The Potential of Vegetation in Reducing Summer Cooling Loads in Residential Buildings

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ABSTRACT

The potential of trees and other vegetation to reduce building cooling loads has been recorded in a number of studies, but the meso- and microclimate changes producing such savings are not well understood. This paper describes a preliminary attempt to model the effects of landscaping on temperature, humidity, windspeed and solar gain in urban climates using information from existing agricultural and meteorological studies, with particular attention placed on quantifying the effects of plant evapotranspiration. The climate model is then used in conjunction with the DOE-2.1C building simulation program to calculate the net reductions in air-conditioning requirements due to trees and other vegetation.

Preliminary results show that an additional 25% increase in the urban tree cover can save 40% of the annual cooling energy use of an average house in Sacramento, and 25% in Phoenix and Lake Charles. If this additional tree cover is located to optimize summer shading, the savings are further increased to more than 50% in Sacramento and 33% in the other two cities. The calculated savings are minimal for Los Angeles because the base case cooling energy use is small (65 hours) on the assumption that window venting is used whenever possible in lieu of mechanical cooling. There are additional benefits in lowering peak power consumption, where the savings are as much as 34% in Sacramento, 18% in Phoenix, 22% in Lake Charles, and 44% in Los Angeles. Parametric analysis reveals that most of the savings can be attributed to the effects of increased plant evapotranspiration, and only 10% to 30% to shading. The energy penalties of reduced windspeeds are found to be small in all four locations.

The preliminary results suggest that while the conservation benefits of planting trees are appreciable at the individual house level, equally dramatic savings can be realized at the urban level through modifications of the urban climate by increasing the total amount of vegetative cover. Such a conservation strategy may be effective in countering the summer heat island evident in cities and may improve ambient conditions as well as reduce summertime air-conditioning requirements.

1. Introduction

Many horticulturalists and landscape architects have noted that, in addition to their aesthetic value, trees, shrubs, and lawns also have an added value for saving energy, particularly in cooling climates. Case studies in recent years have documented dramatic differences in cooling energy use between houses on unlandscaped and landscaped sites (Lauchelt and Williams, 1976; Buffington, 1979; Parker, 1981). A good discussion of the microclimate effects of urban vegetation is given in Hutchison et al. (1983). This paper will forego a general literature survey and describe only the development of a simple quantitative model for the microclimatic effects of urban vegetation and the predicted savings in cooling energy shown by this model for various vegetation conditions in different cooling climates.

The microclimate model described in this paper is based on a growing literature of recent meteorological and agricultural studies documenting and analyzing the effects of vegetation on the temperature, windspeed, and humidity of their microclimates (Geiger, 1957; Rosenberg, 1974; Oke, 1978). To predict the effect of these changes on building energy use, the microclimate model is then linked with the DOE-2.1C building energy simulation program to calculate cooling energy savings for a typical one-story house.

DOE-2.1C is a documented public-domain building energy program that simulates the energy performance of a building hour-by-hour depending on its climate, building envelope, equipment use, and occupant schedules (U.S. Dept. of Commerce, 1980). For its climate input, DOE-2.1C uses hourly weather tapes which are generally available from sources such as the U.S. National Oceanic and Atmospheric Administration (NOAA). The vegetation model developed in this work is implemented partly by modifying the input weather file and partly by altering the building description input file, since DOE-2.1C can accept information to some degree on the surrounding conditions. Since most hourly weather files are based on airport data, the modified weather produced by the model should be interpreted as due to relative differences in vegetation from airport conditions.

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For this preliminary work, our intention is to quantify the relative importance of different vegetation effects such as shading, wind reduction, or evapotranspiration, and to show that in addition to the savings for individual houses due to direct shading from a tree, there are additional potential savings at a neighborhood or citywide level through the moderation of summertime urban temperatures. To avoid misleading impressions of accuracy, we have kept the modeling of microclimatic effects simple on purpose. We will discuss the limitations of the simplifying assumptions, how they affect the results, and potential methods for improving the model.

2. Modeling the microclimate effects of vegetation

During the daytime cooling season, trees and vegetation reduce air-conditioning loads through several processes: 1) reduce solar gain on windows, walls, and roofs by shading, 2) reduce longwave heat gain by maintaining lower surface temperatures than impermeable surfaces such as asphalt and concrete, and 3) reduce conductive and convective heat gain by lowering drybulb temperatures through plant evapotranspiration. These cooling benefits must be weighed, however, against the possible detrimental effects of 1) reduced net outgoing longwave radiation, 2) increased latent cooling loads from the added moisture (i.e., higher humidity ratios) from evapotranspiration, and 3) reduced natural ventilation potential and convective heat loss due to lowered windspeed. The last factor is of minor significance for houses cooled strictly by air-conditioning, but can be significant in houses that capture outdoor air movement to maintain comfort conditions.

a. Reduced solar gain

The shading effects of trees can be simulated on the DOE-2.1C program as exterior building shades, once the geometry and transmissivity of the trees have been determined. Tree transmissivities vary by species, ranging from 6% to 30% during summer months (Thayer et al., 1983; McPherson, 1984). For this study we consider two conditions of tree shading: 1) uniform increases in the tree canopy area reflecting tree plantings in residential neighborhoods without particular attention to placement for summertime shading, and 2) trees placed for shading on the west or south side of the house.

For the first condition, we have modeled the shading effect of typical canopy with an average tree height of 10 m as a "building shade" uniformly distributed around a house at a height of 6.5 m (Fig. 1). We assume that the trees extend to the edge of the house but do not provide direct shade over the roof. Percent increases in the canopy density are approximated as equivalent reductions in the transmissivity of the "building shade." A one-to-one correspondence is assumed between increases in canopy area density and reductions in solar transmission since trees have an average transmissivity of 20%, but are generally planted more densely around houses (for discussion of tree shading patterns in typical residential areas in California, see Myrup and Morgan, 1972, pp. 13–21). We have considered transmissivities of 90% and 75% in the "building shade," corresponding to increases of 10% and 25% in the urban tree canopy density. We judge that increases over 25% are unlikely due to physical constraints in the city and the fact that typical American cities already have existing tree covers approaching 30% of their surface areas (Myrup and Morgan, 1972).

Fig. 1. Generalized tree canopy shading as modeled in DOE-2.1C simulation.
To explore the conservation potential of trees planted for summer shading, we have modeled the effects of one tree planted on the west, and two more on the south side of the house (Fig. 2). We have assumed that each mature tree has a top view projection area of 50 m² and a suburban housing density of one house per 500 m² of land. Therefore, the equivalent increases in the urban tree canopy for these two configurations are 10% and 30%, which corresponds to one or three trees per typical housing lot.

Tree shading reduces not only the direct solar gain striking the building envelope, but also the diffuse light reflected from sky and surrounding surfaces. This change is approximated in the DOE-2.1C model by modifying the inputs for sky- and ground-form-factors (the amount of each visible from a building surface), and the ground reflectance of the surroundings.

In addition, tree shading alters the exchange of longwave radiation between the building and its surroundings. During the day, vegetative surfaces reduce longwave heat gain to the house because their surface temperatures are low compared to hard surfaces such as sidewalks, asphalt, or bare ground. At night, however, trees reduce radiative cooling by blocking the amount of night sky visible from the walls and roof. The impact of these changes on building cooling loads cannot be modeled by the DOE-2.1C program, but a simple calculation shows that the effects are small compared to those due to reductions in direct solar gain (Myrup and Morgan, 1972).

b. Reduced wind speed

Whereas shading and evapotranspiration are beneficial in reducing summer cooling loads, reductions in

Fig. 2. Tree canopy planted for shading as modeled in DOE-2.1C simulation; (a) the model for one tree on the south side of the house; (b) the model for three trees on the south and west side of the house.
wind speed are detrimental during those hours in the cooling season when natural ventilation can be used to extend the comfort zone, and thus reduce reliance on mechanical cooling. During peak cooling hours when ambient temperatures are very high, wind speed reductions may reduce cooling loads slightly by lowering the amount of wind-driven infiltration.

For houses in open terrain, reductions in wind speed due to shelterbelts can be estimated from the density and height of the trees, their orientation relative to the wind, and their distance from the house (Nageli, 1946; DeWalle and Heisler, 1983). For houses in typical suburban areas, however, wind speed reductions at the building height (0–5 m above ground) are due partly to the general roughness, density, and height of the urban canopy as well to the location of nearby trees. Since we are interested in typical suburban conditions, we chose an empirical function relating wind speed reductions to increased tree canopy densities.

In his study of urban microclimates in Davis, California, McGinn (1982) found that winds speeds at 5 m above ground for various tree canopies compared to that for a control open field site varied as a function of the density, and not height, of the canopy (Fig. 3). Polynomial regression of the concurrent wind speed data for five canopy densities varying from 3% to 35% resulted in the following equation:

\[ u = u_0 (0.946 - 0.091 C + 0.0043 C^2 - 0.00007 C^3) \] (1)

where \( u \) is wind speed at site, \( u_0 \) wind speed on open urban field and \( C \) is percent canopy cover.

Although there have been more detailed efforts to correlate wind speed changes in urban areas to physical parameters such as surface roughness or average building height (Myrup and Morgan, 1972), we chose at this point to use Eq. (1) because it was developed from suburban data using a control site quite similar to the conditions at most weather stations (an open urban field) and shows the relationship of wind speed reductions to increased tree canopy density.

c. Evapotranspiration

A major microclimatic impact of trees and other vegetation that is frequently overlooked is their capability to affect daily temperature swings through the evaporation and transpiration of moisture through leaves, a phenomenon agriculturalists call evapotranspiration.\(^1\)

\[ \text{FIG. 3. Wind speed reductions for different tree canopy densities as a ratio of wind speed at control site with no trees (McGinn, 1982, p. 65).} \]

From the point of view of energy conservation, a tree can be regarded as a natural “evaporative cooler” using up to 100 gallons of water a day (Kramer and Kozlowski, 1960). This rate of evapotranspiration translates into a cooling potential of 230 000 kcal day\(^{-1}\). This cooling effect is the primary cause for the 5°C differences in peak noontime temperatures observed between forests and open terrain, and the 3°C difference found in noontime air temperatures over irrigated millet fields as compared to bare ground (Geiger, 1957, p. 294). Temperature measurements in suburban areas recorded similar but smaller variations in daytime peaks of 2°C to 3°C between neighborhoods under mature tree canopies and newer areas with no trees (McGinn, 1982, p. 59). More pronounced cooling effects have been measured in large urban parks where evapotranspiration has been further driven by wind, resulting in an “oasis” 4°C cooler than surrounding neighborhoods (Fig. 4).

To develop a quantitative model for microclimate modifications due to evapotranspiration, it is necessary first to determine the amount of evapotranspiration as a function of time and ambient conditions, and then to relate that amount of added moisture to changes in the microclimate. To estimate the amount of plant evapotranspiration, we rely on an empirical model originally developed for estimating water loss in crops. Because of its importance to agriculture, botanists and micrometeorologists have proposed numerous methods for measuring and predicting evapotranspiration rates in crops (Rosenberg, 1974, pp. 186–193). These studies distinguish between actual and potential evapotranspiration. The former is a measure of the actual amount of moisture released by plants under given

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\(^1\) The replacement of vegetation by hard impermeable surfaces such as asphalt and concrete is frequently mentioned as one of the causes for the summer “heat island” in the cities. Although some studies indicate that humidities are generally lower in downtown areas, other have found evapotranspiration rates in suburban areas are similar to those in the countryside due to the prevalence of artificial watering (Oke, 1979). Thus, the net change in urban evapotranspiration is still debatable and needs to be investigated further.
conditions and is highly sensitive to both air conditions as well as the availability of ground water. The latter is a measure of the theoretical amount of evapotranspiration possible assuming an ample supply of water.

Since the goal of our work is to assess the potential cooling effects of vegetation, we assume that the vegetation will be well watered and, hence, releasing water at the potential evapotranspiration rate. After reviewing several models, we decided to use one developed by Jensen and Haise (1963) from the study of 1000 reported measurements in which potential evapotranspiration is given as a function of drybulb temperature and solar radiation (this formula is modified from the original where evapotranspiration and radiation are expressed in terms of inches of water per day, and the temperature in degrees Fahrenheit):

$$ETP = (0.0252T - 0.078)R_s$$  \hspace{1cm} (2)

where ETP is the potential evapotranspiration in centimeters of water per day, $T$ the ambient air temperature in °C and $R_s$ solar and sky radiation in centimeters of evaporated water day$^{-1}$.

Jensen and Haise (1963) state that studies over the previous 15 years have demonstrated repeatedly that evapotranspiration rates were more closely related to net solar radiation than to air temperature or humidity. Their equation for potential evapotranspiration was based on measurements of the ratio of evapotranspiration to solar radiation ($ETP/R_s$) for crop conditions and locations where the vaporization of water was judged to be unlimited (Fig. 5). The dataset included four types of crops (alfalfa, cotton, oats, and winter wheat) in six states (Arizona, California, Nebraska, Washington, Kansas, and Texas).

We selected this model for our preliminary work because it was based on empirical data for arid and

![Fig. 4. City temperatures (°F) in San Francisco at 2300 local time, 2 March 1952. The rectangle at left-center represents Golden Gate Park with a temperature of 54°F, while the surrounding neighborhood is at 62°F, a difference of 8°F (4°C) (Duckworth and Sandberg, 1954).](image)

![Fig. 5. Variations in the $E_T/R_s$ ratio for selected field crops in relationship to mean air temperature (Jensen and Haise, 1963).](image)
semi-arid locations where evaporative cooling would be effective, and required as input only solar and dry-bulb temperature data easily available from weather tapes. A validation effort by Jensen and Haise (1963) for a clipped grass field in Davis, California, indicated that the model was accurate over periods of five days or more, while an independent test by Rosenberg (1974, p. 190) indicated good results for cases with minor advection due to wind, but serious underprediction for cases with large advection. The use of this model in our study should be regarded as an interim step, since it remains to be seen whether it is applicable for all climates and plant types, or for predicting hourly evapotranspiration rates in suburban settings. Although some data exist on evapotranspiration rates for different types of trees, we think it inappropriate at this stage to include this detail into our simple microclimate model.

In order to translate the evapotranspiration rate into changes in the ambient air conditions, we need to determine the amount of air within which this cooling occurs. Although existing data indicate that this cooling can be localized at the neighborhood level (Fig. 4), correct solution of these local effects requires a three-dimensional urban climate model. For this preliminary work, we have made the simplifying assumptions that 1) the air over the city is well mixed with no differences in potential temperatures and humidity ratios (i.e., the only temperature differences are due to the adiabatic lapse rate), and 2) the cooling effect of evapotranspiration from an increased number of trees is uniform throughout the urban microclimate.

We assume that the evaporatively cooled air is uniformly mixed into an air volume defined by the area of the city times the average mixing height over the city, with an additional “air change” term to take into account wind speed. At large wind speeds, the mixing volume is simply proportional to the wind speed itself. At very low wind speeds, the mixing volume is the summation of the newly displaced air plus the remaining unsaturated air from previous hours. Therefore, the mixing volume will be larger than that of the wind-driven volume. To approximate this condition, we assume that the volume rate decreases linearly as a function of wind speed to w/h/2 and then stays constant (solid line in Fig. 6):

\[
\text{Volume rate} = \begin{cases} \frac{u w h}{t}, & u \gg u_c \\ u w h, & u < u_c \end{cases}
\]

where \( u \) is wind speed; \( w, l \) the characteristic length and width of city; \( h \) the height of mixed air layer and \( u_c \) the characteristic wind speed defined as \( l / 2 \Delta t \) for \( \Delta t \) the calculation time interval (1 hour in this case). We also have used an alternative approximation that the volume rate is zero at wind speeds below \( u_c \) (dotted line in Fig. 6). The resultant microclimatic effects using the two approximations did not differ significantly.

The mixing height defines a volume below which the air is assumed well-mixed. As an essential element in many meteorological models, its height has been the subject of numerous measurement and theoretical modeling efforts. General meteorological principles suggest that the mixing height is low at night (less than 300 meters), rises quickly after sunrise, and reaches anywhere from 0.5 to 3 km by early afternoon (Oke, 1978, pp. 53–54). The height at a specific time and location, however, is quite variable and depends on a wide range of climate parameters.

For our study, we used an empirical model developed by Leahey and Friend (1971) from New York data for predicting the mixing height over an urban heat island.

\[
h^2 = \frac{2}{c_p u \rho h x_1} \int_{x_1}^{x} (H + Q_s - \sigma(T_0^4 - T_{oc}^4)) dx
\]

where

- \( h \) mixing height (m)
- \( H \) artificial heat release rate (kW m\(^{-2}\))
- \( x_1 \) starting transition point of heat island (m)
- \( x \) distance from transition point (m)
- \( c_p \) specific heat of air [kJ/(kg K)]
- \( \rho \) air density (assumed to be constant) (kg m\(^{-3}\))
- \( \sigma \) Stefan–Boltzmann constant [5.7 \times 10\(^{-8}\) kW (m\(^2\) K\(^{-4}\))] 
- \( w \) wind speed (m s\(^{-1}\))
- \( T_0 \) ground surface urban temperature (K)
- \( T_{oc} \) ground surface temperature at transition point (K)
- \( \alpha \) difference between rural and urban lapse rates (K m\(^{-1}\))
- \( Q_s \) sensible heat flux (kW m\(^{-2}\)).
It should be noted that this formula has been used over the first 5 km downwind from the transition point, and that the mixing heights used in our energy performance simulations are the averages of the mixing heights obtained over the 5-km zone for each time interval.

We chose this model over others because it incorporates the effects of manmade urban heat and of the cooling downwind in an urban area. To illustrate our use of the Leahey–Friend model, the following assumptions are used as inputs with an hourly weather tape for Sacramento: 1) a constant heat island magnitude of 3.5°C, 2) an artificial heat addition rate based on Torrance and Shum (1975, Fig. 7), 3) a rural lapse rate of 0.004°C m⁻¹ based on sounding data from Vandenberg Air Force Base, and 4) no change in albedo. The calculated mixing heights for a typical clear summer day are shown in Fig. 8. These heights average around 600 m at night and remain under 1 km until 1200 local time, when they start to rise, reaching a maximum of 3 km by 1700 local time. As shown by the spikes on Fig. 8, the model is very sensitive to the hourly wind speed. For comparison between different locations, Fig. 9 shows summer mixing heights averaged over entire urban areas for several hot climates using the Leahey–Friend model. As with the evapotranspiration calculation, many questions still remain about the appropriateness of using this mixing height model for all climates and urban conditions.

Once the mixing height is known, we can compute the volume rate for a city based on Eq. (3). Using Eq. (2) to calculate the evapotranspiration rate as a function of temperature and insolation, we then estimate the resultant changes in the urban microclimate. We assume the increased tree canopy does not alter the overall heat balance of the urban microclimate, i.e., the effect of the additional evapotranspiration is adiabatic and results in lowered drybulb temperatures, increased humidity ratios, but no change in wetbulb temperatures. We have implemented the above steps into a weather preprocessor program that modifies the drybulb temperatures and humidity ratios on a standard hourly weather tape depending on the input urban canopy density and the original temperatures, solar radiation, and wind speeds each hour. This modified
weather tape is then used as input to the DOE-2.1C program. Figures 10 to 12 show the modified drybulb temperatures on a typical summer day for Sacramento, Phoenix, and Lake Charles. Since the original weather tape reflects existing conditions, the percent coverages noted should be interpreted as increases in, rather than total, tree canopy densities.

After we have developed a better understanding of the microclimate effects using the simple citywide model, we intend to refine it by improving the calculation of evapotranspiration rates and accounting for uneven air mixing and localized effects with different techniques such as two- or three-dimensional atmospheric diffusion models.

3. Prototype house description

The prototype building simulated using the DOE-2.1C program is a one-story detached house of wood-frame construction with 143.1 m² of floor area, 14.3 m² of windows (10% of floor) and 123.4 m² of wall area (Fig. 13). Construction details are based on standard U.S. building practices (NAHB, 1979), while operating conditions and infiltration rates are taken from statistical surveys of current house conditions. The house has a thermal integrity typical of current construction in the warm U.S. locations, with $R = 3.35 \text{ m}^2 \text{ K W}^{-1}$ ceiling, $R = 1.94$ walls, no slab perimeter insulation, single pane windows, and an air change rate of 0.7 h⁻¹ averaged over the winter months. The hourly air change rate varies with outdoor temperature and wind speed, and is calculated using the empirical Achenbach–Coblenz equation. The house has been simulated with an air-conditioner with a rated cooling capacity of 34 600 kJ hr⁻¹ and a SEER of 9.2. The cooling thermostat is set at 25.5°C, and natural venting is assumed when the temperature and enthalpy of outside air is lower than that indoors, and the cooling loads

Fig. 10. Drybulb temperature modifications calculated by microclimate vegetation model for a typical summer day (27 July) in Sacramento with increases of 10% and 25% in the urban tree canopy density.

Fig. 11. Drybulb temperature modifications calculated by microclimate vegetation model for a typical summer day (2 June) in Lake Charles with increases of 10% and 25% in the urban tree canopy density.

Fig. 12. Drybulb temperature modifications calculated by microclimate vegetation model for a typical summer day (15 August) in Phoenix with increases of 10% and 25% in the urban tree canopy density.
for that hour can be totally met by ambient air at 10 air changes per hour. The windows are assumed to have shades half drawn during the summer, resulting in a shading coefficient of 0.63. (A detailed description of the assumptions and methodology used in DOE-2.1C residential simulations is given in Huang et al., 1986.)

To investigate the sensitivity of the predicted cooling energy savings to building insulation levels, simulations were also done for the same prototype house with neither ceiling nor wall insulation. This alternate condition is more typical of houses in warm locations that predate the 1973 oil crisis. However, since we expect future houses will be built at least with current insulation levels, we used only the results for the insulated house in our analysis.

4. Predicted cooling energy savings for prototype house

The microclimate model including shading, evapotranspiration, and wind reduction effects is used in conjunction with the DOE-2.1C program to simulate the cooling energy use for the typical one-story house described above in four locations: Sacramento, Phoenix, Lake Charles, and Los Angeles. The base case condition is represented by the unmodified weather tape. Two increased canopy conditions of 10% and 25% or 30% are then considered. To assess the impact of individual effects, incremental sensitivity analyses are done, considering first shading, then shading and wind reduction, and finally, shading, wind reduction, and evapotranspiration. In reality, of course, the three effects occur simultaneously.

Results for cases with the generalized canopy are

<table>
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<tr>
<th>Location</th>
<th>None</th>
<th>10% Shade only</th>
<th>Shade + wind + evapotranspiration</th>
<th>25% Shade only</th>
<th>Shade + wind + evapotranspiration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base case energy use (no savings)</td>
<td>(Δ)</td>
<td>(Δ)</td>
<td>(Δ)</td>
<td>(Δ)</td>
</tr>
<tr>
<td>Sacramento</td>
<td>1420</td>
<td>34</td>
<td>26</td>
<td>261</td>
<td>18.4</td>
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<tr>
<td>Annual kWh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak kW</td>
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<td>0.09</td>
<td>0.14</td>
<td>0.66</td>
<td>9.3</td>
</tr>
<tr>
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<td>14</td>
<td>9</td>
<td>144</td>
<td>15.9</td>
</tr>
<tr>
<td>Phoenix</td>
<td>6911</td>
<td>63</td>
<td>60</td>
<td>725</td>
<td>10.5</td>
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<tr>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>0.13</td>
<td>0.66</td>
<td>7.4</td>
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<td>10</td>
<td>4</td>
<td>151</td>
<td>4.1</td>
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<tr>
<td>Lake Charles</td>
<td>3908</td>
<td>28</td>
<td>26</td>
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<td>10.5</td>
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<tr>
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<tr>
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<td>~0</td>
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<tr>
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<td>8</td>
<td>5</td>
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<td>63.0</td>
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Table 1. Savings in annual cooling energy use and peak cooling power for one-story prototype house with increased urban tree canopy with generalized shading. All entries except Column 1 are savings compared to the base case in that column; Δ = savings.
shown in Table 1, and those with trees planted for shading in Table 2. For comparison, energy savings for an uninsulated house under the generalized canopy is shown in Table 1A. For all cases, the results show significant cooling energy increases due to decreased wind speed. It should be noted, however, that the DOE-2.1C simulations account for natural ventilation in terms only of lowering the building cooling load, and not of

<table>
<thead>
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<th>Location</th>
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<th>10% Shade + wind + evapotranspiration</th>
<th>25% Shade + wind + evapotranspiration</th>
</tr>
</thead>
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<td>Base case energy use (no savings)</td>
<td>Shade only (Δ)</td>
<td>Shade + wind (Δ)</td>
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<tr>
<td></td>
<td>281</td>
<td>23</td>
<td>7</td>
</tr>
</tbody>
</table>

TABLE 2. Savings in annual cooling energy use and peak cooling power for a one-story prototype house with increased urban tree canopy located for summer shading. All entries except Column 1 are savings compared to the base in that column; Δ = savings.

<table>
<thead>
<tr>
<th>Location</th>
<th>None</th>
<th>10% (=1 tree/house) Shade + wind + evapotranspiration</th>
<th>30% (=3 trees/house) Shade + wind + evapotranspiration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base case energy use (no savings)</td>
<td>Shade only (Δ)</td>
<td>Shade + wind (Δ)</td>
</tr>
<tr>
<td>Sacramento</td>
<td>1420</td>
<td>122</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>7.10</td>
<td>0.66</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>904</td>
<td>36</td>
<td>29</td>
</tr>
<tr>
<td>Phoenix</td>
<td>6911</td>
<td>208</td>
<td>208</td>
</tr>
<tr>
<td></td>
<td>8.87</td>
<td>0.47</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>3647</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Lake Charles</td>
<td>3908</td>
<td>81</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>7.17</td>
<td>0.36</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>2489</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>359</td>
<td>~0</td>
<td>~0</td>
</tr>
<tr>
<td></td>
<td>4.46</td>
<td>0.43</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>12</td>
<td>8</td>
</tr>
</tbody>
</table>
raising the comfort threshold by inducing indoor air movement. In addition, the ventilation algorithm used in the program assumes a fixed air change rate at 10/hour when windows are open. In reality, the cooling energy penalties due to reduced winds are probably larger than shown, although the amount will vary greatly depending on the design and orientation of the house relative to the wind direction.

The results, however, do show sizable reductions in annual cooling energy requirements due to shading and evapotranspiration for three of the four cities. For Los Angeles, the reductions are minimal because the base case cooling energy use is very low (65 cooling hours) calculated using the assumption that window venting is used whenever possible. For the other cities, a 10% increase in the generalized canopy produces savings of 261 kWh (18%) in Sacramento, 725 kWh (11%) in Phoenix, and 412 kWh (11%) in Lake Charles, while a 25% canopy increase produces savings of 603 kWh (42%), 1766 kWh (25%), and 1071 kWh (27%) in the respective three cities. If the increased tree canopies are ideally planted for summer shading, the savings are further increased by 2% to 8% for the 10% increased canopy, and 7% to 10% for the 25% increased canopy. Test simulations show even more dramatic savings for a 50% increase in the tree canopy density, but we judge such an increase to be physically impossible.

Compared to that for a current construction house, the percent energy savings for an uninsulated house under the generalized canopy are very similar (Table 1A), but the total savings are substantially larger because of the greater cooling requirements. Increased tree cover will produce some energy savings for an uninsulated house, even in Los Angeles, whereas for a typical house there is almost no cooling load.

In analyzing the causes of the cooling energy reductions, shading accounts for only 6%–17% of the total savings in the generalized canopy cases, and for 10%–35% even in the shading cases. The remaining savings result from the lowered temperatures due to evapotranspiration. The ratio of the two savings is affected by the thermal integrity of the house, which we have assumed to be moderate. Older houses of lower thermal integrity will show greater savings due to shading, while the opposite will be true for tight new houses.

In all four locations, the results show savings in peak cooling loads of 8% to 11% for a generalized canopy increase of 10%, and 12% to 30% for a canopy increase of 25%. For the summer shade canopy, the peak energy savings are 9% to 20% and 17% to 44%, respectively.

5. Economics

A simplified economic model along with the estimates of possible power and energy savings for the four-tree canopy conditions are used to calculate the Cost of Conserved Energy (CCE) and the Cost of Avoided Peak Power (CAPP). CCE is obtained by dividing the annualized investment ($/yr) by the annual saved energy, i.e.

\[
\text{Cost of Conserved Energy (CCE)} = \frac{\text{Annualized Investment ($/yr)}}{\text{Saved Annual Energy (kWh/yr)}}, \quad (5)
\]

Annualized Investment

\[
= \text{Total Investment} \times \frac{d}{1 - (1 + d)^{-n}},
\]

where \(d\) is discount rate and \(n\) the time horizon. CAPP is obtained by dividing the total investment normalized for life of a nominal power plant (normally 20 years) by the avoided peak power, i.e.,

\[
\text{Cost of Avoided Peak Power (CAPP)} = \frac{\text{Total Investment ($)}}{\text{Avoided Peak Power (kW)}}. \quad (6)
\]

The Present Value (PV) of the power and energy saved by planting trees for the four canopy configurations simulated are shown in Tables 3 and 4. Two economic scenarios based on the age of trees and their prices are selected to provide upper and lower limits for the costs of conserved energy and power. In the first scenario we assume planting seedlings at a price of $5 per tree (McPherson, 1984, p. 173) which take ten years to reach full height at maturity (McPherson, 1984, p. 159). For the second scenario, we assume planting 5-ft. (1.5 m) trees at a price of $60 per tree including labor costs (Heisler 1984, p. 173) which take seven years to grow to full size. We add these costs to that for water in order to obtain the total cost of each tree.

The water consumption of a tree is estimated to be \(\sim 1\) kg \(h^{-1}\) (Bernatzky, 1982), which translates to an annual consumption of \(\sim 2000\) gal \(y^{-1}\). Current prices of water varies between 7–10 cents per hundred gallons.\(^2\) Therefore, total water consumption of a tree is about $2 yr\(^{-1}\). The additional water needed by a tree to maintain high summertime evapotranspiration rates is generally made up from available ground water. In addition to the above, we have made the following assumptions.

- The energy and power conservation potential of trees during the initial growing period is neglected.
- As trees mature, their roots grow deep in the ground and for most parts of the country they will become self-sufficient in absorbing water from ground; they do not need further watering.
- Even though the average life span of a tree is high

\(^{2}\) The current price of water from the San Francisco East Bay Municipal Utility District is 63.5 cents per one hundred cubic feet.
(100 years) we have assumed here a time horizon of 20 years, same as an average power plant.

- Interest rate is assumed to be 7% real.

The results from Tables 3 and 4 are encouraging. The cost of conserved energy (CCE) and avoided peak power (CAPP) is between 0.3 to 4.3 $/kW·h and 19 to 217 $/kW for all four locations studied. The present value of conserved energy is much higher in Phoenix and Sacramento than Los Angeles. The high but indeterminate values of conserved cooling energy in Los Angeles are due to the small base air-conditioning energy use calculated assuming night ventilation whenever possible. It is interesting to note that the average price of electricity is about 8 $/kW·h, and major utilities in California offer a rebate of $100–$300 for each kW of peak power avoided. Therefore, even with the upper limit cost of trees, the CCE and CAPP seem extremely appealing.

6. Discussion

Because of the exploratory nature of this study, many technical issues have been raised which we hope can be addressed in the future. Some of these require measured data to validate or improve theoretical models, others need better understanding of physical processes and more detailed modeling of those processes. The most critical issues are

1) Evapotranspiration rates. The Jensen–Haise model had been developed for daily periods in arid and semi-arid climates. There is a need to gather hourly evapotranspiration data for verifying the accuracy of the model on an hourly basis. If such an investigation yields negative results, we would then have to look for a more suitable model or find a procedure for distributing the calculated evapotranspiration rate by the hour of day. We also need to compare the calculated evapotranspiration rates to measured data for different climate conditions, notably the hot humid locations. Lastly, we need to investigate whether this model is appropriate to use in estimating evapotranspiration in trees rather than crops.

The Jensen–Haise model calculates potential rather than actual evapotranspiration. Therefore, the simulated savings in cooling energies represent maximum theoretical limits. Although we realize that it would be more realistic to investigate actual evapotranspiration rates, such an effort requires much more data on soil and plant conditions.

2) Mixing heights. We need to investigate the appropriateness of using the Leahey–Friend model for different cities in different climates. The model has also proven to be highly sensitive to certain input parameters such as the magnitude of the urban heat island and the amount of artificial heat flux. Therefore, we also need more data for characterizing the urban climate.

3) Adiabatic mixing. There are two basic assumptions in the existing microclimate model that need to be studied and refined. These are that 1) the increased urban canopy does not change the basic heat balance of the urban climate, and 2) the cooling effect of the plant evapotranspiration is well-mixed into the entire urban air volume. Both of these assumptions need further study and refinement.

### Table 3. Present value of saved cooling energy kWh and peak cooling energy in 1986 dollars for a one-story prototype house with increased urban tree canopy with generalized shading. The two values for each entry correspond to planting seedlings or 5-ft trees at $5 and $60, respectively. Water consumption for a growing tree is estimated to average ~$2/yr for 10 years for the seedling and 7 years for the 5-ft tree. A time horizon (n) of 20 years for trees and a discount rate (d) of 7% real is assumed. See text for CCE and CAPP equations.

<table>
<thead>
<tr>
<th>Location</th>
<th>None</th>
<th>Base case power use (kW)</th>
<th>10% (=1 tree/house)</th>
<th>25% (=2½ trees/house)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shade only</td>
<td>Shade + wind</td>
<td>Shade + wind + evapotranspiration</td>
<td>Shade only</td>
</tr>
<tr>
<td>Sacramento</td>
<td>7.10</td>
<td>6.8–31.6</td>
<td>8.8–33.7</td>
<td>0.9–4.0</td>
</tr>
<tr>
<td>Phoenix</td>
<td>8.87</td>
<td>3.6–17.2</td>
<td>3.8–18.0</td>
<td>0.4–1.4</td>
</tr>
<tr>
<td>Lake Charles</td>
<td>7.17</td>
<td>8.1–38.8</td>
<td>8.9–41.5</td>
<td>0.6–2.6</td>
</tr>
</tbody>
</table>
Table 4. Same as Table 3 except with increased urban tree canopy located for summer shading.

<table>
<thead>
<tr>
<th>Location</th>
<th>None</th>
<th>10% (=1 tree/house)</th>
<th>30% (=3 trees/house)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base case power use (kW)</td>
<td>Shade only</td>
<td>Shade + wind</td>
</tr>
<tr>
<td>Sacramento</td>
<td></td>
<td>7.10</td>
<td></td>
</tr>
<tr>
<td>CCE (¢/kWh)</td>
<td>1.9–8.8</td>
<td>2.0–9.4</td>
<td>0.7–3.1</td>
</tr>
<tr>
<td>CAPP ($/kW)</td>
<td>36–172</td>
<td>33–158</td>
<td></td>
</tr>
<tr>
<td>Phoenix</td>
<td></td>
<td>8.87</td>
<td></td>
</tr>
<tr>
<td>CCE (¢/kWh)</td>
<td>1.1–5.2</td>
<td>1.1–5.2</td>
<td>0.3–1.2</td>
</tr>
<tr>
<td>Lake Charles</td>
<td></td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>CCE (¢/kWh)</td>
<td>2.8–13.4</td>
<td>2.9–13.5</td>
<td>0.5–2.3</td>
</tr>
<tr>
<td>Los Angeles</td>
<td></td>
<td>4.46</td>
<td></td>
</tr>
<tr>
<td>CCE (¢/kWh)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>CAPP ($/kW)</td>
<td>55–264</td>
<td>53–253</td>
<td>26–126</td>
</tr>
</tbody>
</table>

4) Localized effects. In the present microclimate model, we have overlooked the fact that the cooling effects of trees may be concentrated in the vicinity of the vegetation rather than uniformly distributed throughout an urban area. This localization is suggested by measurements showing variations in daytime temperatures within a city, with noticeably cooler values near large urban parks (Duckworth and Sandberg, 1954; Oke, 1978). This uneven temperature distribution implies that our simple model may be underpredicting cooling effects in the immediate vicinity of trees and overpredicting them for more distant areas.

Two possible methods to estimate localized microclimate effects due to trees include use of a three-dimensional urban climate model (Bornstein, 1984), or an atmospheric dispersion model such as the SHORTZ program developed by the Environmental Protection Agency (Bjorklund and Dowers, 1982).

In this paper, we also have not covered in detail shading and wind reduction effects due to specific types, geometries, and location of trees relative to the house. These, however, can be handled in a straightforward manner with the existing model if the tree transmissivity, geometry and location are known (Thayer et al., 1983).

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