MEAN WIND SPEED BELOW BUILDING HEIGHT IN RESIDENTIAL NEIGHBORHOODS WITH DIFFERENT TREE DENSITIES

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ABSTRACT

There is little available knowledge of the absolute or relative effects of trees and buildings on wind at or below building height in residential neighborhoods. In this study, mean wind speed was measured at a height of 6.6 ft (2 m) in neighborhoods of single-family houses. Building densities ranged between 6% and 12% of the land area, and tree-cover densities were between 0 and 77%. Measurements were made with cup anemometers at points either ½ or 1 building height from 15 sample houses. An anemometer at 6.6 ft at a local airport provided the reference wind speed, U_o. *Approach wind speeds toward houses in a neighborhood with no trees were reduced an average of 22% compared to* U_o. *In a neighborhood with similar building density and 77% tree density, reductions in approach wind by both trees and buildings averaged 65% in winter and 70% in summer. Empirical models were derived to predict the effect of trees on wind separately from the effect of buildings. The models were based on tree and building geometry derived from map measurements, aerial photos, and fisheye photos from wind-measuring points.*

INTRODUCTION

Any broad policy of vegetation management or landscape design to modify an urban heat island as expressed in air temperature will also affect other variables: wind, solar irradiance, long-wave radiant transfer, and humidity. The largest effects on variables important to human well-being will be the effects on wind and solar radiation. Trees in dense arrangements may reduce mean wind speed and solar radiation below the top of the tree canopy by up to about 90% compared to open areas (Heisler and DeWalle 1988).

The effect of trees on wind in residential neighborhoods is important because wind is one of the factors that influence energy use for heating and cooling buildings (e.g., DeWalle and Heisler 1988; McPherson et al. 1988). Wind speed and direction also influence other environmental conditions, such as the comfort of people outdoors and dispersion of air pollutants.

Even though residential neighborhoods usually have few of the traditional windbreaks that consist of rows of closely spaced dense trees, the total effect of trees distributed individually may affect wind substantially in all seasons. The aggregate of these individual trees in urban and residential areas is often referred to as the "urban forest."

Most of the studies of tree effects on energy use in buildings have considered individual buildings with relatively simple tree arrangements. However, most single-family homes, of which there are more than 60 million in the U.S., are located in housing developments on relatively small lots, and their microclimate is influenced by components of the urban forest throughout the development or even the city.

Determining the effect of the urban forest on wind is a complex problem because vegetation and buildings are generally interspersed in irregular patterns, making it difficult to separate effects of buildings from effects of trees and shrubs. The wind measurements and numerical modeling of airflow that have been done for dense, continuous forests and orchards would seem to have little relevance in the complex suburban situation. Wind tunnel models have been used to evaluate tree effects on pressure coefficients of residences (e.g., Mattingly et al. 1979), but only for relatively simple configurations of trees and buildings. In the literature, there are few reports of measurements of aggregate tree effects on wind below house height in residential neighborhoods. McGinn (1983) measured wind speeds with an anemometer in the open and with another in one of several neighborhoods in turn, but his measurements were only in summer and for points close to house height.

As part of a study of tree effects on energy use for heating and cooling houses, mean wind speeds were measured at the 6.6-ft (2-m) height in four neighborhoods of single-family houses. The measurements were made near houses that had no tall hedges or trees in dense rows immediately adjacent to the house. Tree cover in the neighborhoods ranged from negligible to quite dense. Wind at a local airport served as a reference. Statistical

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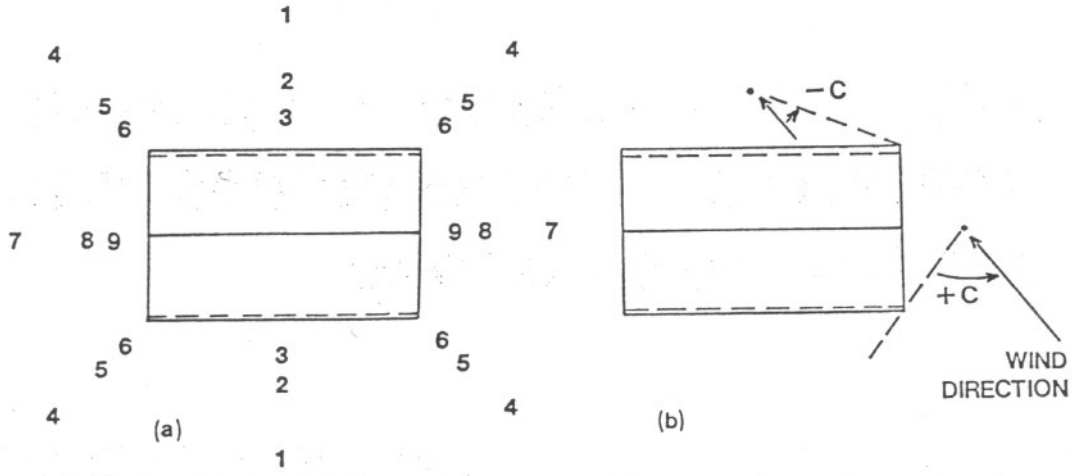

Figure 1 Plan views of isolated building indicating (a) position types (b) wind/corner angle (C)

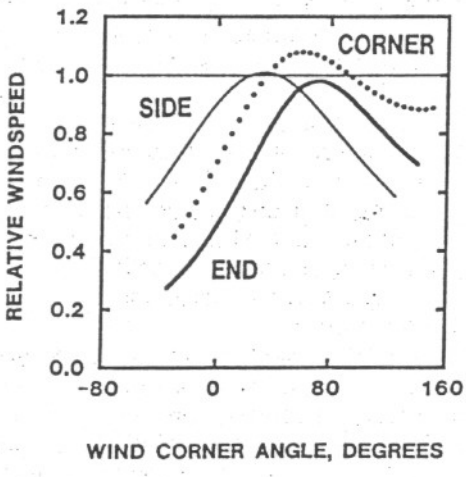

Figure 2 Relative windspeed at sides, ends, and corners of isolated building at a horizontal distance of 1 building height. The wind corner angle (C) is defined in Figure 1. The ends of the curves represent wind direction perpendicular to the sides or ends, or parallel to the bisector of the corner, either toward the building (+C) or over it (−C).

models were derived to predict the effect of trees on wind separately from the effect of buildings. This paper briefly summarizes the study. A detailed report to the primary sponsor is available (Heisler 1989).

METHODS

Residential Area Sampling Points

One goal of this study was to provide information on wind reductions by trees throughout neighborhoods so that tree influences on building energy use could be simulated. In energy analysis programs, the input required for wind is hourly mean wind speed at one reference height, such as ceiling height (Sherman and Modera 1984). In this study, the 6.6-ft (2-m) height was chosen for wind measurements on the assumption that windspeed at 2 m is representative of flow around the house, or at least that 2 m is sufficiently close to "ceiling height." As a practical matter for this study, instruments were placed temporarily around houses within neighborhoods on each of 14 measuring days. The need for fast setup time would have precluded the placing of anemometers at a much greater height. Although tree effects on wind differ with height, differences below the bottom of tree canopies are relatively small.

Another goal in this study was to develop data for modeling energy use in specific sample houses. Therefore, measurements near houses—rather than in a vacant lot away from houses—were needed. If the requirement for evaluating flow around particular houses had not been present, measurements in vacant lots might have sufficed. Finding suitable vacant lots would have been difficult, however; there were few of them in the neighborhoods studied.

Single-Building Measurements

To evaluate wind flow approaching a house of interest in a neighborhood, it often is not possible to place anemometers sufficiently far from that house to avoid its influence on the measurement. Even in the upwind direction, wind speed may be reduced up to 5 or even more heights from an obstacle (Heisler and DeWalle 1988). At sides and corners (relative to approach wind direction), wind speed may be greater than approach speed. Therefore, before selecting measurement points around the houses in the residential areas, measurements of wind speed around an isolated single representative building were made to develop corrections for the effect of the sample houses themselves. The assumption was made that corrections for the individual building in the open could be applied to measurements at houses in residential neighborhoods.

The goal of the single-building measurements was to establish a relationship between local wind speed (U_b^s) (see "Nomenclature") at points near the isolated building and the approach windspeed (U_a^s) measured outside the influence of the building, 10 building heights upwind. The near-building wind speed, U_b^s, was measured at 24 points at distances D = ½, 1, or 2 h (h building height) from the sides, corners, and ends of the building. The points were designated as position types 1 through 9 (Figure 1). For each wind observation, the wind/corner angle, C, of the average wind direction from a line to the corners of the building (Figure 1) was evaluated.

Regression equations were developed to predict

TABLE 1
Averages of Building Descriptors by Neighborhood Tree-Density Group

Tree Density Group	Buildings 1000 ft upwind			Nearest building distance	
	Density[1]	Height ft	Volume Index[2] ft	Upwind (building heights)	Downwind (building heights)
No trees	.06	12	1.0	25	22
Low	.12	12	1.5	17	128
Medium	.09	16	1.7	18	15
High	.10	.14	1.5	19	20

[1]Density is the average percent of land covered by buildings as determined from maps and averaged over upwind directions from each wind point.
[2]Building volume index has units of ft because it was derived from density (nondimensional) and building height (ft.) (1 ft = 0.3048 m)

TABLE 2
Averages of Tree Descriptors by Neighborhood Tree-Density Group

Tree Density Group	Season	Trees 1000 ft upwind			Fisheye view	
		Cover	Height ft	Volume Index ft	Density V_d	Angle V_a Deg.
Low	S	.24	29	7	.86	27
	W	.24	25	6	.40	23
Medium	S	.67	47	31	.85	47
	W	.68	44	30	.53	50
High	S	.77	56	43	.83	76
	W	.77	60	46	.49	54

relative wind speed, $R = U_b^s/U_a^s$, as a function of C and D, $R = f(C,D)$. These relationships were used to obtain predicted approach wind speeds (U_a^n) at houses in the residential neighborhoods, as $U_a^n = U_b^n/(\text{predicted } R)$, where U_b^n was the measured wind speed in the neighborhood. In Figure 2, the relationship $R = f(C,D)$ is shown for the distance $D = 1\ h$. In analyzing measurements in the neighborhoods, only data with C positive were used.

Wind Measurements in Neighborhoods

Measurements were made at 15 houses in four neighborhoods with different tree densities that can be used to categorize the neighborhoods approximately as: no trees, low-tree-density, medium-tree-density, and high-tree-density. Tall fences or hedges were not part of the study, and only houses without these features were selected for sampling.

Wind measurements in neighborhoods were made on seven days in winter and seven days in summer. At each of the four to seven houses that were included in the measurements on a particular day, measurements were made at up to four positions that were analogous to one of the position types at the individual building (Figure 1).

Neighborhoods were selected to minimize topographic effects. The neighborhoods were up to 5 miles (8 km) apart and up to 3 miles (5 km) from the reference site. Elevations in the neighborhoods differed by as much as 235 ft (72 m) from the reference site's elevation. Slopes in the neighborhoods were up to 8%, which is generally small relative to the degree of slopes that have been shown to significantly influence wind speed near the ground (Rutter 1968).

For wind measurements in the neighborhoods, up to 15 relatively inexpensive but rugged, four-cup anemometers were used. Though not the most sensitive available, they were matched and calibrated against sensitive cup anemometers before the measurements. In the neighborhoods, individual electronic counters totalized wind run of the anemometers over each hour. The counters required observation sometime during the following hour for manual recording of the wind run.

Concurrently with measurements in the neighborhoods, a reference mean windspeed (U_o), vector wind direction (θ), standard deviation of direction, and net all-wave radiation were measured at the local airport. A data logger measured these values at 3-s intervals and hourly averages. Wind reductions by obstacles vary with turbulence of the airflow, which depends, in part, on the thermal stability of the atmosphere. Hence, an index of stability (T) was estimated for each hourly observation period according to Turner (1961) from calculated solar elevation and airport observations of cloud cover and height.

Measurements in neighborhoods were made only in daytime periods and not during significant precipitation or extreme cold. Hence, the measurements reported here are not totally representative of a year's wind climate.

Building and Tree Morphology Measurements

Morphological characteristics of the buildings in the upwind and downwind directions from neighborhood wind-measuring points were evaluated from maps that showed the location and height of each house, using a procedure similar to that previously used for central city buildings (Heisler and Grant 1987). For each measurement hour, building characteristics at each neighborhood wind point were determined along three lines—through average wind direction, θ, and 15° to each side of it. The three values of each measured building characteristic were combined to yield averages, maximums, minimums, or largest difference between two of the three values of the characteristic for that hour. The characteristics included: distance in building heights to the nearest upwind and downwind building; upwind building average heights and densities (fraction of area covered) over 0 to 300-ft (91-m) and 300-ft to 1000-ft (305-m) distances; and density times average height, which formed an index of building volume.

Tree characteristics were evaluated similarly to building characteristics, but with photographs rather than maps. At each wind-measuring point, a 180-degree fisheye slide photo was taken to evaluate the vertical angle subtended (V_a) by and the density (V_d) of tree crowns visible from the wind points. This was done by projecting each slide onto a polar grid so that vertical angles and densities could be estimated as averages over 15-degree segments. Separate photos were taken for summer and winter. The percentage of tree-crown cover in the 0 to 300-ft and 300-ft to 1000-ft distances in the upwind direction from the center of each sample house was estimated from aerial photos by a dot-grid method. Average tree height was derived from field data.

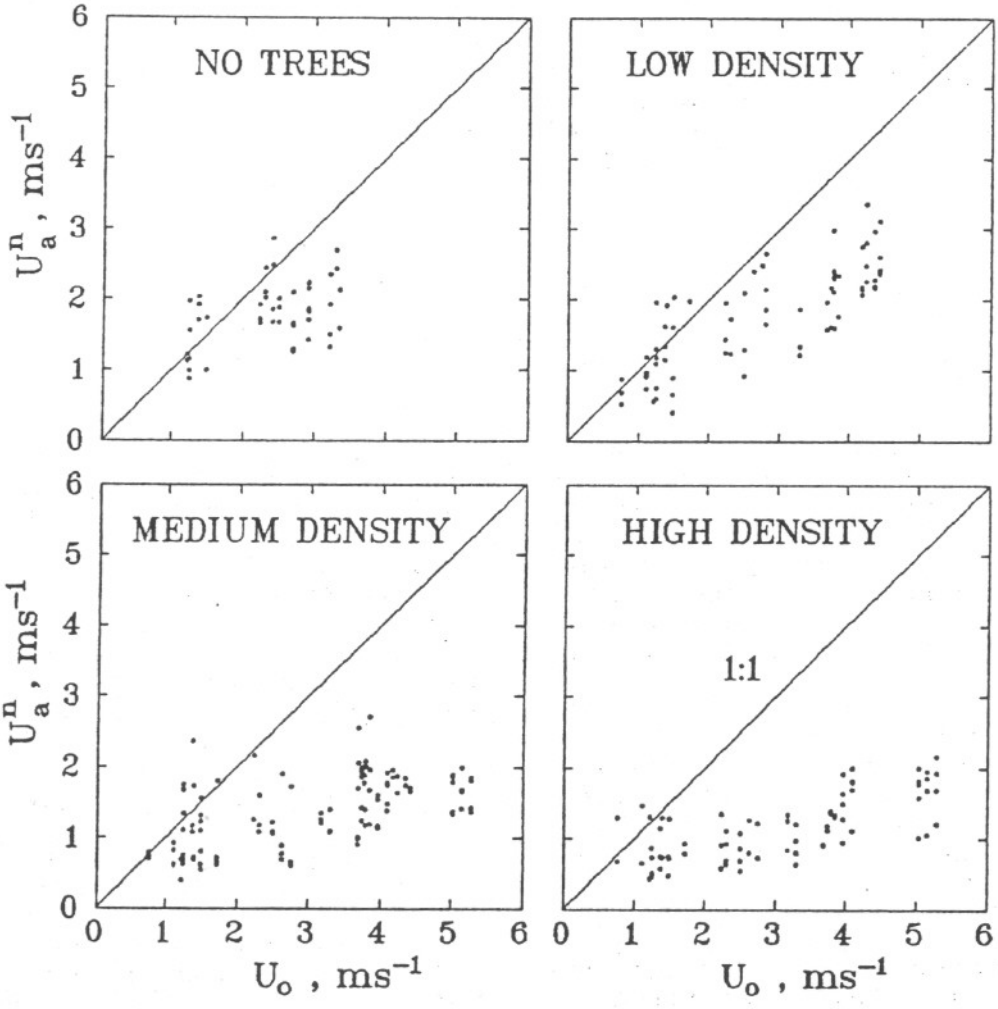

Figure 3 *Approach wind speed toward houses U_a^n in winter vs. reference windspeed (U_o) by tree density*

RESULTS

Building and Tree Morphology

Averages of building descriptors generally characterize the house morphology within each neighborhood. There were some differences (Table 1). The low-tree-density neighborhood had the highest building density with 12% of the land area covered by buildings. The large value of the nearest downwind building distance in that neighborhood occurred because one house was on the edge of the development.

Averages of tree descriptors (Table 2) indicate general differences in trees in the neighborhoods. Although cover indicates the fraction of ground covered by tree crowns without including a crown density factor that would differ with the season, cover (and height) within a density grouping differs slightly from summer to winter because wind direction θ differed and the data are averaged over θ during measurements. Tree-volume index is derived from tree cover and height. Tree cover and height are generally correlated. Average tree-crown density (V_d) in the three groupings is similar. Average winter. density ranged from 47% to 62% of summer density. The dominance of tree cover in these neighborhoods is indicated by the fact that trees cover about twice the area that buildings cover, even in the low-tree-density neighborhood.

Wind Reductions by Neighborhood

An initial impression of tree influences on wind is shown by scatter plots of all data as approach wind speed in the neighborhoods, U_a^n plotted against airport wind speed, U_O, by tree density groups in winter (Figure 3) and summer (Figure 4). The values of neighborhood U_a^n in Figures 3 and 4 are calculated as neighborhood $U_a^n = U_b^n$/(predicted R) as described above, where U_b^n is wind speed measured at a neighborhood sample building. Predicted R had a mean of 0.89 and ranged from 0.37 to 1.11. Mean values by neighborhood of U_b^n and calculated U_a^n differed by up to 4%.

Higher wind speeds in neighborhoods than at the reference site in the open may be anticipated for some points at building corners or where channeling occurs in neighborhoods with little vegetation. However, below 3.5 mph (1.6 m·s^{-1}) some unreasonably large increases in U_b^n and U_a^n over U_o were present, and all data with U_o less than 3.5 mph were deleted. This is justified partly on the basis of simultaneous wind measurements at two open sites about 3 mi (5 km) apart that showed good correlation

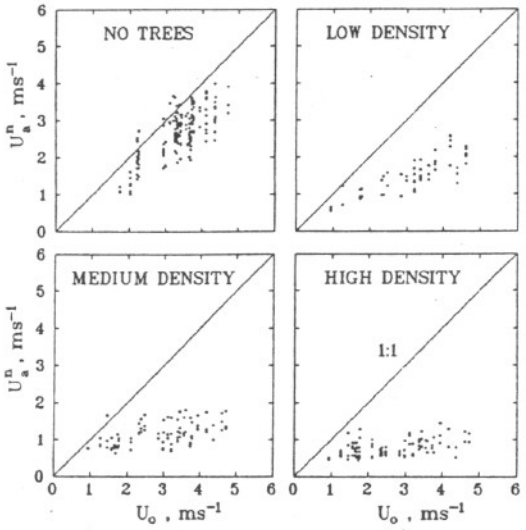

Figure 4 *Approach wind speed (U_a^n) in summer vs. reference wind speed (U_o) by tree density*

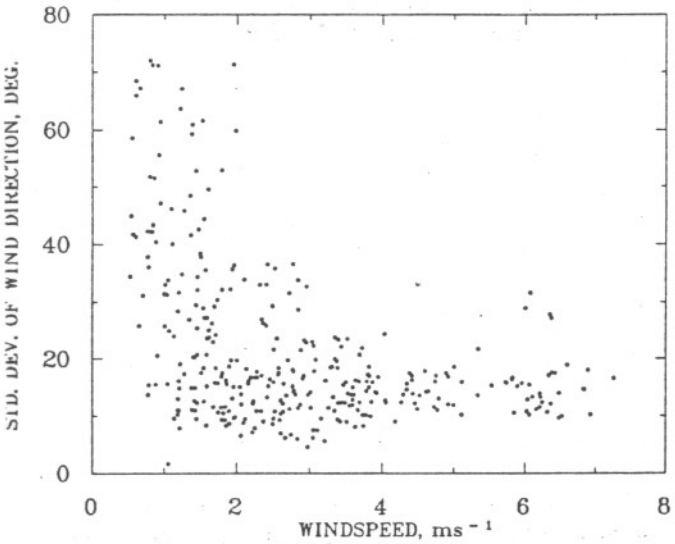

Figure 5 *Standard deviation of wind direction at the 6.6-ft (2-m) height in an open area. Each point represents a one-hour period.*

in both speed and direction at higher wind speeds but low correlation below 3.5 mph. The lack of correlation is expected, because wind directions tend to be much more variable below 3.5 mph than at higher wind speeds (Figure 5). Also, the anemometers were less accurate during periods of very low speed when the wind may be slower than anemometer threshold speed of about 1.5 mph (0.7 m·s^{-1}) part of the time. Anemometers at airport weather stations, from which weather data for energy analysis are generally obtained, usually have threshold speeds in excess of 2 mph (1 m·s^{-1}).

The overall effect of trees and buildings on wind in the different neighborhoods is indicated by averages of approach wind speed reduction, $\delta U = (U_o - U_a^n)/U_o$, over neighborhood and season as in Figure 6. Here, summer and winter data for the no-trees neighborhood are combined. This implies that building effects are the same in the two seasons, contrary to the expectation of smaller reductions by obstacles with more unstable atmospheric stability classes (Heisler and DeWalle 1988; Rutter 1968), which were generally present in summer. In fact, when summer

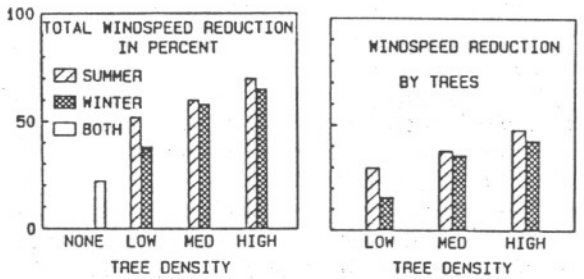

Figure 6 *Mean total wind speed reductions and apparent reductions by trees shown by tree density for all data with $U_o > 1.6$ ms^{-1}*

and winter data were combined, although atmospheric stability class varied from class 1, extremely unstable, to class 4, neutral, the effect of T on δU in the neighborhood with no trees was not statistically significant.

Regression Analysis of Tree and Building Effects on Wind Reduction

The buildings in the neighborhood with no trees reduced U_a^n by an average of 0.22 (Figure 6). To determine whether this was representative of the reductions by buildings in the other neighborhoods—that is, to separate building and tree effects on wind speed reductions—the data for all neighborhoods were combined, and wind reduction, δU, was regressed on building and vegetation variables. The building and vegetation variables were transformed to physically meaningful nonlinear forms and used as interactions to yield many potential independent variables (see Heisler 1989). In stepwise regression analysis, a large number of both building and tree variables entered as significant along with the standard deviation of wind speeds in the open and net allwave radiation there. For all observations with $U_o > 3.5$ mph (1.6 m·s^{-1}), the coefficient of determination, R^2 reached 0.73. For the less scattered reductions in the data with $U_o > 3$ m·s^{-1}, R^2 was 0.82 (Heisler 1989). Most of the residuals (observed-predicted values) in these analyses were less than 20 percentage points, though some were as high as 40, indicating something less than complete success in pre-

TABLE 3
Average Reductions in U_a^n by Buildings and Trees in the Neighborhoods with Trees, as Evaluated by Regression Models

Tree-density group[1]	By buildings	—By trees— Summer	Winter
Low	.24	.28	.14
Medium	.21	.39	.37
High	.24	.46	.41

[1]The different neighborhoods are indicated by the tree density.

dicting percentage wind reductions at individual points for a particular hour.

With tree variables set to the values they would have with no trees, the mean predicted building effect on δU in the neighborhoods with trees ranged from .21 to .24 (Table 3). This is close to the value of 0.22 for the neighborhood with no trees (Figure 6). The predicted building effects in the different neighborhoods in Table 3 are generally proportional to the building density index in Table 1.

The apparent tree reductions ranged up to 0.46 for the high-density neighborhood in summer. Except in the low-density neighborhood, apparent wind reductions by trees in summer were not much greater than in winter. The difference between summer and winter tree density (V_d) was greatest in the low-density neighborhood (Table 2), and this is at least partly responsible for the larger differences between summer and winter in wind reductions by trees. The generally small differences between summer and winter tree effects might be related to generally more thermally unstable atmospheric conditions during summer days than during winter days, but Turner atmospheric stability class did not appear as a statistically significant independent variable in regressions for δU.

Wind speed reductions were much less closely correlated with any of the building-morphology indicators than with the tree-morphology indicators. When δU was regressed on individual independent variables, the largest coefficient of determination, R^2, for a building variable was 0.15 for the building volume index. Tree cover was the single tree variable most closely related to δU, with an R^2 of 0.62. The tree-morphology indicators probably described tree morphology better than the building-morphology indicators described building morphology. However, the higher correlation of tree morphology indicators with wind reduction is evidently caused primarily by a greater magnitude and range of influence of trees on wind speed in these neighborhoods.

There was a general trend of increasing percentages of wind reductions with increasing U_o up to about U_o = 7 mph (3.1 m·s^{-1}). With U_o between 7 and 12 mph (3.1 and 5.4 m·s^{-1}), total reductions in U_a^n by both houses and trees in the four neighborhoods averaged between 4 and 12 percentage points higher than when U_o was between 3.5 and 7 mph. During the daytime, higher reductions at higher speeds might occur because the higher wind speeds cause less thermal stratification in the lower atmosphere, which results in larger percentage reductions in mean wind speed by obstacles. However, this logical explanation is contradicted by the

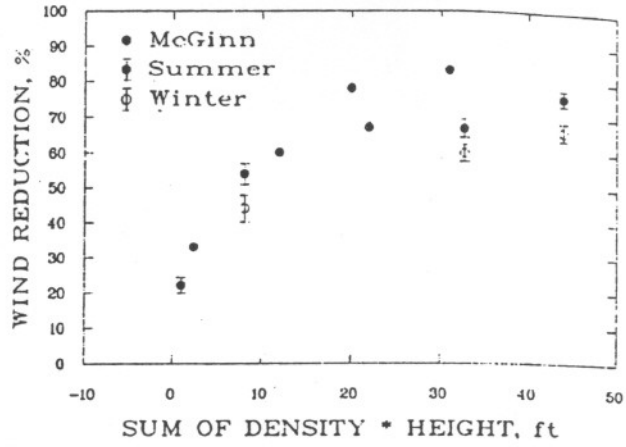

Figure 7 *Wind reduction in residential neighborhoods vs. the sum of area density × average height for buildings and trees from McGinn (1978) for summer and the measurements in this sutdy for summer and winter. The error bars indicate 95% confidence limits about the means.*

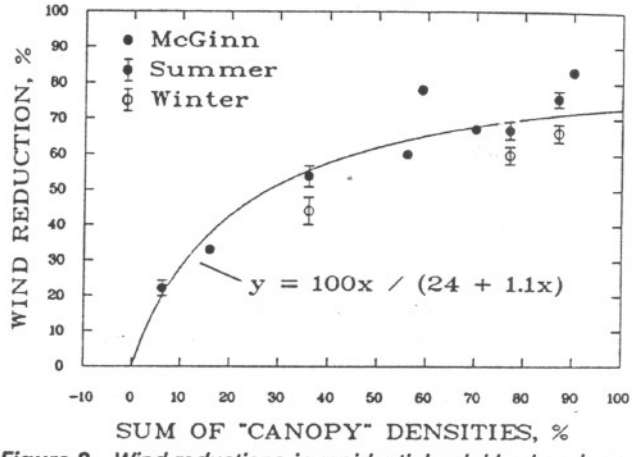

Figure 8 *Wind reductions in residential neighborhoods vs. the sum of area density of buildings and trees from McGinn (1978) for summer and the average neighborhood values from this study for summer and winter. The error bars indicate 95% confidence limits about the means.*

statistically nonsignificant effect of Turner stability class on δU. Turner class provides an indicator of thermal stratification.

A comparison can be made between summer δU averages of this study and the measurements of McGinn (1983). His "suburban canopy density" is a sum of fractional land area covered by trees times their height plus fractional area covered by buildings times their height. This produces an index that is approximately equivalent to the volume index for buildings plus the crown volume index for trees in this study. McGinn's "density" ranged from 2.0 with no trees to 31.5 in an orchard. The equivalent building plus tree-crown volume index in this study ranged from about 1.0 to 44. McGinn (Figure. 7) extrapolated greater reductions at high density. However, his high density case was an orchard with higher coverage of land area by tree crowns than is likely to ever be found in a residential neighborhood. Tree height in the orchard was only about 35 ft (10.7 m), not as tall as trees

generally present in residential neighborhoods with very dense tree cover. The short tree height in McGinn's orchard resulted in a rather small density index, given the cover percentage.

Wind reductions plotted vs. the sum of building and tree densities in the neighborhoods in this study along with the data of McGinn (Figure 8) seem to yield a little less scatter in the data than in Figure 7 where height is included. The curve is fit to our summer means.

In Figures 7 and 8, the average reductions are slightly larger than in Table 3 because in the figures, only data for open wind speed U_o between 7 and 12 mph (3.1 and 5.4 $m \cdot s^{-1}$) are included, whereas in the table, U_o ranged from 3.5 mph (1.6 $m \cdot s^{-1}$) to 12 mph. In the figures, summer and winter average canopy characteristics are combined. The error bars represent standard errors of estimates of the means (not standard deviations of the observations), and they are relatively small because of the large number of points (31 to 65) upon which each estimate is based.

APPLICATIONS

Although additional work is needed (see next section) to include a larger range of tree, building, and atmospheric stability conditions, the current results provide an initial means of extrapolating wind reductions by trees and buildings to other neighborhoods. The methods for map- and photo-derivation of building and vegetation morphology as reported here and in more detail in the final report (Heisler 1989), along with the prediction equations for reduction in U_a^n (δU) in that report, could be used to obtain approximate extrapolations to neighborhoods with building density that is not too different. In extrapolating, one method would be to select at least one "wind point" on each side of the building and then evaluate building and tree morphology over all wind-direction sectors. Wind reduction over a year would be modeled by selecting the hourly wind direction from a year's TMY or TRY data. By calculating C values, the δU values from any points with positive C (i.e., on the upwind side of the building) could be averaged.

For the purpose of modeling energy use in the buildings in this study, wind reductions for each season will be the seasonal average reductions from the tree-density group in which the house is located. In the transitional months of April and October, the summer and winter reductions will be averaged.

For approximate estimates of wind reduction below building height in neighborhoods of less than about 25% building density, values might be extrapolated from Figure 7 or 8. The points for summer wind reductions differ from the curve in Figure 8 by a maximum of 12 percentage points.

RECOMMENDED FUTURE RELATED WORK

This study suggests the need for many additional measurements and studies, such as:

1. Continuous measurements of wind reductions in residential neighborhoods over periods long enough to sample all atmospheric stability conditions and higher wind speeds in all seasons. A relatively small number of points would suffice.

2. Measurements in developments around houses with large masses of on-site trees, such as dense rows of conifers, to evaluate the effect of on-site trees in the turbulent air of a rough suburban surface.

3. Measurements to evaluate mean wind speeds at different heights in neighborhoods with trees.

4. Concurrently with wind measurements in items 1 through 3, measurements of air temperature and humidity.

5. Simplified methods of modeling tree effects on solar radiation, and validation of existing models.

6. Improved methods of extrapolating weather data between separated sites in the presence of topographic variation.

7. The influence of trees and buildings on turbulent wind fluctuations within the canopy layer is also of interest, although current energy analysis programs do not include turbulence as an input.

CONCLUSIONS

A striking result of this study is the apparently large potential of the aggregate urban forest to reduce mean wind speeds in residential neighborhoods of single-family houses. Where houses reduced wind speed about 24%, trees in mostly scattered arrangements reduced wind speed up to an additional 46%. Even in neighborhoods where most of the large trees were deciduous, reductions of wind speed by trees in winter averaged 50% to 90% of reductions in summer. Wind reductions during nighttime may, on average, be larger than those reported here, which were all made in daytime. Predictive equations from regressions of wind reductions on descriptors of building and tree morphology explained up to 82% of the variability in wind reduction at points in residential neighborhoods.

The measurements reported here are preliminary to planned measurements to include a wider range of stability conditions, to evaluate the effect of dense windbreak rows within developments, and to evaluate wind speeds at other heights above ground.

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NOMENCLATURE

C = horizontal angle at a wind-measuring point between wind direction and a line through the corner of the building
D = horizontal distance from a building in units of h
h = building height in ft
R = relative wind speed U_b/U_a
T = Turner atmospheric stability class
U_a = approach wind speed toward a building but outside its influence

U_b = wind speed near a building within range of its influence
U_o = mean wind speed at open control site
U^n = wind speed within neighborhoods
U^s = mean horizontal wind speed in single building measurements
δU = reduction in wind speed in neighborhoods
$= (U_o - U_a^n)/U_o$
V_d = density of tree crowns from wind points
V_s = subtended angle of tree crowns from wind points
θ = wind direction azimuth

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