Energy Use in Four Canadian Cities." *Energy*, Vol. 17, No. 2, pp. 141-149.

Atwater, M.A. 1972. "Thermal Effects of Urbanization and Industrialization in the Boundary Layer: A Numerical Study." *Boundary-Layer Meteorology*, Vol. 3, pp. 229-245.

Changnon, S.A. Jr. 1976. "Inadvertent Weather Modifications." *Water Resources Bulletin*, Vol. 12, pp. 695-718.

Heisler, G.M. 1989. "Effects of Trees on Wind and Solar Radiation in Residential Neighborhoods" (Final Report on Site Design and Microclimate Research). ANL No. 058719, Argonne National Laboratory, Argonne IL.

Landsberg, H.E. 1981. *The Urban Heat Island*, Academic Press, N.Y.

Taha, H., H. Akbari, D.J. Sailor, and R.L. Ritschard 1990. "Causes and Effects of Heat Islands: The Sensitivity of Urban Microclimates to Surface Parameters and Anthropogenic Heat." Lawrence Berkeley Laboratory Report # LBL-29864.