THE EFFECT OF VEGETATION ON RESIDENTIAL ENERGY USE IN ANN ARBOR, MICHIGAN

by Robert J. Laverne and Geoffrey McD. Lewis

Abstract. Computer models have shown that proper placement of trees around climate- controlled buildings can significantly contribute to energy conservation by lowering cooling requirements in summer months and heating requirements in the winter. A study conducted in a residential neighborhood of Ann Arbor, Michigan, uses electric and natural gas utility company records to examine energy demand for homes in 3 areas with distinctly different levels of tree stocking. Field measurements quantify the density of vegetation that casts shade directly on homes, and aerial photo interpretation is used to evaluate potential wind shielding offered to individual homes by vegetation and adjacent buildings. Statistical analysis of data indicates that variability of structures, including different levels of insulation, infiltration, and efficiencies of space-conditioning appliances mask the effects of vegetation on energy use. Analysis is further complicated by a wide range of energy use habits of individual homeowners. However, trends are observed that suggest proper placement of trees with regard to seasonal solar gain and wind patterns may yield substantial savings of energy. Improper placement of trees may yield a significant increase in net levels of energy used for space conditioning.

Energy conservation continues to be a major concern for most utility companies and consumers. The oil embargo of the 1970s highlighted the limited supply of natural resources that serve as sources of energy. Continued concern for the environment, including global climate change, has renewed interest in energy conservation and efficiency.

Combustion of fossil fuels emits carbon into the atmosphere. There is considerable debate surrounding the degree to which increased carbon in the atmosphere contributes to global climate change, but the fact that atmospheric carbon dioxide is rapidly increasing cannot be disputed (5,17). International demand that the United States recognize its role in creating this problem has led to the Clinton administration's Climate Change Action Plan. This plan calls for rolling back greenhouse gas emissions to 1990 levels by the year 2000.

Tree conservation, planting, and maintenance can play a multifaceted role in energy conservation and control of atmospheric carbon dioxide. All trees store or "sequester" carbon, and vigorously growing natural forests act as carbon sinks. Depletion of tropical rain forests has resulted in a loss of carbon storage capacity and a release of large amounts of stored carbon (10). In addition to providing carbon storage, properly placed trees in developed areas can provide cooling shade, which results in less electricity required to operate air conditioners. Therefore, less fossil fuel is burned at power plants and less carbon enters the atmosphere. Reducing peak energy demand benefits utility companies and lowers utility bills to homeowners. Trees also indirectly contribute to energy conservation through shading of hardscape and dark surfaces, such as parking lots, which absorb sunlight and reradiate the energy as heat. In addition to providing shade, trees move water vapor into the air through transpiration, which also reduces air temperature—making trees particularly effective at diminishing urban heat islands (1).

In winter months, properly placed trees can reduce residential energy use by slowing and diverting cold winds. Most studies on the use of vegetation as windbreaks have focused on rows of trees arranged to intercept prevailing winds, but trees need not be arranged in a shelterbelt formation to provide protection from winter winds. Indeed, shelterbelts are usually not possible in an urban or suburban setting due to space constraints. Tree canopies over homes provide protection by collectively slowing wind speeds and reducing infiltration of cold air into houses through gaps in caulking, weatherstripping, or insulation. The height and density of tree canopies determine the amount of slowing and turbulence created in directional winds (8).

Improperly placed trees can be detrimental to energy conservation, particularly in northern climates, where trees to the south of buildings block beneficial solar gain during winter months (16). The placement of trees must consider the net impact on both heating and cooling requirements of buildings to achieve optimum levels of energy conservation.

The suggestion that trees can contribute to energy conservation is supported by previous research. A limited number of studies have been based on on-site data collection (2,4) while a greater number have been conducted primarily with computer-generated models (7,9,14,18). The potential for energy savings is dependent on regional climate. Studies conducted in the southwestern United States have focused primarily on reducing energy use for cooling (15). Northern climates prove to be more complex in terms of energy conservation. Shade-produced energy savings during the cooling season can be more than offset by higher energy requirements for heating during winter months. In addition to shade, wind becomes an important factor in northern climate space-conditioning requirements. Sand (16) provides a concise summary of the important points concerning residential energy use and vegetation in heating-dominated climates. This study conducted in Ann Arbor, Michigan, was designed to take an important step in developing a methodology to investigate the effect of urban trees on energy use.

Study Site

The study site is a residential neighborhood in Ann Arbor, Michigan. The center of the study site is located at 42°17'07" north latitude, 83°41'10" west longitude, and the elevation at the site varies between 850 and 900 ft above sea level. Aerial photo interpretation (October 1991, 1:7200 color infrared transparencies) from a previous study (11) revealed 3 distinct levels of tree canopy closure. The first strata has 66% canopy cover (hereafter referred to as "high"), the second has 45% canopy cover ("medium"), and the last strata has 15% canopy cover ("low"). Figure 1 is a black-and-white reproduction of the original color infrared photography.

Examination of historical aerial photography shows the site consisted of a natural woodlot and agricultural fields prior to development. In 1969, clearing for roads and house lots began. The homes that occupy the original woodlot were built under the canopy of existing mature trees ("high"). The homes built in the fields during the late 1960s to the mid 1970s have benefitted from landscaping, which included tree planting. Many of these trees are now approaching maturity and provide significant levels of shade to the homes ("medium"). The remaining area was not developed until 1981, when most of the homes in "low" stratum were built. Some landscaping has been done around these homes, but the trees are immature and provide little shade or shielding from the wind.

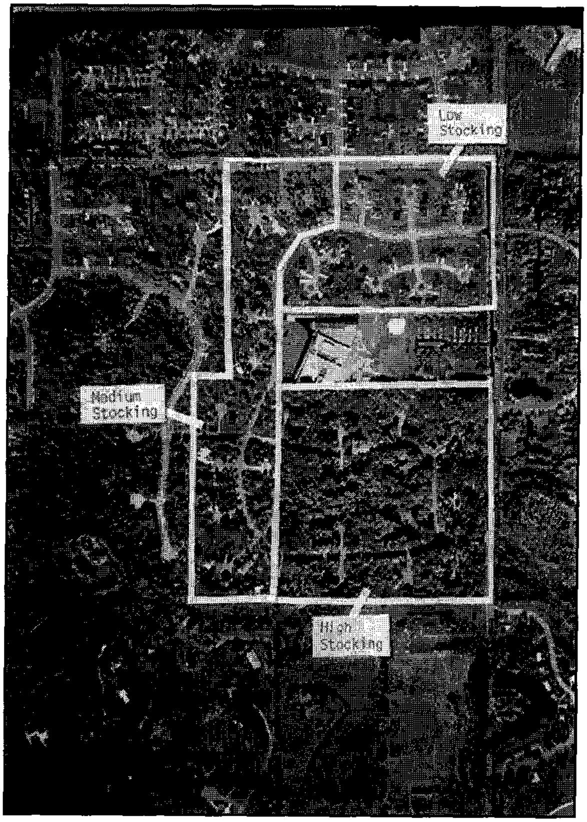


Figure 1. Aerial photo of test site with borders of 3 test strata.

Methods

Homeowner energy use survey. In November 1993, an introductory letter was distributed to all 142 homes in the study area. Included with the letter was a photocopy of an *Ann Arbor News* article (3) that publicized previous work conducted by the researchers in the community. Researchers then began door-to-door visits. Homeowners were asked to sign a release form to allow researchers access to Detroit Edison and Michigan Consolidated Gas Company utility records, and to complete a brief survey with the researchers. The survey provided information on significant energy-consuming appliances and occupant behavior that impacts energy consumption (Table 1).

Of the total 142 homes in the study area, 101 homeowners signed release forms and completed energy use surveys, 26 homeowners could not be contacted, and 15 homeowners declined to participate.

Utility data. Natural gas and electricity consumption data were provided by Michigan Consolidated Gas Company and Detroit Edison. Gas and electricity use data were reported for 15 billing periods between March, 1993, and May, 1994, and grouped into heating and cooling seasons. Billing period end-dates were used to determine the boundaries of the heating and cooling seasons. The heating season was defined as October 11, 1993, through April 12, 1994, and the cooling season as May 20, 1993, through September 15, 1993. The periods between heating and cooling seasons were considered transitional. Natural gas consumption was reported in hundreds of cubic feet (CCF); electricity consumption was reported in kilowatt hours (kWh). These units were standardized to British thermal units per day (Btu/sq ft/day) for comparison and analysis (1 CCF = 100,000 Btu, 1 kWh = 3,413 Btu).

Table 1. Sample questions from residential energy use questionnaire.

Appliance/structure-related questions	Behavior-related questions
Have there been changes in square footage?	How long have you lived here?
Have there been changes in insulation?	How many people live here now?
What is your primary heating fuel?	What are your normal thermostat settings?
How old is your furnace?	Do you close off rooms in your house?
Do you have a secondary source of heat?	Do you use storm windows in the winter?
Is your home air-conditioned?	Do you open a window for ventilation?
Is your garage heated?	Do you keep the garage door closed?
Do you have a fireplace?	How often do you use your fireplace?
What type of range/stove do you have?	
How many refrigerators do you have?	
Is your clothes dryer gas or electric?	
Is your water heater gas or electric?	
Are your windows original or replacement?	
Do you have other high-energy appliances?	

Measurement of shade from vegetation on homes. To quantify the effect of vegetation on energy use, it is necessary to quantify the density of the vegetation that casts shade on a building or shields a building from wind. Four variables determine whether shade is cast on a building by a tree: 1) sun position in the sky, 2) tree position relative to the building, 3) tree height, and 4) tree crown density.

The extremes of the solar path occur during the winter solstice and the summer solstice. During the winter solstice in the northern hemisphere, the sun will trace its shortest and lowest path, rising in the southeast and setting in the southwest, and shadows cast by trees will be longer than during any other day. Conversely, the sun will trace its longest, highest path on the summer solstice. On this day the sun will rise in the northeast and set in the northwest, and shadows cast by trees will be shorter than on any other day during the year.

Diurnal solar paths throughout the year were determined using solar path charts (13). For this study, the January 21 solar path was selected to represent winter conditions and the July 21 solar path selected to represent summer conditions. These dates represent typical seasonal conditions, avoid the solar path extremes of winter and summer solstice, and correspond to dates used in previous studies (6). Many of the trees in the study area are deciduous, and therefore cast denser shade in the summer than in winter. For this reason, it was necessary to conduct 2 sets of measurements. Therefore, field measurements were

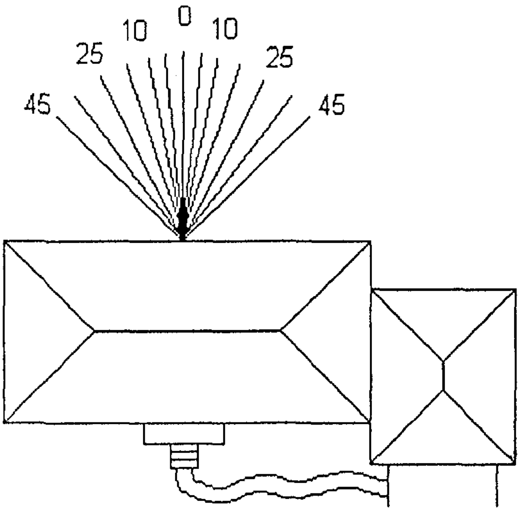


Figure 2. Angles at which shade sample points were taken (only 1 facade illustrated).

done during leaf-off conditions using the January 21 solar path and during leaf-on conditions using the July 21 solar path.

For each house, winter and summer daily shading patterns on each side of the building were recorded using the appropriate solar path chart, a compass to determine horizontal sun position (azimuth), and a clinometer to determine vertical sun position (elevation). The presence of vegetation was recorded along the solar path for angles of plus and minus 45 degrees from the perpendicular to the plane of each building facade. The presence of vegetation along the January 21 and July 21 solar paths was noted at 5, 10, 15, 25, 35, and 45 degrees from the perpendicular to a facade (Figure 2).

Additional information relevant to the space-conditioning requirements of the houses was gathered including: 1) estimated square footage of walls of each building facade, 2) estimated square footage of windows of each building facade, and 3) roof color.

Wind shielding by vegetation. Because the sun is a point source of radiant energy, its predictable path can be used to determine which trees will directly impact a building through shade. Wind, however, does not originate from a point source and is much less predictable. It is thus much more difficult to determine which trees significantly and directly impact a building through shelter from wind. Estimating density of vegetation relative to direction provides a first measurement of the potential wind shielding benefits of trees adjacent to houses.

To evaluate the density of vegetation on a house-by-house basis, tree canopy closure was measured on aerial photographs using a template representing a 200 ft radius from building center around each building. The circle formed by the 200 ft radius was subdivided into eight 45 degree wedges or octants. The borders of the octants were formed by the compass points N, NE, E, SE, S, SW, W, and NW. Percent total canopy closure was estimated for each octant using a dot grid procedure repeated 3 times to provide greater precision.

Adjacent buildings also provide wind shielding to the houses in the study area. The same 200 ft radius circle template was used on the aerial photos to assess the profile of adjacent buildings relative to the center point of test houses. Within each octant the angle subtended by adjacent buildings was measured to the closest 5 degrees. As the distance between buildings becomes smaller, building profiles subtend larger angles and therefore contribute greater wind shielding. The combination of canopy closure and adjacent-building data derived from aerial photography gives a measure of obstacles that affect wind speed and direction. The researchers viewed percent canopy closure as a measure of wind shielding because it measured horizontal vegetation density in sections of space (octants) around a building, while winter shade and summer shade were viewed as measures of shading because they quantified vegetation obscuring the path of the sun in the sky.

Statistical Procedures

A variety of parametric and nonparametric procedures, as well as diagnostic procedures, were performed using SYSTAT and Excel installed on a personal computer. A 0.05 level of significance (á) was used to determine statistical significance. Analyses were performed for individual utility billing periods and for the collective heating (October 11, 1993, to April 12, 1994) and cooling (May 20, 1993, to September 15, 1993) seasons. Seasonal energy use was defined as the average daily energy use through the season. The dependent variable for all analyses was energy intensity (energy used per square ft of floor area).

The Lilliefors test, normal probability plots, and skewness and kurtosis coefficients were examined to assess the presence and severity of departures from the assumption of normality for all parametric procedures.

The parametric one-way analysis of variance (ANOVA) and nonparametric Kruskal-Wallis (KW) tests were used when appropriate to determine differences in energy use between strata. The Bonferroni method of multiple pairwise comparisons was used to ascertain which strata were significantly different, for both ANOVA and KW. The parametric one-way analysis of covariance (ANCOVA) was used to explore the effect of different variables, used as covariates, on differences in energy use between strata, with the Bonferroni method used for multiple pairwise comparisons. The repeated-measures analysis of variance (ANOVA-RM) was used to test for linear, quadratic, and cubic trends over time in energy use.

Pearson's product-moment correlation coefficient (r), Spearman's rank correlation coefficient (r_s), and stepwise multiple linear regression models (MLR-S) were used to explore the relationship between vegetation structure and energy use and also to assess the importance of independent variables, including vegetation and building measures, in explaining the variation in energy use. Multiple linear regression models (MLR) were built separately for vegetation variables and building variables before assembling a combined model utilizing both vegetation and building variables.

Results and Discussion

Survey data and vegetation measurements. The introductory letter and the *Ann Arbor News* article distributed to homeowners proved to be quite valuable when it came time to visit homes on a door-to-door basis. Homeowner participation was vital to the project, and a nonintimidating, informative yet brief introduction seemed to be a key element in gaining acceptance.

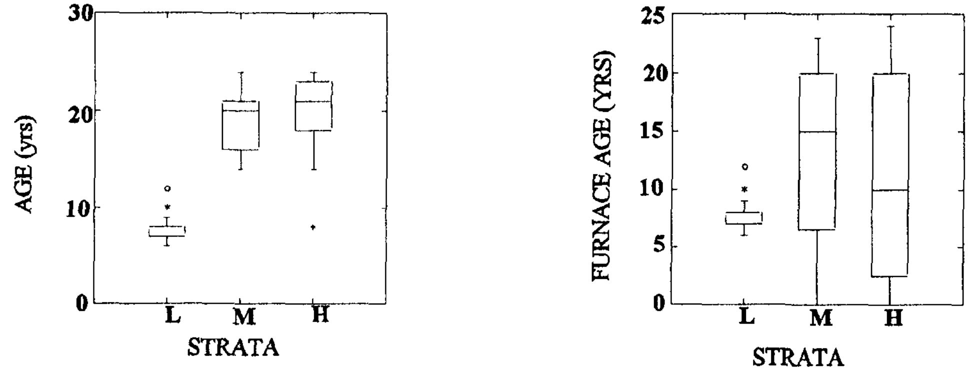
The most difficult variables to measure accurately are those associated with different energy use patterns of individual families. The survey data provides interesting insights into some of the building characteristics that influence energy use. Three of these characteristics–building age, furnace age, and total square footage—are plotted by strata along with the 3 vegetation measurements in Figure 3 (air conditioner age is, in the majority of cases, similar to furnace age, so comments about furnaces apply to air conditioners).

The diagrams in Figure 3 are referred to as "box and whiskers" plots. The box and whiskers illustrate the level of variability within the data. The line in the center of the box denotes the median value. The top and bottom of the box are called hinges and are determined by the values at the outer edges of the second and third quartiles. The absolute value of the difference between the hinges is called the interquartile range or midrange. The whiskers show the range of values falling within 1.5 times the midrange of the hinges with values greater than this (outside values) shown as asterisks. Values farther than 3 times the midrange of the hinges are called far outside values and are shown as circles.

These plots, as well as statistical tests, indicate that the medium and high strata are quite similar in terms of building age, furnace age, and square footage but differ from the low stratum. Buildings in the low stratum are newer and smaller than most buildings in the medium and high strata. Furnace ages in the medium and high strata are highly variable, ranging from new to 24 years old. All houses in the study area have gas furnaces.

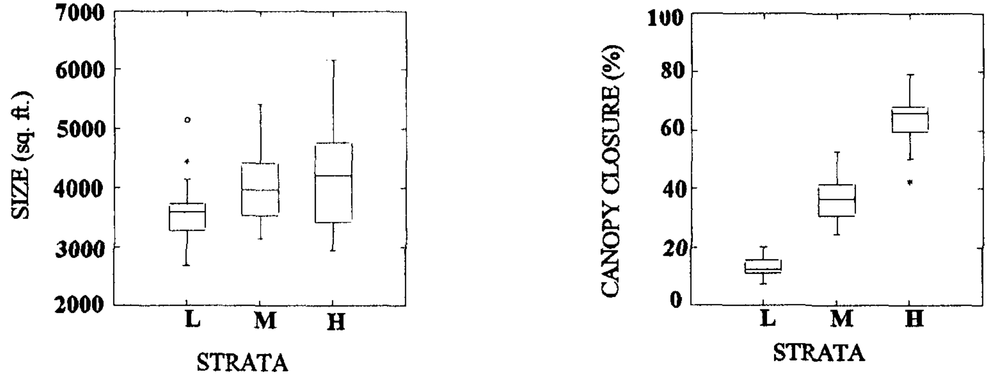
Differences in square footage between strata are not as dramatic as differences in building age and furnace age, and are easier to account for in the analysis of energy use, requiring only that energy use be standardized to square foot of living space. Unfortunately, building age and furnace age could not be dealt with so handily. Newer houses generally have more insulation and are less leaky than older houses, but age by itself is not a very good measure of insulation or infiltration, both factors that directly affect energy use. Likewise, furnace age has no simple relationship to furnace efficiency.

The measurements of wall area and window area for each house facade were considered both as square footage and as a proportion of each



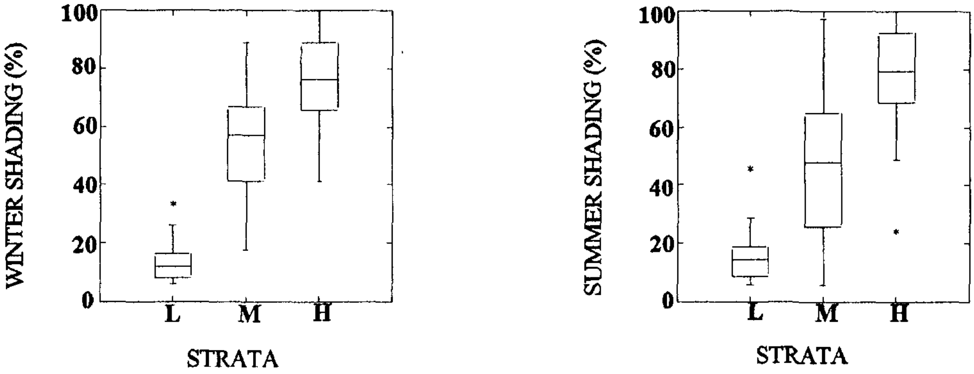
a. Building Age

b. Furnace Age



c. Building Size

d. Canopy Closure



e. Winter Solar Path Shade

f. Summer Solar Path Shade

Figure 3. Box plots of building and vegetation variables by strata (L = low, M = medium, H = high).

facade that is window area. Neither window area nor proportion of window area on individual house facades follows any obvious pattern related to strata. Increased proportion of windows on the north facade is somewhat correlated with increased winter energy use (Pearson r correlation coefficient = 0.357; Spearman r_s correlation coefficient = 0.285). This correlation is to be expected because the sun never directly shines in north facing windows, because most air infiltration occurs around windows and because the coldest winds come out of the north. Thus, the survey data indicate that the study area is not homogeneous in terms of building characteristics, making it difficult to separate vegetation effects from building effects on home energy use.

Because the strata were differentiated based on vegetation characteristics, percent canopy cover, and winter and summer shade by vegetation vary among the strata (Figure 3). Winter and summer shade displayed a wider variation than canopy cover. Increased winter shade is moderately correlated (Pearson r correlation coefficient = 0.507; Spearman r_s correlation coefficient = 0.504) with increased winter energy use.

Energy use data. Because building energy use data is affected by numerous factors, it is difficult to determine the effects of trees on energy use without accounting for all of the other influencing factors. The natural gas and electricity use data were plotted by strata over time (Figures 4 and 5). From these plots, differences between energy use in the low stratum and in both the medium and high strata are evident. Considering the same patterns occurred among the strata based on building characteristics, it is likely that energy use differences among strata are largely due to differences in building characteristics. The houses in the low stratum are newer and are likely to be more airtight and better insulated.

Another interesting relationship to note regards the patterns of energy use (Figures 4 and 5). Gas use has 1 peak in the winter (heating season), while electricity use has a peak in the summer (cooling season) due primarily to air conditioning, and a smaller peak in the winter due to furnace fans and increased need for lighting. The winter peak in gas use is 10 times as large as the summer electricity peak, confirming that Ann Arbor is in fact a heating-dominated area, from an energy point of view. However, due to the cost of providing expensive electricity generation and distribution capacity to meet the peak summer demand, more research has focused on electricity conservation.

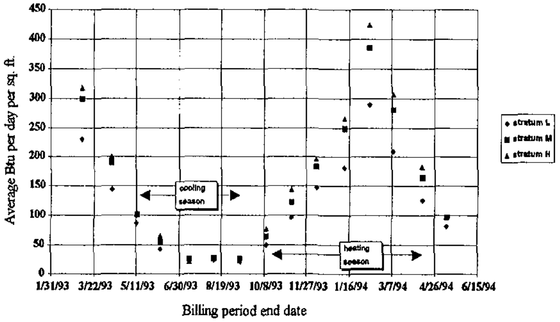


Figure 4. Plot of stratum mean gas energy use over time.

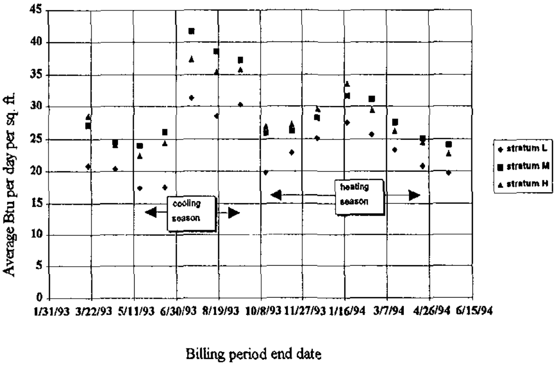


Figure 5. Plot of stratum mean electric energy use over time.

Natural gas energy use. The medium and high strata were not significantly different in gas energy use in any individual billing period or over the heating season as a whole. The low stratum had significantly lower gas use during the winter months.

Heating requirements for a house are determined by the building characteristics and the environment around the building, specifically solar gain and heat losses due to wind (infiltration) and temperature (conduction through the building envelope). Vegetation affects the environment around the building by moderating wind speed and, depending on location, inhibiting solar gain. Thus, it is possible that the low stratum has lower energy use than the medium or high strata because solar gain is a much more important factor of energy use than wind sheltering in winter (which has not been established) and/or because the houses in the low stratum are better insulated, more airtight, and/or have more efficient furnaces (which seems to be the case).

There are some possible reasons for the lack of a significant difference in gas energy use between the medium and high strata. First, the houses in these 2 strata are quite similar in those building characteristics that have a strong impact on energy use. Second, these strata are more alike in shading, as measured by winter shade, than in wind shielding, as measured by percent canopy closure. If solar gain is a stronger factor than wind shielding in determining energy use in winter, the vegetation would tend to help make these strata more similar in energy use.

Also, even though there is no statistical difference between the medium and high strata, the high stratum has higher average gas energy use in every billing period during the heating season. This stratum receives, on average, less solar gain and more wind shielding than the medium stratum, lending some credence to the idea that a lack of solar gain is related to higher heating requirements, and possibly that solar gain is a stronger factor than wind shielding in determining energy use. The data do not prove these assertions, but they do hint at what may be occurring.

Electricity energy use. There were only 2 billing periods with a statistically significant difference between strata (those with end dates of 6/13/93 and 10/15/93). The large number of uses for electricity (lights, television, refrigerator, etc.) leads to larger variation in electricity use than in gas use, and thus limited detection of significant differences between strata.

The low stratum had lower average electricity use for every billing period considered (Figure 4). This is an indication of the importance of building characteristics in determining energy use. Despite higher solar gain in houses with limited shade from trees in the summer heat, more efficient air conditioners and insulation still resulted in lower electricity use in the low stratum.

The pattern of average electricity use between the medium and high strata, which are fairly similar in building characteristics, again provides some clues to what might be happening in terms of effects on building energy use. Despite no significant difference in the age of air conditioners between these 2 strata, the medium stratum has higher electricity use in every billing period during the cooling season. The medium stratum also has less summer shade. It is not difficult to infer that there is a connection here between solar gain and electricity use, especially because there is no real pattern in use the rest of the year.

Anecdotal evidence, such as the amount of time air conditioners were running, how uncomfortable researchers got working in the sun, and how long snow cover stayed on the ground in winter all indicate that vegetation is a large factor in determining the microclimate around buildings, at least that portion of microclimate which is due to solar gain.

A more detailed description of this study, including methods, statistical procedures, and results, can be found in Lewis (12).

Future Research

Future studies will attempt to isolate and quantify the effect of vegetation on residential energy use. First, research will be conducted to measure the differences in microclimate around the houses in comparison to a reference condition outside of the study area. Temperature, wind direction ,and wind speed will be measured at sample points distributed throughout the study area in a manner similar to the study described by Heisler et al. (8). Energy use would be inferred as a result of the altered microclimate due to vegetation.

The investigation of microclimate provides a comparison between 3 areas of distinctly different canopy closure over the same span of time. It is also desirable to consider changes in energy use at a single location as vegetation density changes over time. A second phase for future study monitors energy use for heating and cooling in houses that have recently had adjacent large trees removed.

Summary

Data were collected on building characteristics, energy use, vegetation, and, to a lesser extent, occupant behavior in a residential neighborhood in Ann Arbor, Michigan, with 3 distinct levels of vegetation density. Stratum L had low vegetation density, stratum M was moderate, and stratum H high. Statistical and graphical analyses were performed to examine the effect of vegetation on energy used for heating and cooling in single-family residential buildings.

Strata M and H were similar in building characteristics, while stratum L was different from both other strata. Strata M and H were similar in gas energy use per square ft over all time periods considered. Stratum L had the lowest gas energy use, except for several billing periods in the summer. There was no statistically significant difference in electricity energy use per square ft among strata, except for 2 minor cases. Differences in patterns of energy use between strata were apparent, although they lacked statistical significance.

Building characteristics are a strong factor in determining energy use, and are likely responsible for the lower average energy use in stratum L. Differences in energy use between strata M and H, which are more similar in building characteristics, may be the result of differences in vegetation. Higher energy use in stratum H in winter was consistent with the higher amount of shade there, and higher electricity use in stratum M in summer was consistent with the lower amount of shade there.

It should be remembered that the variation in energy use was high and there were many factors that affect energy use. This study primarily considered factors in two categories, building characteristics and vegetation, while grouping all other factors, including occupant behavior, as random variation or "noise."

This study is the first step toward a methodology to be used in the field to quantify the effect that vegetation has on residential space-conditioning energy use. The techniques described here were designed to not be intrusive and to require a minimum of time from the homeowners. They did not, unfortunately, provide enough information to reliably correct for some of the most influential factors. The results described here indicate that vegetation is a factor in determining energy use, but stop short of quantifying the strength of the relationship.

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Résumé. *Une étude, menée dans un quartier résidentiel* de Ann Arbor au Michigan, a employé les données statistiques des entreprises de services de gaz et d'électricité afin d'examiner la demande en énergie des résidences de trois secteurs comportant des densités différentes en arbres.Les données recueillies sur le terrain ont servi à quantifier la densité en végétation qui ombrageait directement les maisons et la photointerprétation aérienne a servi à évaluer l'effet potentiel protecteur de la végétation contre les vents sur les résidences individuelles et les édifices adjacents.L'analyse statistique des données indique que la variabilité de structures et l'efficacité des appareils de climatisation masquent les effets de la végétation sur la consommation d'énergie.L'analyse est davantage compliquée par le large éventail d'habitudes de consommation d'énergie de chacun des propriétaires résidentiels.Quoiqu'il en soit, les tendances observées suggèrent qu'une localisation judicieuse des arbres en regard du gain d'ensoleillement selon les saisons et de l'orientation des vents dominants permet des économies significatives en énergie.