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**Use of Vegetation to Ameliorate
Building Microclimates:**

**An Assessment of Energy-
Conservation Potentials** ✓

Boyd A. Hutchison
Fred G. Taylor
Robert L. Wendt
The Critical Review Panel

ENVIRONMENTAL SCIENCES DIVISION
Publication No. 1913

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A06 Microfiche A01

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Contract No. W-7405-eng-26

USE OF VEGETATION TO AMELIORATE BUILDING MICROCLIMATES:
AN ASSESSMENT OF ENERGY CONSERVATION POTENTIALS

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ENVIRONMENTAL SCIENCES DIVISION
Publication No. 1913

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Date Published: April 1982

ORNL/CON--87

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ABSTRACT

HUTCHISON, Boyd A., Fred G. TAYLOR, Robert L. WENDT, and
THE CRITICAL REVIEW PANEL. 1982. Use of vegetation
to ameliorate building microclimates: An assessment
of energy conservation potentials. ORNL/CON-87.
Oak Ridge National Laboratory, Oak Ridge, Tennessee.
86 pp.

This report evaluates the space-conditioning energy conservation potentials of landscapes designed to ameliorate building microclimates. The physical bases for vegetative modifications of climate are discussed, and results of past study of the effects of vegetation on space-conditioning energy consumption in buildings are reviewed. The state-of-the-art of energy-conserving landscape designs is assessed and recommendations are presented for further research.

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PREFACE

The purpose of this project was to assess the energy conservation potential of landscaping designed to ameliorate the microclimates of buildings. Our original intent was to make this assessment through synthesis of data available in the scientific literature. However, when we began our literature search, we found that there was a considerable amount of ongoing research being conducted by members of the Forest Amenities Working Group of the Consortium for Environmental Forestry Research. This consortium consists of eleven northeastern universities that have agreed to conduct forestry research in cooperation with each other and with U.S. Forest Service scientists under the sponsorship of the Forest Service's Northeastern Forest Experiment Station headquartered in Broomall, Pennsylvania. Because the Forest Amenities Working Group was actively involved in research dealing with vegetative effects on building and other microclimates and because its members were in close contact with other American scientists actively working on this problem, it was decided to utilize this group as a major information resource. To do this, the Critical Review Panel (see p. ix), whose nucleus consisted of this Forest Amenities Working Group, was convened. The group was supplemented by appropriate U.S. university and Forest Service scientists to provide additional regional perspectives as well as by a few representatives of the users of energy-conserving landscape design information. The Critical Review Panel met in February 1981 in State College, Pennsylvania, where members were briefed about current research efforts and advised about

sources of information in the scientific literature. Following the meeting, the Oak Ridge contingent searched the relevant literature and made contact with other landscape architects and environmental scientists working in this field. The information resulting from these activities was then summarized in draft form and circulated to the rest of the members of the panel for their review. Comments and criticism by panel members were used to make final revisions of this report which represents a collective effort of the review panel and constitutes a final report for the Impacts of Vegetation Upon Building Microclimates Project to the U.S. Department of Energy.

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INTRODUCTION

Humankind, evolving in a milieu characterized by some as "...red in tooth and claw," was and is poorly equipped, physically, to adapt to the varied environments of our world. Consequently, the human species has depended strongly on environmental modification to ensure, early in our history, survival of the species and, more recently, higher qualities of life for some if not all members of the human population. It is tempting to explain clothing, shelter, and even vernacular landscaping as a conscious modification of the human environment to create conditions more favorable to the human species. While this possibility cannot be ignored, the relationships between man's needs and environmental modifications are confounded by man's cultures. Dubos (1965) makes the distinction that whereas other life forms react with environmental stimuli, man responds to such stimuli. This distinction is necessary because man's interpretation of environmental stimuli and his responses to those stimuli are largely defined by his culture. Consequently, as Rapoport (1969) convincingly argues, sociocultural factors rather than biological ones tend to be the determinants of vernacular architectural styles and associated landscape designs rather than environmental conditions. This latter factor acts to modify, rather than define, vernacular architecture and landscapes as well as many other human modifications of the natural environments of our earth.

Thus, without considerable knowledge of the culture extant in ancient China, for example, it is probably impossible to know whether the practitioners of "Feng-shui" were landscaping for more favorable

human environments as Lesuik (1979) implies or whether they were attempting to, in the words of Wheatley (1971), "...project images of cosmic order on to the plane of human experience," Whatever the reasons, Marco Polo recognized both aesthetic and practical benefits of Chinese landscaping efforts during his travels there in the 13th century and remarked on the widespread practice of roadside planting of tall trees which defined the roads when covered by winter snow and which provided welcome summer shade along with ornamentation (Marco Polo 1934 ed.). However, he hastens to add that the Khan's propensity for causing wide-spread planting of trees was reinforced by his astrologer's divination that those who plant trees enjoy long lives.

Less ambiguous historical examples of vegetative amelioration of environmental conditions are extant, however. Rudofsky (1964) presents a photo of windscreens in the Shimane Prefecture of Western Japan. The farmers of this region continue the tradition of planting L-shaped windbreaks around their homes and gardens for protection from winter winds and from snow storms. Similar but larger-scale shelter plantings are common across the prairies and steppes of the United States and Russia wherever precipitation amounts are such that trees can be made to survive.

Another example is provided by the fabled hanging gardens of Babylon, built by Nebuchadrezzar for one of his wives. According to Durant (1935), this wife, a daughter of Cyaxeres, a King of the Medes, was unaccustomed to the hot sun and dust of arid Babylon and longed for the coolness and verdure of her native land. As a result Nebuchadrezzar had gardens built atop 23-m (75-ft)-tall columns. Here, in the shade of

tall trees and surrounded by shrubs and flowers, his harem could walk unveiled, secure from the eyes of commoners, in an environment specifically created for their comfort and pleasure.

It also seems likely that the myriad public and private gardens of early Egypt and Persia represent examples of the use of created landscapes to favorably modify the environment of the peoples of those cultures (Lesiuk 1979, Wilber 1962). The vegetation planted in those gardens would have provided shelter from the hot, dry desert winds and shade from the subtropical sun. The abundance of water in the form of pools and fountains combined with the lush vegetation of the gardens would have resulted in some cooling of temperatures through evapotranspiration, although it is not clear that these gardens were of sufficient size to maximize such an effect. That culture also played a role here is evidenced by the fact that the Persian word for "garden" was also sometimes used as a synonym for the term "paradise" (Wilber 1962) which implied a more perfect existence elsewhere. This would be in keeping with the notion of using vegetation and structures to improve comfort and pleasure.

The point is made that there is a long and rich tradition in human history for integrating architecture and landscape to improve the environments of human life. The question of whether these modifications represent a conscious attempt to enhance environmental features or whether the improvements realized were merely accidental consequences of environmental manipulations performed for other reasons is not of great importance here. What is important is that, in recent times, culturally and perhaps economically mediated responses to environmental conditions

have resulted in maladaptive environmental modifications; modifications that, while maladaptive from their very inception, were made tolerable by virtue of the cheap and abundant supplies of fossil fuels that powered machines designed to neutralize the effects of adverse environmental modification. Now that energy is no longer cheap or abundant, problems arise.

In terms of vegetation effects on building microclimates, this process led to an abandonment of the passive techniques traditionally used for the improvement or maintenance of more favorable environmental conditions within and without man's homes and places of work. As a result, the regionally characteristic architecture and landscapes of the United States and other developing nations, which were at least somewhat adapted to the regional climatic conditions, were replaced by styles reflecting novelty as opposed to tradition. New structures were built to satisfy arbitrary standards based on what often turned out to be short-lived aesthetic values. The use of native vegetation for shade and protection from wind became economically unnecessary with the development of mechanical space-conditioning devices that utilized the cheap and abundant energy available from fossil fuels. Because these styles and the buildings and grounds reflecting them have outlived the era of cheap and abundant energy, inhabitants of such buildings today find themselves trapped by an increasingly expensive and tenuous technology used primarily to offset effects of environmentally maladaptive architectural styles and landscape designs.

Bates (1945) described one example of this process. Early settlers of the American Great Plains built small sod or log homes with low, flat

roofs in depressions along waterways or in excavations in the south slopes of the rolling prairie terrain. These low structures took advantage of reduced wind speeds near the ground, their roofs accumulated snow in winter adding insulation, and the topography provided wind protection. In addition, the cottonwood trees that abound along prairie waterways provided summer shade and additional winter wind protection. The "dugouts," those structures partially imbedded in south facing slopes, gained heat from the winter sun, and the earth berm served as a massive heat sink helping to moderate exterior temperature changes. It appears that an environmentally sound, vernacular architecture developed early during the settlement phase of the prairies of the American midland. However, in the mid-nineteenth century, conditions were ripe for a major cultural shift in man's response to the prairie environment. The Victorian style of architecture came into vogue; transportation systems were in place across the plains; vast supplies of high quality and cheap construction lumber were available as a result of the heavy logging of the Lake States pineries, the vast pine forests of the upper Great Lakes states and provinces; and levels of affluence among the populace of the Great Plains were rising. As a result, roomy, two-story or more, square structures were erected, usually on the most exposed sites available, to replace the earlier homes. As Bates (1945) pointed out, the existence of this kind of architecture could not be justified in that setting. The architectural style is ill-suited to the wind and cold of the plains. Furthermore, available construction techniques, lack of insulating material, and economics severely limited the ability of the builders to create tight, well-insulated structures.

Finally, because of the exposed sites where the drying effect of the winds was maximal, trees could not be made to grow well around these structures, further limiting their inhabitants' ability to improve the microclimates around them.

Similar examples of this process are abundant in other regions, though perhaps not so extreme. As a result, there are great numbers of older homes in our country which depend heavily on fossil energies to maintain habitability at a time when those energies are no longer cheap or abundant. Such homes are among the kinds of structures in which retrofitting of insulation and energy-conserving landscapes will have greatest impact. As will be developed here, significant, if small, reductions in energy consumption for space conditioning can be effected through well-designed plantings of trees and shrubs.

More recent construction reflects rising energy costs in the use of newer, tighter construction techniques and in the installation of greater amounts of insulation. The super-insulated homes of the past few years reflect a modification of conventional architecture to minimize space-conditioning costs. Unconventional architecture also developed, ranging from underground or earth-bermed structures (contemporary versions, perhaps, of the dug-outs of the early American Midwest) to innovative structures incorporating active or passive heating and cooling systems powered by solar or geothermal energy (e.g., see Olgyay and Olgyay 1963; Community Builders 1980). This interest in energy-efficient architectural design and construction techniques was accompanied by a resurgence of interest in energy-efficient landscape design as well.

The questions that we address, then, in this assessment are:

- (1) What magnitudes of energy savings can be realized through energy-saving landscaping of older existing homes, of new single- and multiple-family dwellings, and of mobile homes; and
- (2) What are the possibilities for larger-scale community-wide vegetative modifications of energy consumption?

However, before addressing these questions, a review of the physical and perceptual bases for energy conservation through vegetative amelioration of climatic conditions is necessary. This review is necessary because several erroneous interpretations of research results have been propagated throughout most of the popular and much of the technical literature on this subject.

THE PHYSICAL AND PERCEPTUAL BASES FOR ENERGY CONSERVATION
THROUGH VEGETATIVE MODIFICATIONS OF CLIMATES

Our review of the literature and our discussions with other reseachers indicate that energy consumption for space conditioning in buildings is an extremely complex function of a number of factors:

- (1) The regional or macroscale climate in which the building is located;
- (2) Mesoscale modifications of macroclimate (e.g., lake and ocean, topography, cultural feature, or vegetation-induced modifications of macroscale climatic conditions operating on scales from one to tens of kilometers);
- (3) Microscale modifications of macro- or mesoscale climatic conditions, (e.g., modifications as above but on scales of 10s to 100s of meters;
- (4) Building characteristics (e.g., architectural design, building orientation and siting, type and quality of construction, and type and efficiency of space-conditioning equipment);
- (5) Life-styles of building occupants and uses made of building; and
- (6) The occupants' perception of what constitutes comfortable conditions.

Of these factors, the first four involve mostly physical phenomena. The last two involve physiological processes and the psychology of perception and values in addition to purely physical phenomena. It will suffice, for our purposes, to note that vegetation effects are involved in factors (2) and (3) and perhaps (6).

The Physical Bases

The influence of macroclimate on energy consumption for heating or cooling of homes and other buildings is intuitively clear. More energy will be required to heat buildings in cold, windy regions than in more temperate, less windy ones. Conversely, the warmer the macroclimate, the greater the need for mechanical cooling. On a nation-wide basis, energy consumption for space-cooling is quite small compared to that consumed for space-heating. Nevertheless, summer-cooling energy requirements are substantial in the southern portions of the United States.

Effects of Vegetation on Regional Climates

Large-scale modifications of vegetation may or may not affect macroclimates; theory indicates that such an effect does occur, but hard data substantiating regional climatic modification as a result of vegetative manipulation are lacking. Unfortunately, the data required for testing this hypothesis may be provided in the near future as deforestation of the Amazon River Basin continues (Molion 1975, Baumgartner 1976). However, manipulations of vegetation on regional scales are clearly beyond the realm of landscape architecture, especially in a society that does not understand or accept land-use planning on this broad a scale. It appears, for our purposes, that the macroclimate is relatively immutable, except for its own vagaries.

Effects of Vegetation on Mesoscale Climates

Mesoclimatic effects on space-conditioning energy consumption are also qualitatively straightforward. Any mesoscale physiographic, cult-

ural, or vegetative feature that modifies the macroclimatic temperature regimes will have some effect on space-conditioning energy consumption. However, because mesoscale meteorological phenomena are so poorly understood, the nature and magnitude of effects of mesoscale surface features of our earth on macroclimates are also poorly understood. Consideration of urban effects on climate, which have received considerable study, indicates something of the magnitudes of the mesoscale modifications of macroclimates that are possible. Such consideration also indicates that there is considerable potential for energy conservation on a subdivision or community-wide basis through integration of architectural design, site development, landscape design, and urban forest management over this same areal scale. Some planners are attempting to predict relative energy consumption levels as a function of site topography and vegetative cover to identify and utilize energy-efficient building sites, leaving inefficient sites for other uses (e.g., Squaw Run Area Watershed Assoc. 1981).

It is common knowledge that urban areas tend to be warmer than the rural areas surrounding them. This phenomenon is termed the "urban heat island" and reasons for its existence are fairly well understood. However, urban areas are not only warmer but are also usually much drier and less windy and have different atmospheric compositions (higher pollutant loads) than rural areas. Because cities are mesoscale cultural features, these modifications of regional climate represent mesoscale modifications of macroclimate effected by the physical presence of the city. Unfortunately, as Landsberg (1956) points out, the overall climatic effects of urbanization have had adverse consequences

on human health. More recently, it was discovered that the health of many of man's desirable urban commensals (e.g., shade trees, song birds) is also affected detrimentally by urban modifications of macroclimates. Effects of urbanization on regional climates also appear to have generally adverse effects on energy consumption, although some improvements have been documented [e.g., in London, England, fuel consumption for space heating was found to be lower in the central city than in outlying areas (Miller 1958)]. In most cases, the high-density, high-thermal-mass materials which predominate in inner cities cause large amounts of thermal energy to be stored in summer, increasing energy demands for summer air conditioning. In winter, less solar energy is received and stored. During the heating season, the urban heat island is largely the result of space-heating energy losses to the urban environment (Herrington, 1977). A net increase in annual energy consumption usually results from these phenomena.

The importance of vegetation as a modifier of mesoscale climatic conditions has been documented by more recent studies of urban climate. Myrup (1969), on the basis of energy budget comparisons for urban areas and forests, postulated that a city with trees would be cooler in summer than that same city without trees (Fig. 1). Outcalt (1972) performed similar analyses and, because of the fact that many cities have a treeless inner city surrounded by old residential areas having numerous, large shade trees, postulated that the urban heat island would be surrounded by an urban cold annulus. While the existence of this cold annulus has not been clearly documented, Flynn (1979) found that vegetated urban areas are indeed cooler than nonvegetated urban areas and

Fig. 1. Schematic diagram showing pattern of urban-rural (u-r) temperature differentials across various land-use situations (adapted from Oke 1975).

that the temperature difference is a function of both the amount and the areal pattern of the vegetative cover.

Consideration of the partitioning of radiant energy by the various surfaces exposed to the atmosphere in urban and rural areas explains these surface-climate interactions. The energy balance of any volume may be expressed as:

$$R_n = I_s + I_l = H + LE + S + G + P ,$$

where R_n = net radiation flux, I_s = net short-wave radiation flux, I_l = net long-wave radiation flux, H = sensible heat flux, LE = latent heat flux through the top of the volume, S = sensible heat storage in the thermal mass contained in the volume between the levels where R_n and G are measured, G = conduction of sensible heat into the ground or lower surface of the volume, and P = the "metabolic" energy sinks or sources within the control volume (e.g., radiant energy converted to chemical form in photosynthesis, metabolic energy production by homeotherms such as people, or, in the case of cities, energy ultimately dissipated as sensible heat in the urban environment from internal combustion engines, manufacturing processes, lighting, and space heating and cooling). It is important to note that this formulation neglects possible horizontal transfers of H and LE by wind.

In inner cities, the predominant surfaces exposed to the atmosphere are concrete and asphalt. Both of these materials are good absorbers (75 to 90%) of the incident solar radiation (I_s) (Heisler 1974), which implies warmer temperatures because absorption of radiant energy by any

surface converts that energy to sensible heat (H) which is sensed, as its name implies, as warmth by both living things and by thermometers. These materials also have high thermal mass, which implies that large amounts of sensible heat will be stored as S and G, to be returned to the aerial environment only slowly, thus maintaining elevated temperatures for prolonged periods. Thus, inner cities tend not to cool off at night as much as suburban or rural areas. The geometry of the "urban canopy" also increases absorption and hence conversion of solar energy to H by effecting multiple reflections of incident solar radiation which increase opportunities for absorption.

These same concrete and asphalt surfaces are impervious to water. Consequently, every shower or rainstorm produces cascades of water running off buildings, streets, sidewalks, and parking lots into storm sewers that quickly channel the water away from the city (Mastalerz and Oliver 1974). Thus, except for brief periods following precipitation events, latent heat exchange (LE) resulting from evaporation is practically nonexistent in urban areas without vegetation.*

Finally, because of the concentration of human activities in cities, large amounts of electrical, mechanical, heat, and chemical energy are dissipated as sensible heat (P) in the urban environment. In northern cities in winter, this factor can account for over 12% of R_n (Heisler 1975). Thus, the energy balance of nonvegetated central city areas is dominated by various forms of sensible heat and exhibits a reduced and

*Oke (1975) reports that LE accounts for around one-third of urban energy budgets, but most of this energy originates from combustion; hence, such LE exchange in cities is really a "metabolic" input (P) rather than a sink for R_n .

ineffective latent heat component. The end result is the urban heat island.

In a rural area, on the other hand, abundant vegetation transpires large amounts of moisture (as long as soil moisture is not limiting) which effects a conversion of radiant energy into latent heat. This form of energy (LE) is not sensed as heat. Furthermore, the thermal mass of vegetation is very low so little sensible heat is stored in the form of S, and this same vegetation shades the soil beneath, thereby reducing the soil heat storage (G) (Deering 1952). Finally, the metabolic energy component (P) in the case of vegetation is photosynthesis, and although small ($<1\%$ of R_n), it represents an energy sink rather than a source term as in the energy budget of inner cities.

The result is that cities tend to average 0.5 to 1.0°C warmer during the day and 5°C or more warmer at night than do vegetated rural areas (Landsberg 1956, Peterson 1969, Miller and Heisler 1979). Myrup (1969) estimated that in a treeless city about 40% of R_n is converted directly to H, while 60% is stored as $S + G$ to be released each night as I_1 and H, thus maintaining the elevated urban temperatures throughout the night. In a summer forest, however, his estimates are that H accounts for about 10% of R_n , $S + G$ accounts for another 10%, with LE accounting for nearly 80% of the incoming radiant energy.

Myrup's (1969) analyses indicate that substantial alterations of the energy balance of cities can be effected through the presence of vegetation. It is therefore possible to negate the urban heat island effect through the use of vegetation. Estimates of the amount of tree cover required to counter the super-heating of cities vary. Myrup (1969)

suggested that a 20% canopy cover would be sufficient, but more recent analyses indicate that at least one-half of the area should be vegetated to offset the development of the urban heat island (Miller and Heisler 1979).

Older residential areas in eastern and midwestern cities have relatively large proportions of their areas covered by tree crowns. In five cities in Eastern Kansas, canopy cover ranged from 10 to 35% (Marotz and Coiner 1973). Canopy cover in Minneapolis-St. Paul averaged about 33% prior to the arrival of the Dutch elm disease (Schmidlin 1979). Northeastern cities may have larger amounts of tree cover if Syracuse is at all typical. According to studies by Richards and his students (L.P. Herrington, personal communication), the canopy cover of Syracuse averages 57%. Thus, it appears that many cities, or at least portions of many cities, have sufficient vegetation for some relief from summer overheating at the scales we are addressing here. Further research is necessary to clarify the relationships between amounts of cover and degree of climate modification resulting in different climates, but it is clear that mesoscale landscaping can impact macroclimate with consequent effects on energy consumption for space conditioning in buildings.

Other questions also need to be addressed. One involves whether this effect of vegetation operates only at the mesoscale or whether it represents the collective impact of numerous microclimate modifications. The answer to this question is that the effects of vegetation on urban climates are a combination of meso- and microscale modifications. The cooling effected by vegetational transpiration appears to operate only at the mesoscale, while the reductions in stored sensible heat ($S + G$)

and in radiation load ($I_s + I_l$) result from microscale phenomena. These facts are of critical importance; however, they appear to be neither widely recognized nor appreciated.

To illustrate the problem more clearly, consider Federer's (1976) analysis of the cooling resulting from the LE exchange effected by a single, large, open-grown tree transpiring 380 L (100 gal) of water per day. This amount of evaporation represents 9.6×10^5 kJ (230,000 kilocalories) of energy in the form of LE rather than H. Thus, this 9.6×10^5 kJ figure is actually a measure of the amount of cooling produced each day by this tree. Comparing this figure with the cooling capacity of average-sized room air conditioners, Federer (1976) found that five such units running 20 h/d would be required to produce an equivalent amount of cooling by mechanical means. Quite obviously, the LE exchange effected by such a tree has a profound effect on the energy budget of its immediate surroundings. Therefore, we are tempted, as others have been, to conclude that a single tree in a residential lawn will provide cooling equivalent to many air conditioners. Unfortunately, while Federer's (1976) calculations are correct, this conclusion is absolutely wrong. The problem is that, in this analysis, we ignored the advective and convective heat exchanges caused by wind and by buoyancy effects. That is, the rapid mixing of the layer of the atmosphere near the surface of the earth that results from wind and temperature differences causes the cooling effect of a single tree to be rapidly diffused, and therefore diluted, into the comparatively infinite volume of air adjacent to the earth's surface. The end result is that no measurable cooling results from this LE exchange in the immediate vicinity of the

tree or anywhere else, despite a substantial alteration of the surface energy budget.

Equally invalid is the conclusion that the LE exchange effected by well-watered vegetation does not affect air temperatures. The collective effect of large numbers of transpiring trees is indeed a reduction of air temperature. At this time, we do not know how many trees or how large a tree-covered area is required to effect this cooling. We do know that air temperatures in San Francisco's vegetated Golden Gate Park average about 8°C cooler than the more vegetation-free urban areas adjacent to the park (Duckworth and Sandberg 1954).^{*} We also know that when a vegetated area exceeds some large areal extent, this evaporative cooling effect of the vegetation extends beyond the borders of the vegetated area. For example, Herrington (1977) noted that the cooling effect of the LE exchange of New York City's Central Park (343 ha) is reported to extend well beyond park boundaries, while he found that the cooling effect of a 29-ha park in Syracuse ended abruptly at its edges. Further study of mesoscale climate and vegetation interactions are indicated.

Effects of Vegetation on Local (Microscale) Climates

Given that evaporative cooling effects of vegetation are discernable only at some undetermined scale involving one to tens of kilometers, the average homeowner might well ask, at this point, what, if any, climatic improvements are possible through landscaping of individual

^{*}Because of the location of this park relative to the Pacific Ocean however, there is some question of whether this temperature differential is an effect only of the presence of vegetation or if it represents an integration of ocean and vegetative influences.

residential lots? Fortunately, we are able to identify several microscale modifications of climatic factors via vegetation that can markedly improve building microclimate. Of the three scales of climate, the microscale features are easiest to modify and the interactions of vegetation with microclimatic processes are fairly well understood (Heisler and Herrington 1976). Carefully selected and sited vegetation can provide shade for both buildings and people and can offer protection from or enhancement of the convective cooling of wind (Heisler 1977). For new construction, integration of architectural design, site utilization, construction methods, and landscape design can reduce energy demand for space conditioning in the finished structure by substantial amounts. For existing structures, retrofitting with energy-conserving landscaping can reduce space-conditioning energy requirements, but actual amounts of energy conserved depend on many other factors.

There are a number of popular books and articles (e.g., Foster 1978, Moffat and Schiler 1981), many state university extension bulletins (e.g., Barrick and Black, undated, Laechelt and Williams 1976, DeWalle and Farrand 1978, Kissida et al. 1978, Cox 1979, Pitt and Gould 1979, Weatherly and Williams 1979, Black 1981, Beck 1981), and a few publications of utility districts (e.g., Sacramento Municipal Utility District, undated) and government agencies (e.g., USDA 1978) which describe, mostly in qualitative terms, how to design energy-conserving landscapes. We consider these efforts commendable. In general, the recommended landscape designs are those that provide shade from the summer sun, channel cooling summer breezes toward windows, allow winter sun to reach the structure and, particularly, to penetrate southerly windows,

and provide protection from winter winds. There are important regional variations in these recommendations reflecting macroclimatic differences, but generally, they are valid.

Recommended species or classes of trees and shrubs for producing shade are invariably deciduous ones. The rationale for this recommendation is obvious; plants that lose their leaves in winter allow winter solar energy to pass through vegetative canopies to be absorbed by surfaces on or within buildings beneath. In the summer, when protection from radiation load is needed, the leaves of the plant crowns intercept both I_s and I_l , thereby effecting cooler surface temperatures on or in structures shaded by the plants. Misconceptions exist in this regard, however. Because deciduous plants lose their leaves in winter, some of the older literature recommends that deciduous trees be planted to the south of buildings to provide both summer shade and access to winter sun. Recent study has shown that the woody biomass of trees (i.e., the twigs, branches, and boles) intercept surprisingly large amounts of the incident winter insolation (see Fig. 2). Heisler et al. (1981) found insolation reductions of 40% under leafless elm trees and 50% under leafless London plane trees. Johnson et al. (undated) measured the shade cast by the leafless crowns of 15 common eastern deciduous tree species. Beech and black locust (>60% interception) were found to cast greatest amounts of winter shade, while red maple (~ 35%), sycamore (~ 33%), and redbud (~ 26%) cast the least. In a nearly pure tulip-poplar forest, the overstory canopy attenuation of winter radiation averaged over 50% (Hutchison and Matt 1977). As Heisler et al. (1981) point out, over much of the United States a 40 to 50% reduction

Fig. 2. Pattern of shade on the southeast wall of a house cast by a large, leafless elm tree on a clear winter day in central Pennsylvania. Photo shows that the shade cast by the tree bole and branches obscures a significant fraction of the house wall relative to window area. Not visible (to the eye or the camera) are the reductions in transmitted radiation effected by penumbral phenomena which obscure the shade cast by smaller twigs and branches but which, nevertheless, significantly reduce transmission of radiation through the leafless tree crown. Thus, solar energy gains via transmission through windows will be drastically reduced when the shadows impinge on windows. (Photo taken at about 10:30 a.m., EST, on January 31, 1981, by Dr. Gordon Heisler, U.S. Forest Service.)

in winter insolation would increase energy consumption for winter space heating more than the summer cooling-energy consumption would be reduced because of the summer shade, causing a net annual increase in space-conditioning energy requirements. Therefore, for most of the United States at least, shade is recommended only for east and west sides of structures, leaving the south face exposed to maximize winter solar energy inputs. Protecting the south sides of buildings from heating effects of summer insolation is relatively simple through structural modifications (e.g., increased ceiling insulation, wide roof overhangs to shade windows from summer sun). Spirn et al. (1981) present a variety of vegetative treatments for providing summer shade and unimpeded access to winter sun.

Tree shading of homes and other buildings is desirable in summer over essentially all of the United States. The shade cast by vegetation drastically reduces the conversion of radiant energy, either I_s or I_l , to sensible heat in the form of H, S, or G, thereby reducing temperatures of surfaces of objects shaded by the vegetation. In the case of people, this improves comfort. In the case of buildings, heat gains via conduction of sensible heat through walls and ceilings (Deering 1956, McPherson 1981a) as well as via transmission of solar energy through glazed openings (DeWalle and Heisler 1980a) are reduced with consequent reductions in air-conditioning energy use. Furthermore, this shading can induce a lag in the rate of heating of buildings (Deering 1956, McPherson 1981a) which might be utilized in certain situations to shift cooling energy demands to off-peak demand periods, thereby reducing not only total energy consumption but also the need for supplemental

peak-demand energy generating facilities. Studies by Johnson et al. (undated), Heisler et al. (1981), and McPherson (1981a) documented that the shade cast by trees with leaves is a function of species and crown density, among other things. However, different instruments and techniques were used in each of these studies, confounding comparison of results. An accurate and efficient standardized technique for the assessment of radiation transmission through tree crowns, whether in-leaf or leafless, is needed.

The other microclimatic effect of vegetation of importance to energy demands for space conditioning of buildings involves the interactions of the aerial portions of plants with the wind. A vast literature exists regarding the use of shelter-belts or windbreaks to ameliorate microclimatic conditions, indicating that the need for wind protection is widespread. However, most of this literature deals with the protection of crops or livestock and the suppression of wind-induced soil erosion. Nevertheless, the physical principles involved are similar, and this vast literature provides much information useful in the design and placement of windbreaks around homes (Miller et al. 1980).

It appears that windbreaks offering the greatest potentials for reducing home heating energy consumption have vertical sides [i.e., are "bluff" (Read 1964)], are moderately dense (Caborn 1965), and have a height equal to or greater than the building to be protected (Mattingly and Peters 1977). Obviously, the windbreaks should be located upwind of the building to be protected and at distances of 15 to 60 m from the building (DeWalle and Farrand 1978). More recent analyses by DeWalle and Heisler (1981) indicate that while maximum wind speed reductions

occur from 2 to 4 windbreak heights downwind, maximum air-infiltration rate reductions occur at one tree height downwind of the barrier. Very dense or solid barriers to the wind are to be avoided because, with such windbreaks, the reduction in wind speeds are accompanied by increased levels of turbulence (Caborn 1965). Hence, reductions in the air infiltration or convective heat losses from a home or other building owing to reductions in wind speed could be offset by increased heat losses effected by the higher levels of turbulence (gustiness).

Another way in which the interactions of wind and vegetation may be utilized for energy conservation is through use of vegetation to channel cooling summer breezes toward homes or other buildings. For example, extensive wind tunnel simulations conducted by White (1954) indicate that, depending upon the position of the planting relative to prevailing winds and the structure to be ventilated, such plantings can augment or reduce natural ventilation. More recently, Parker (1981) proposed some landscape features, termed "shrub-valves," designed to improve spring and fall ventilation and to provide protection from hot summer winds in the Miami, Florida, area (Fig. 3). While Parker's (1981) ideas are intriguing, we feel that some of his postulated aerodynamic effects are questionable. Wind tunnel or full-scale tests are clearly needed.

Thorough discussion of the ways in which architectural design, type and quality of construction, building site utilization, and type and efficiency of space-conditioning equipment affect energy consumption is beyond the scope of this report. It is important for our purposes to note that energy exchanges occur via three major processes: heat

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Fig. 3. Shrub valve system: Shrub placement facilitates breezes when windows are open and reduces infiltration when windows are closed (from Parker 1981).

conduction through the exterior shell of the building, transmission of solar radiation through windows, and air infiltration. Air infiltration, which is simply the exchange of air between the inside and outside of the building that occurs through cracks in the exterior shell, is really the net effect of two different physical phenomena. As wind blows over and around a structure, pressure differentials between the inside and outside are established, causing air to be exchanged through cracks in the building shell. Also, because of the fact that warm air is less dense than cool air, temperature differentials between the inside and outside can also establish this same kind of convective exchange of air through the exterior shell (Mattingly and Peters 1977). It appears, in the United States at least, that air infiltration has a greater impact on space-heating energy use than on that used for space cooling because of the greater differentials between inside and outside temperatures in winter as compared to summer. However, in subtropical or tropical climates, this generalization may not hold (DeWalle and Heisler 1980a). Also, it seems that, in general, air infiltration energy losses resulting from wind effects on pressure distributions over and within buildings are substantially larger than those arising because of the temperature differentials (i.e., the stack or chimney effect).

Clearly, the air infiltration resulting from pressure differentials will vary as a function of wind speed. According to wind tunnel and analytical studies by Harrje et al. (1981), wind-induced air infiltration accounts for about 15% of the total heat loss from a 7.5- x 10.6- x 7.5-m-high two-story house exposed to a 16-km/h (10-mph) wind and an ambient temperature of 4°C. Increasing the wind speed to

32 km/h (20 mph) while maintaining the 4°C temperature increases the pressure differential component of the air infiltration loss to 34% of the total loss. Adding in the air infiltration resulting from the temperature differential, they found that about one-half of the total heat loss occurred through air infiltration in the 32-km/h wind, 4°C situation. From these results, it is evident that vegetation around a building that reduced wind speeds to (or below) 16 km/h would result in a substantial reduction in energy loss (nearly 20%), with a consequent reduction in heating energy consumption. Figure 4 further illustrates the effects of wind speed and ambient air temperature on air infiltration rates.

Because the rate of conduction of heat energy through a solid is a function of the temperature gradient across the solid, any reduction in the temperature differential between the inside and outside surfaces of the exterior shell of a building will reduce conductive heat gains or losses. Also, the conduction of heat energy between solid surfaces and air occurs at rates at least an order of magnitude lower than those of convective heat exchanges between surfaces and adjacent air. This implies that the wind reductions effected by windbreaks will serve to reduce convective heat losses from the exterior surfaces of buildings because rates of convective exchange in the forced convection situation are directly related to windspeed. In winter, if convective heat losses are reduced, higher building surface temperatures will obtain; consequently, the temperature gradient across exterior walls will be reduced, with the end result that heat losses via conduction are also slowed.

Heisler (G. M. Heisler, personal communication) points out that because

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Fig. 4. Relationships among winter air infiltration rates (AIR) for a small mobile home and wind velocity (U) and temperature difference between inside and outside air (ΔT). In "tighter" buildings, AIR would generally be lower, but the same type of functional relationship between AIR, U, and ΔT would be present (from DeWalle et al. 1981).

conductive heat losses through walls are typically small (negligible through insulated walls), a windbreak which reduces wind speeds by two-thirds, say from 24 to 8 km/h, would only reduce heat loss from the walls of the protected building by around 1%. However, the effect of such a wind reduction on heat losses through windows is much more dramatic. According to preliminary estimates by Heisler (personal communication), such wind protection could result in as much as a 13% reduction in conductive heat losses through a single-glazed window.

Another use of vegetation suggested by a number of reports involves the planting of densely crowned shrubs or small trees immediately adjacent to building walls (Fig. 5). The idea is that such plantings will create a still air layer or pocket next to the wall, which has the effect, by virtue of the elimination or reduction of convective heat exchanges, of increasing the insulation value of that wall. Nisbet (1977) reports that fuel savings from 10 to 25% are possible through these mechanisms, but it is not clear, from the popular article in which this claim appears, whether this has been substantiated. We found no other quantitative estimates of either heat loss reductions or fuel savings realizable in this fashion. Additional studies of vegetation effects on convective and conductive heat losses or gains in the buildings are needed.

Because of the tendency to build more heavily insulated, tighter houses as energy costs become ever greater, greatest energy savings through use of vegetation as an ameliorator of building microclimates will be realized through retrofitting older, more poorly insulated, and leakier structures with energy-conserving landscapes. This may

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Fig. 5. An insulating hedge (from Moffat and Schiler 1981).

involve landscaping of previously unlandscaped buildings as well as replacement of existing, improperly designed and energy-inefficient landscape features. Vegetative reductions of wind and interception of radiation will have less impact on energy consumption in the super-insulated home. However, it will be many years before such structures outnumber leakier and under-insulated buildings. In addition, even in super-insulated buildings, winter heat losses and summer radiation gains via windows and doors can be substantial. Thus, potentials for energy conservation through vegetative amelioration of wind and radiation conditions at openings of such homes exist. The proper tests and studies have not been conducted to demonstrate this potential or that such treatment would be economically viable. However, we point out that some form of landscaping almost invariably accompanies new construction and the cost of this treatment is justified on the basis of aesthetics rather than economics. Thus, if home builders and landscape architects have access to information about energy-conserving landscape designs, such design features might be incorporated into landscaping of newer, energy-efficient homes despite long pay-back periods.

The Perceptual Basis

We noted above that the impact of life-style and perception of comfort on energy use in homes and other buildings for space heating or cooling involves physiological and psychological phenomena as well as physical ones. Life-style reflects an integration of our value system

with our perception of the world in which we live. As such, it represents a major psycho-social determinant of space-conditioning energy demand in particular and in total energy consumption in general. A recent Gallup Poll conducted for Gardens For All illustrates this. Results from this poll indicate that people who garden are two to three times more likely to recycle wastes, weatherize their home, drive less, and use solar energy than those who do not garden (Anonymous 1981). The implication to the subject at hand is that value systems act in concert with economic criteria to determine energy demand. Because vegetative amelioration of microclimate is involved only as an effect, not as a causal agent, in the life-style--energy-demand relationship, our discussion of this factor will conclude with one example of a quantitative effect of life-style upon energy consumption. Mattingly et al. (1979) found that air-infiltration losses accounted for about 33% of the total heat loss from townhouses in Twin Rivers, New Jersey, when doors and windows were closed. However, with a door or window cracked open, air-infiltration loss accounted for 75% of the higher total heat loss. Thus, it is clear that building occupants whose life-style reflects energy consciousness and who are therefore careful to keep doors and windows closed during the heating season will consume substantially less energy than people who carelessly leave doors or windows cracked or open.

Physiology enters the equation that defines building energy consumption because of the effects of metabolism on the perception of comfort. People whose life-styles involve physical activity will tend to feel comfortable at somewhat lower temperatures than those pursuing more

sedentary activities because of the increased metabolic production of body heat accompanying physical exertion. Also, it appears that older people often require somewhat higher temperatures for comfort than younger people. This, at least in part, reflects changing metabolic rates with age and consequently represents an impact of human physiology upon energy demand.

The perception of comfort, according to Ruch (1965), involves the responses of eight environmental senses (hearing, vision, smell, taste, touch, balance, heat, and cold) to environmental stimuli. Overly strong signals from any one of these senses trigger a feeling of discomfort. However, discomfort can also result from simultaneous, weaker signals from several senses, even though none of these signals, taken individually, would create the sensation of discomfort. Thus, feelings of comfort or discomfort represent an integration of responses of our senses to environmental stimuli.

This fact complicates the problem of designing for human comfort. On the other hand, it may provide sound justification for holistic approaches to design, construction, and maintenance of human dwellings and environments. This is of special importance to the subject at hand. If homes and other environments are aesthetically pleasing and relatively free of undesirable noise and smell, the people living there may be more tolerant of temperature conditions which are marginally comfortable. That is, people living in a well-designed environment may feel comfortable at temperatures that would be perceived as uncomfortable in less pleasing surroundings.

Vegetation in the form of landscaping is obviously viewed as aesthetically pleasing because aesthetics are usually the justification for landscaping. Furthermore, many studies have documented the noise-suppressing qualities of plant stands (e.g., van Haverbeke and Cook 1974a, 1974b, Cook and van Haverbeke 1977, Heisler 1975, 1977), while other studies have documented the cleansing effect of vegetation upon the atmosphere (e.g., Geiger 1965, Rich 1971). Consequently, in addition to the purely physical amelioration of meso- and microenvironments by vegetation, plants may also affect the perception of comfort by providing environments of greater beauty, having less noise and fewer obnoxious tastes and smells. We submit that holistically designed landscapes which take human environmental senses into account may result in energy savings additional to the purely physical effects of vegetation on energy exchanges between a building and the environment. The possibilities for landscape designs which stimulate and promote psychological feelings of well-being should not be overlooked.

Furthermore, it is possible that energy savings additional to those resulting from reduced space-conditioning energy consumption in properly landscaped buildings may accrue in cities as a result of holistic landscape design. Consider that if streets and roads were shaded in summer and protected from chilling winds in cooler seasons by trees, people might be more disposed to ride bicycles than to use air-conditioned automobiles. Consider also that if bus stops and rapid transit stations were similarly protected, people waiting to use mass transit facilities would feel far more comfortable than they would when unprotected from summer sun and winter winds. Perhaps vegetative amelioration of the

microclimates of mass transit stops would result in greater use of mass transit facilities. The possibilities for using vegetation to ameliorate and improve human environments outside buildings as well as inside should not be ignored.

POTENTIALS FOR ENERGY CONSERVATION
THROUGH VEGETATIVE AMELIORATION OF BUILDING MICROCLIMATES

It has been estimated that 32% of all energy consumed in the United States is used in buildings (Savitz 1975). Of this amount, 70% is utilized in residences and 30% in commercial buildings. Because 69% of Americans live in single-family dwellings (Heisler 1978), energy consumption in such residences is of the order of 15% of the total. Savitz (1975) estimates that 57% of building energy consumption is utilized for space conditioning, which leads us to conclude that roughly 8% of the total U.S. energy consumption is used to heat and cool single-family dwellings. Savitz (1975) also estimates that around 40% of the energy utilized in buildings is wasted because of inadequate construction, poor operating practices, inefficient equipment, and unnecessary levels of heating or cooling.

We pointed out that vegetation can serve to somewhat offset inadequate construction by creating more favorable building microclimates. Vegetation can similarly reduce energy waste due to inefficient space-conditioning equipment by reducing the amount of use of such equipment necessary to maintain comfortable conditions in the home. We have also hypothesized that holistic landscaping design may create feelings of comfort and well-being under marginal temperature conditions. Consequently, it appears that energy-conserving landscaping can help to offset several of the major avenues of energy waste in buildings. Because energy waste in single-family homes accounts for about 3% of the nation's

total energy consumption, this figure can serve as an approximation of the maximum potential energy savings realizable through energy-conserving landscaping of single-family homes in the United States.

A considerable body of literature exists involving reports of studies of effects of tree shade on space-conditioning energy consumption in mobile homes. Considerable effort is also reported dealing with space-conditioning energy reduction through landscaping of conventional single-family homes. Almost no reports are found of studies of energy-conserving landscaping for multiple-family dwellings, however. Because economic and environmental factors seem to be operating to limit the availability of single-family dwellings for much of the American populace, it appears that in the future Americans will increasingly rely on multiple-family structures for housing. Studies of energy efficiency improvement of such structures, including ameliorative effects of landscaping, are needed.

Energy Conservation Potentials Of Landscaping Mobile Homes

Mobile homes, in general, suffer greatly from inadequate insulation and from excessive leakiness. Consequently, heat gains or losses via conduction through the exterior shell and via air infiltration tend to be greater in mobile homes than in more conventional structures. It is therefore to be expected that vegetation offers great potential for improving the space-conditioning energy efficiency of mobile homes. Results of studies reported in the literature substantiate this statement.

DeWalle et al. (1981) studied the energy requirements for heating and cooling of mobile homes in central Pennsylvania. Energy consumption was compared for a mobile home in the open, in a deciduous forest, and in a red pine plantation. Heating energy requirements were 8% less in the deciduous forest than those in the open, unlandscaped situation (mostly as a result of the wind protection and, hence, lowered air-infiltration losses effected by the deciduous tree stand). Heating energy consumption increased by 2% in the red pine plantation over that in the open, despite reduced air-infiltration losses because of the heavy winter shade cast by the evergreen canopy. In summer, cooling energy requirements were reduced by an estimated 75% in the deciduous forest stand over those in the open by virtue of the tree shade.

Parker (1981) conducted studies of the reduction of cooling energy requirements through precision landscaping of a mobile home used as a daycare center on the Miami (Florida) International University campus (Fig. 6). Prior to landscaping, with interior temperatures maintained at 24°C (76°F) by mechanical cooling and 35°C (95°F) ambient exterior temperatures, skin temperatures of the mobile home reached 43°C (110°F). As a result, in April, which is not a particularly warm month, over 70% of the total amount of energy used in this structure was used for cooling.

Landscaping was designed and installed to provide shading of the walls, windows, and roof of the structure as in Figure 6. Plants were selected (on the basis of mature sizes and shapes) and planted so as to channel southeasterly breezes over the roof of the structure to carry away that sensible heat created there by absorption of radiation. Drought-resistant, mostly native, species were selected to minimize

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ARROW SHOWS LANDSCAPE CHANNELIZATION OF WIND FLOW TO REMOVE HEAT GAIN FROM ROOF

Fig. 6. Energy-conserving landscape design for a mobile home used as a day-care center on the campus at Florida International University, Miami (from Parker 1981).

maintenance costs and disease incidence. Significantly, Parker (1981) designed this planting plan to provide maximum protection on August 6 rather than on the summer solstice. Because of the thermal mass of the lands and oceans of the earth, climatic conditions lag the seasons as defined by earth-sun geometry. Hence, heating and cooling requirements do not necessarily coincide with the shortest or longest days. Parker (1981) carefully analyzed the climatic records for the Miami, Florida, area and found that maximum annual temperatures usually occurred there in early August. Hence, for the maximal energy-conserving effect, the planting plan was designed for early August, not mid-June, the time of greatest day lengths.

Because it is not economically feasible to install fully grown plants, the full energy conservation benefits that accrue from such landscaping are postponed for several years following establishment and growth of the plantings. Parker (1981) estimated that around five years would be required before any significant energy impact of his landscape design would result. However, after only two years, energy use in the structure was again monitored. Despite minimal growth of the trees and shrubs, energy consumption for air conditioning was reduced by over 57%. This reduction is so substantial that, even allowing for errors in Parker's (1981) analyses induced by problems associated with conducting research in a mobile home used daily for other purposes, we can only conclude that a significant energy savings resulted from implementation of his landscape design. At current electricity prices and assuming a cost for this landscaping comparable to that charged by commercial landscaping firms, Parker (1981) calculated a pay-back period of about four

years. Furthermore, using these same cost estimates, the cost of each kilowatt of electricity saved by this landscape design turned out to be about \$200, less than 10% of the cost of a kilowatt of generating capacity (Parker 1981). The conclusion that it would be far less costly for utilities to subsidize energy conservation through landscaping of mobile homes than to build additional generating capacities is inescapable.

Deering (1956) also studied the effects of tree shade on the cooling energy requirements of a poorly insulated mobile home in California. As shown in Fig. 7, air temperatures within the structure were 11°C cooler in the shade of a grove of fig trees than when the same mobile dwelling was located in an open, unlandscaped field. Not only was the temperature cooler in the shaded situation but the period during which interior temperatures exceeded 24°C was only about 5 h as compared to 11.5 h at the open site (Deering 1956). These results, along with analagous results from studies by McPherson (1981a) discussed below, indicate that, beyond energy savings, landscaping offers potentials for delaying times of peak consumption in structures. Since U.S. electrical generating capacities are generally adequate to meet all but peak load demands, practices that shift peak consumption times could reduce peak demands, thereby reducing needs for additional peak demand generating capabilities.

Other studies of shade effects on energy consumption in mobile homes in Alabama are reported by Laechelt and Williams (1976). Their results indicate that shading of 20% or more of a mobile home roof throughout the day will effect significant reductions in cooling energy consumption. In one instance, a mobile home with an average of 41% of its roof shaded throughout each day required less than one-half the energy required for

Fig. 7. Comparisons of mobile home room temperatures in an unlandscaped field on August 31, 1954; with afternoon shade from a eucalyptus tree on September 25, 1954; and in total shade of fig trees on August 10, 1954 (from Deering 1956) [$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$.]

air conditioning in a similar, unshaded mobile home over the course of a year. Laechelt and Williams (1976) estimate that as of 1976 there were over 200,000 mobile homes in the State of Alabama. Extrapolating their results to all such structures in the State (and assuming, apparently, that all such homes were unshaded), a potential energy cost savings of \$18 million per year was indicated to exist simply from providing shade to mobile homes.

These results are not surprising in light of climatic analyses performed by Stone and Larson (1978). Using generally accepted limits of comfort ranges, they found that shade alone would result in comfortable temperatures throughout 88% of the year in the subtropical climate of South Florida. Landscaping to promote cooling effects of the commonly occurring sea breezes of this region would further increase the proportion of the year during which comfortable conditions could be maintained by purely passive means. Similar analyses should be conducted in other climate zones to indicate potentials for passive maintenance of human comfort and consequent reductions in space-conditioning energy consumption.

Energy Conservation Potentials of Landscaping of Conventional Single-Family Dwellings

Studies of the effect of shading on cooling energy consumption in conventional homes in Florida are reported by Buffington (1978). Buffington's computer simulations of heat loading of single-family homes indicate that light shading (approximately one-third shaded) of east and

west walls would reduce cooling energy use by about 6%. Heavy shading (about two-thirds shaded) would reduce cooling energy needs by up to 11%. Light shading of the roof would effect a further 3% reduction in cooling energy consumed, while heavy roof shading would effect a 9% reduction. With light or heavy shading on both east and west walls and the roof, 14 or 17% energy savings are predicted, respectively.

Radiation heat gains of a four-bedroom home in the hot, dry climate of Mesa, Arizona, under varying degrees of tree shade were simulated by Hansen and Mandraes (1979). Their results indicate that peak demands for cooling energy can be reduced through use of vegetative shading, but they do not present quantitative data. In another study conducted in central Arizona (Center for Environmental Studies 1977), cooling energy and water consumption were compared for three homes: an irrigated, heavily vegetated home; an irrigated, moderately vegetated home; and a nonirrigated, desert-landscaped home. Unfortunately, the three homes were not similar in size, construction, or orientation, and the results were even more confounded by the fact that the heavily vegetated home was cooled with an evaporative cooler while the other two were air-conditioned. The heavily vegetated home required only 8% of the cooling energy used in the home with desert landscaping. However, water consumption at this heavily vegetated home amounted to over 83,000 L (22,000 gal) per week as compared to about 950 L (250 gal) per week at the desert home. If cheap and abundant water continues to be available in the desert southwest, then vegetation can certainly be used to effect drastic reductions in the cooling energy demand of buildings in these desert areas. With increasing demands nationwide for the very finite

water resource, this hardly seems likely. Energy requirements for maintenance of exotic vegetation tend to offset space-conditioning energy reductions effected by such vegetation. As a result, it is doubtful that landscape designs incorporating highly exotic plant species will prove either economical or energy-efficient in the long run anywhere and especially in the more arid portions of the United States.

McPherson (1981a) conducted studies of the effects of shade on cooling energy requirements of single-family homes in Logan, Utah, using two identical one-eighth-scale models of an existing home. Thermal mass and heat conduction were accurately simulated in these models but air infiltration probably was not. One model was maintained in an unshaded state, while the other was placed sequentially under varying kinds of shade. McPherson's (1981a) results show that the dense shade cast by a Norway maple on either the east or west walls reduced cooling energy needs by over 50%, while complete dense shade eliminated the need for supplemental cooling. Assuming a 24°C thermostat setting, the control (unshaded) home would have required air conditioning for over 8 h on the day studied. Even the light shade cast over the entire model home by a honey locust reduced cooling energy needs by 98% (McPherson 1981a).

The effectiveness of tree shade as a passive means of improving human comfort conditions and of reducing air-conditioning energy consumption cannot be questioned. Because tree shade can increase winter heating costs if improperly placed, positions of trees relative to the structures to be protected are critical to energy consumption. McPherson (1981b) and Wagar (1981) developed criteria and computer programs for defining the proper placement of trees around buildings. Once these

techniques are tested and perfected, they will provide a powerful tool to landscape architects concerned with energy-conserving landscape design.

Energy Conservation Potentials of Tree Windbreaks

The use of vegetation in the form of windbreaks has received considerable examination as noted earlier. Here again, the energy conservation potential is substantial. Bates (1945), working with simple models of single-family dwellings and windbreaks in South Dakota, found an 0.8% reduction in fuel consumption for each 1.0% reduction in average wind speeds around the model structure. Translating this to the magnitude of wind reductions found behind full-scale windbreaks, he estimated that heating-fuel consumption in homes on the Great Plains could be reduced by from 25 to 40% through the establishment of windbreaks upwind of such homes. Because of difficulties involved with geometric scaling of crack areas around windows and doors in the model homes used by Bates (1945), these estimates are now thought to be high. Current estimates are that actual fuel reductions of from 3 to 30% are possible (DeWalle 1978a, USDA 1978).

A number of more recent wind-tunnel studies of the effects of windbreaks on air-infiltration energy losses were conducted by Princeton University's Center for Energy and Environmental Studies. Harrje et al. (1981) found that windbreaks situated two to four tree heights upwind of the structure to be protected provide maximum reductions in air-infiltration rates (Fig. 8). Figure 8 also shows that such protection is directly related to windbreak density, i.e., the more dense the

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Fig. 8. Relative air-infiltration rates as a function of house to windbreak distance for four windbreak arrangements (from Harrje et al. 1981).

windbreak, the greater the reduction in air infiltration. They also point out that the windbreak density must be maintained to ground level. If lower branches are pruned from windbreaks, the effectiveness of the shelter is largely destroyed because such gaps provide for a jet of wind beneath the windbreak which increases air infiltration dramatically. Other physical modeling studies at Princeton reported by Heisler et al. (1979) indicated that reductions in wind-induced air infiltration up to 64% are possible with dense, multiple-row windbreaks as long as wind directions are perpendicular to the long axis of the break. Air infiltration due to air temperature differentials (the stack effect) were not addressed in these studies.

Full-scale studies of effects of windbreaks upon home-heating energy consumption were also conducted by this Princeton group and their Forest Service collaborators. A windbreak consisting of a single row of 8-m-tall white pine was installed upwind of one end of a row of townhouses in Twin Rivers, New Jersey, for nine weeks during one heating season. Mattingly et al. (1979) report that this windbreak reduced air infiltration in a townhouse in the interior of the row by 42% when ambient conditions approximated the design climate (i.e., 5.6 m s^{-1} wind speed, wind direction perpendicular to the windbreak and an inside-outside temperature difference of 18°C). This 42% air-infiltration rate reduction was estimated to be equivalent to a 14% reduction in heating fuel consumption. Energy savings for the entire heating season were estimated to be around 3% when effects of wind speed and direction and air temperature differentials which departed from the design conditions were accounted for. A similar study of effects of

wind protection of a mobile home is reported by DeWalle and Heisler (1981). The winter energy savings produced by a 61-m-long windbreak composed of a single row of white pine at one tree height upwind of the structure was estimated to be 12%.

The Princeton studies are the only ones found reported in the literature that deal with multiple-family structures. We found some development-wide energy-conserving landscape designs [e.g., Center for Landscape Architecture and Research (1978), Squaw Run Area Watershed Assoc. (1981)]. Erhley and Jaffe (1979) discuss problems associated with maintenance of existing vegetation on forested development sites while providing solar access for buildings to be constructed there. To our knowledge, studies of energy conservation effectiveness of such designs have not been performed. Because of the difficulties and cost associated with quantitative studies of such large-scale efforts, it appears that physical modeling in wind tunnels or in water channels and computer simulation may be the best ways to evaluate the energy conservation potential of community-wide landscape designs.

Computer Simulation of Energy-Conserving Landscape Design

Halverson et al. (1980) developed a computer code for mapping positions of tree shadows through time which will prove useful in the design of energy-conserving landscapes. A more general model, OBSTRUCT, is reported by Frank et al. (1981) and calculates solar shadowing resulting from multiple obstructions. Wagar (1981) describes a technique, called SOLAR PLOT, which allows definition of canopy-limit surfaces for

specific design dates. Use of this technique, along with careful selection of cultivars on the basis of crown shape, density, and dates of leaf expansion and leaf fall, allows vegetation to be sited and maintained for precise control of canopy transmission of solar energy into buildings via tree or shrub shade, or absences thereof. A somewhat similar technique (SOLMAT) was developed by McPherson (1981b) for selecting and siting trees for solar control in Utah. Various heat load simulators are available, including the National Bureau of Standards Load Determination (NBSLD) Program (Kusuda 1976) and EQUINOX (Watson and Harrington 1979), which allow calculation of heat losses or gains in buildings. Schramm and Grist (1978) present a computer code (GRASP) which permits assessment of effects of site features and existing or planned vegetation upon space-conditioning energy requirements of buildings. Schiler and Greenburg (1980) adapted the NBSLD codes to permit assessment of the effect of different levels of shade on building heat loads and consequent effects on energy consumption. Finally, Terjung and O'Rourke (1980a,b) developed several models (URBAN 1, 2, and 3, CANOPY) which appear to have great potential usefulness in the estimation of space-conditioning energy consumption in mesoscale urban and suburban areas.

While such models represent a significant step in the development of capabilities for realistic assessments of mesoscale interactions of climate, cultural features, and landscaping, at least one major, serious problem remains. The physics of the interactions between the atmosphere and the varied surfaces of our earth have not been seriously addressed by the meteorological scientific community. As a result, our knowledge

of how wind and turbulence interacts with the rough, irregular surfaces of urban areas, residential areas, and forests is extremely limited.

Our knowledge of the effects of wind and especially turbulence on building heat exchange is also limited. Hence, effects of these phenomena on energy consumption in buildings and in aggregations of buildings cannot be simulated at this time. Further progress in the area of assessment of mesoscale vegetative effects on urban space-conditioning energy consumption will not be forthcoming until this situation is improved.

Nevertheless, the empirical evidence indicates that the impacts of vegetation, especially trees, on urban climates at mesoscales are substantial and significant.

CONCLUSIONS AND RECOMMENDATIONS

Vegetation affects climate through its effects on the partitioning of solar energy at the earth's surface and on the turbulent exchange of kinetic and thermal energy, along with materials (especially water vapor) across vegetation canopy-atmosphere interfaces. These effects are most significant and amenable to management at meso- and microscale. Of these two scales, the microclimatic modifications effected by vegetation are by far the better understood. Our knowledge of mesoclimatic alterations resulting from mesoscale vegetation or other surface features of the earth is extremely limited. Similarly, in terms of the overall processes involved, our knowledge of the effects of vegetation upon radiant energy partitioning at the earth's surface is fairly well developed. Knowledge of canopy-atmosphere interactions of importance to turbulent exchange as well as of the implications of increased or decreased levels of turbulence to space-conditioning energy consumption in structures is, on the other hand, lacking. As a result of his recent analysis of this situation, DeWalle (1978b) concluded that our knowledge is such that answers to questions regarding landscaping for energy conservation in buildings on an individual basis are within reach. Answers to similar questions in the context of aggregations of buildings still elude us.

We can say, with some certainty, that the major impact of vegetation on mesoscale climates results from the conversion of radiant energy into latent heat effected by transpiring plants. Thus, the net effect is a cooling of air temperatures during those seasons when transpiration can occur. We cannot, at this time, relate amounts of vegetation with

degrees of cooling effected nor with the area affected. Remote sensing of surface radiant temperatures provides us with a powerful tool for such studies, however. Current research efforts in this area should be expanded.

The major influences of vegetation on microclimates occur through the interception of radiation (i.e., shading) and the deflection of winds by plant canopies. Studies reported in the literature indicate that shade effects on cooling energy consumption are substantial in structures that are poorly insulated. Air-conditioning energy savings through shading of mobile homes and more conventional single-family dwellings generally fall in the range from 50 to 75%, while savings up to 100% are indicated on individual days. However, deciduous trees intercept significant amounts of radiation even when leafless in winter (~30 to >60%), necessitating careful siting of such vegetation to ensure that summer cooling is not obtained at the expense of winter heating. Methods for designing and maintaining landscaping for optimum year-round shade conditions over the lifetimes of both the building and the vegetation used are needed.

The ability of vegetation to deflect wind can be used for energy conservation through reduction of air-infiltration heat losses in winter and through convective cooling via increased ventilation in summer. As with shade trees, siting of trees for wind control is critical because winter shade from windbreaks could reduce solar heat gains to the point that lowered air infiltration and conduction losses are more than offset by the loss of solar energy resulting from that shade. Amounts of heating energy saved by winter wind protection are estimated to range from

3 to 30%, depending on the windiness and temperature of the macroclimate and the nature and quality of construction incorporated in the structure. Methods for assessing the integrated effect of vegetation at neighborhood and larger scales on air flow over and around buildings are needed.

Another aspect of the effect of vegetation on energy consumption of some considerable interest is the potential for landscaping in warmer areas of the country that will delay afternoon solar heating of structures, thereby reducing energy demands during peak demand periods. While the possibility for such a temporal shift in energy uses has been demonstrated, insufficient study has been made to assess either the length of delay possible or the potential magnitude of the impact upon overall peak demand.

Finally, we point out that, in addition to ameliorating climatic conditions, vegetation also serves to improve the beauty of human environments, reduce noise levels, and scavenge pollutants from the atmosphere. The overall effect of vegetation on human habitats can be overwhelmingly positive. While perhaps technically outside the charters of the federal forestry and energy agencies, the concept of holistic environmental planning and design should at least be recognized by these agencies. The potentials for improvements in human environments that result from climatic amelioration, noise suppression, pollution reduction, and aesthetically pleasing surroundings must be defined and their impact upon psychological perceptions of well-being assessed.

According to DeWalle (1978b), landscape design incorporating existing energy conservation design criteria could result in a reduction of space-conditioning energy consumption in both the residential and commer-

cial sectors of about 10%. This translates to a net reduction in total U.S. energy consumption of about 1.4%, which is equivalent to a savings of over $79,000 \text{ m}^3$ (500,000 bbl) of oil each day (DeWalle 1978b).

Because the United States has not yet achieved energy independence, energy shortfalls in our country are currently met by fuel imports, mainly in the form of oil. As a result, United States balance-of-trade deficits continue to be increased by our inability to achieve energy independence. Thus, it is of some importance to consider not only the economic benefits of energy-conserving landscapes to home and other building owners but also the national economic benefits that may accrue from widespread application of energy-conserving landscape design.

United States oil imports thus far in 1981 range from 215,000 to $302,000 \text{ m}^3$ (1.35 to 1.90×10^6 bbl) per day (C.E. Whittle, Institute for Energy Analysis, Oak Ridge Associated Universities, personal communication). For our purposes, we assume an average current import figure of $240,000 \text{ m}^3$ (1.5×10^6 bbl) per day. Thus, DeWalle's (1978b) projected energy savings of over $79,000 \text{ m}^3$ (0.5×10^6 bbl) per day is of the order of one-third of our current import level, a significant fraction by any standard. We conclude therefore, that landscaping for energy conservation should be an attractive energy conservation option in a nation plagued with chronic energy short-fall induced balance-of-trade deficits.

While much is known about certain aspects of landscape design for energy conservation, serious deficiencies in our knowledge exist. We consider these deficiencies and offer recommendations for their correction in terms of the basic mechanisms and processes involved. For our purposes, these mechanisms and processes are:

- (1) Vegetation alterations of radiative energy exchanges between buildings and their environments;
- (2) Vegetative alterations of energy exchanges between buildings and their environments effected or affected by wind and turbulence;
- (3) Mesoscale effects on air temperature of latent heat exchanges resulting from transpiration of vegetation;
- (4) Effects of building and use characteristics on space-conditioning energy requirements;
- (5) Effects of macroclimatic factors on space-conditioning energy consumption in buildings; and
- (6) Implications of psycho-social phenomena involved in the perception of comfort to energy-conserving landscape design.

Vegetative Alteration of Radiative Energy Exchange

It has been shown that the shading of a building by tall vegetation can drastically reduce and, in some instances, eliminate the need for supplemental cooling of structures during warm seasons. Over much of the United States, however, more energy is consumed for winter heating than for summer cooling. Thus, cooling energy reductions effected by vegetative shading at the expense of supplemental solar heating in winter often leads to increased total space-conditioning energy consumption. Consequently, the positioning of vegetation relative to the structure to be protected is of critical importance in terms of energy consumption. While qualitative criteria for placement of trees for energy conservation through shading are available, validated quantitative criteria are only beginning to be developed (McPherson 1981b, Wagar 1981).

Other problems exist as well. For example, information about the radiation transmission characteristics of crowns of tree and plant species is lacking. In addition, the effects of plant crowns and canopies on long-wave radiation exchanges between structures and their environment are not well understood. Finally, management techniques for maintenance of energy-conserving landscapes over the life-spans of both the building and the vegetation have not been developed.

(1) Therefore, we recommend that:

- (a) further studies be carried out to develop quantitative criteria for positioning of vegetation, especially trees, which will maximize year-round space-conditioning energy savings in buildings in each of the four major climatic regions of the United States (i.e., cool, hot-humid, hot-arid, and temperate);
- (b) further studies be conducted, using standard techniques, of the radiation transmission characteristics of crowns of native tree species along with well-established exotic species that are commonly used in residential landscaping to provide the background information required for development of species-selection criteria for specific applications;
- (c) studies of the effects of trees and other vegetation on thermal radiative energy exchanges between buildings and their environments be made and that the consequences of these effects be evaluated in terms of space-conditioning energy requirements of those buildings; and
- (d) techniques and criteria be developed for management of energy-conserving vegetation so that maximal energy conservation values of such plantings are maintained over the life-span of the building.

Vegetative Alteration of Convective Energy Exchange

Many studies have shown that space-heating energy consumption in buildings in windy situations is reduced when vegetative windbreaks are properly installed. It has also been proposed that vegetation can be situated so as to divert or channel winds toward buildings or windows in buildings, thereby providing supplemental, passive cooling during warmer seasons. Limited experimental verification of this practice is reported in the literature. In addition, it has been hypothesized that shrubs and hedges can be positioned adjacent to walls of buildings in such a way as to create still-air spaces that have the effect of improving the insulation value of the wall.

(2) With these factors in mind, we recommend that:

- (a) studies be conducted to define the crown and canopy densities and other characteristics required to elevate the streamline flow of the free wind above the canopy thereby effecting significant windspeed reductions within and below even discontinuous canopies where buildings are or can be located;
- (b) further studies be implemented on the use of vegetation to divert or channel winds in order that energy-conserving landscape design criteria can be developed;
- (c) studies be made of the effectiveness of various kinds and species of vegetation in creating and maintaining still-air spaces adjacent to building walls and of the effect of such still air on heat exchange between the structure and its environment; and
- (d) current efforts to develop quantitative parameters for characterization of tree windbreaks in a physically plausible and generalizable manner be continued (e.g., Miller et al. 1980).

Mesoscale Effects of Vegetation-Induced Latent
Heat Exchange on Urban Air Temperatures

Existing empirical and theoretical evidence substantiates the theory that vegetated portions of cities are cooler than nearby nonvegetated portions. While vegetative shading of high-density, high-thermal-mass materials is certainly involved, latent heat exchanges effected by non-water-limited vegetation probably dominates in this effect. Recent analyses of remotely derived information about urban surface characteristics and temperatures indicate that urban air temperatures are affected not only by the amount of vegetative cover but by its pattern, density, and areal extent (Flynn 1979). Such studies and analyses should be expanded to a variety of urban, suburban, and rural situations having different kinds of vegetation in each of the four major United States climatic regions. Information gained from these studies, in combination with that obtained from studies as recommended in 2(a) above, will provide a starting point for defining criteria for community-wide energy-conserving landscape design and will improve our understanding of the urban heat island effect and other urban climatologic phenomena.

- (3) Specifically, we recommend that analyses of remotely sensed surface temperature and vegetative cover characteristics data be made for areas in and around representative metropolitan areas in each of the four major U.S. climate zones.

Effects of Building and Use Characteristics on
Space-Conditioning Energy Consumption

Detailed examination of the effects of type and quality of construction, building siting and orientation, uses made of buildings, and life-styles and values systems of building occupants upon energy consumed for building space conditioning is beyond the scope of this assessment. We noted, however, that such factors do have profound effects on energy consumption. Thus, while identification of research needed to determine these effects is beyond our capability, certain deficiencies exist within the scope of this project that limit the ability of landscape architects to design optimal energy-conserving landscapes.

(4) We therefore recommend that:

- (a) recently developed techniques for measurement of air infiltration rates in buildings (see DeWalle and Heisler 1980b, Harrje and Grot 1977/78) be compared in order that the comparability of research results previously obtained using these two techniques can be established; and
- (b) further studies of heat exchange rates and mechanisms between buildings and their environments be conducted for a limited variety of structural types (e.g., mobile homes, masonry buildings, frame buildings, and single and multifamily residences) in order that the important mechanisms involved in heat exchange of each type are identified and order-of-magnitude estimates of their rates are established.

Effects of Climatic Factors on Building Space Conditioning Energy Requirements

Despite the considerable amounts of research performed on heat exchanges in buildings, our knowledge of how climatic factors influence these exchanges is far from adequate. As implied by recommendation 4(a), this inadequacy is partly the result of a lack of measurement techniques. But, this inadequacy is also the result, to a significant degree, of the complexity of the problem. No two buildings are ever identical and, similarly, no two building sites ever have quite the same climate. The number of possible combinations of building types, building uses, inhabitants' life-styles, and building-site microenvironments seems to be beyond our ability to classify, much less study. Consequently, it appears that simplifying assumptions and broad categorizations will be required to generalize past, present, and future research results. Standard experimental methods should be developed and baseline studies should be carried out using such standard techniques in a variety of climatic situations to define the range of climatic effects on heating and cooling energy requirements to be expected.

(5) We recommend that:

- (a) the effects of the presence and absence of tree shade on space-conditioning energy requirements be established for a limited variety of structural types [as in 4(b) above] in each of the four major climate zones;
- (b) the effects of varying exposures to wind on space-conditioning energy requirements be determined as in 5(a);
- (c) further research into the effects of plant coverings of walls and roofs (e.g., ivy, vines on trellises,

espaliered trees and shrubs) on space-conditioning energy consumption be conducted; and

- (d) the ability of vegetation-induced modifications of climates be assessed in terms of shifting timing of peak space-conditioning energy demand to off-peak periods and that the significance of this shift in timing of peak demand to the utility industry be determined.

Such studies should utilize standardized measurement techniques and should be replicated across major building types [as, for example, those listed in recommendation 4(b)] in each of the major U.S. climate zones.

- (e) In addition, we recommend that studies of the effects of varying levels of turbulence intensities on air infiltration rates in buildings be made because vegetation can be used to modify atmospheric turbulence near the ground as well as wind speed.

Implications of Psycho-Social Phenomena Involved in the Perception of Comfort

The perception of comfort is thought to involve psycho-social factors as well as physiological and physical ones. However, detailed knowledge of these factors falls outside the areas of expertise represented in The Critical Review Panel. Consequently, our hypothesis that human environments which are holistically designed to minimize negative environmental stimuli may enhance energy conservation through maintenance of conditions perceived as comfortable despite marginal air temperatures cannot be evaluated here. Because of the myriad implications of this hypothesis, its validity should be assessed.

(6) We therefore recommend that:

- (a) the influence of psychological state on the perception of comfort be further evaluated and that the relative effects of positive and negative environmental stimuli of varying strengths on feelings of comfort and well-being be determined in the context of holistic environmental design and management;
- (b) analyses of technology transfer and marketing techniques be conducted to develop effective methods for transmitting knowledge of energy-saving landscape design to user groups including landscape architects and individual homeowners; and
- (c) to further recommendation 6(b) and to increase awareness of the potentials for energy conservation through vegetative amelioration of building microclimates, full-scale demonstration projects using state-of-the-art energy-conserving landscape designs be constructed in each of the four major U.S. climatic regions.

Additional Recommendations

Outside the northeast, researchers and practitioners concerned with landscape design for space-conditioning energy conservation in buildings work largely in isolation. In the northeast, on the other hand, the Consortium for Environmental Forestry Research provides a framework and a mechanism for communication and collaboration which are lacking elsewhere. Judging from the numbers of literature citations stemming from this consortium included here, the communication and collaboration have had a very positive effect in terms of research accomplishments. (Around 25% of the citations found in our exhaustive review of the literature on this subject are consortium publications.) We believe that scientists and practitioners elsewhere would derive great benefits from improved communication. Furthermore, as recognized in recommendation 6(b), there

is concern on the part of the Critical Review Panel that more effective means be developed for transmitting research results to practitioners in the field of landscape architecture.

For these reasons, we strongly recommend that the federal forestry, energy, and meteorology agencies combine to sponsor periodic national and international workshops on the subject of using vegetation in the form of landscaping for the amelioration of building microclimates which will result in reductions in space-conditioning energy consumption in those buildings. These workshops should involve both practitioners and researchers in this and closely related areas (e.g., architecture, heating and cooling engineering, forest meteorology, urban forestry, etc.). The purpose of the initial workshop should be to assess further the state-of-the-art of energy-conserving landscape design; to define, clarify, and refine research needs; and to provide a forum for discussion between practitioners and scientists. Further workshops should be convened as necessary to maintain the dialogue established at the initial meeting.

Finally, we noted that the basic science required for an understanding of mesometeorologic processes and of turbulent exchanges across interfaces between rough, porous plant canopies and the atmosphere has simply not been done. Because of these limitations in our knowledge, we cannot quantitatively address the energy conservation potential of community-wide landscape designs, nor are criteria available that would allow landscape architects to design effectively on such scales. The lack of basic knowledge of the exchange of energy and mass at the lower boundary of the atmosphere further limits our ability to design and

assess the effectiveness of large-scale energy-conserving landscapes. This lack precludes theoretical solutions of microscale vegetative effects on wind and turbulence as well, necessitating costly and time-consuming experimental study of such phenomena. Moreover, this lack of knowledge is of critical importance to many other environmental problems facing our society, including transport and dispersion of pollutants and other man-made materials in the atmosphere and the ultimate deposition, fate, and environmental impact of these pollutants and materials. While resolution of this problem is beyond the scope of energy-conserving landscape design and research, we point out that continued neglect of the effects of vegetative canopy-atmosphere interactions upon planetary boundary-layer meteorology will have negative repercussions in our abilities to develop larger-scale energy-conserving landscape designs.

SUMMARY

In summary, it appears that energy savings of the order of one to a few percent are possible on a nationwide basis through management and design of vegetation to ameliorate building microclimates in ways that will reduce space-conditioning energy consumption. Energy consumption can be reduced far more than this on an individual structure basis, depending on a variety of environmental, structural, and psycho-social factors. This is especially true because vegetation can both increase and decrease energy use. The difference between energy use where existing vegetation increased energy needs of a building and energy use after the vegetation is managed for energy saving may be quite large. For the majority of Americans living in older homes suffering excessive leakiness and inadequate insulation relative to current energy costs, great economic benefits appear to be possible through installation of energy-conserving landscaping. Such landscaping of tighter and better-insulated homes is less economically attractive; however, it will be many years before well-insulated homes are in the majority. Furthermore, because some landscaping is usually performed for aesthetics alone, possibilities exist for additional, if small, energy savings via vegetative amelioration of the microclimates to which doors and windows in highly insulated structures are exposed. Finally, for multiple-family dwellings whose vertical dimensions do not greatly exceed the heights of trees, energy savings comparable to those experienced in single-family dwellings would seem to be realizable, although practically no study of such situations has been made. For high-rise structures, the scale of

the structures exceeds the scale of vegetation thereby eliminating direct wind control and shade benefits of vegetation to such buildings. However, the reduction in sensible heat storage, G , in the ground or other surfaces surrounding such structures as a result of vegetation at its base will have some impact on long-wave radiation exchanges, I_1 , between high-rise buildings and their surroundings. The magnitudes of such effects could be assessed through use of existing computer simulations. It is also to be expected that the vertical extent of the mesoscale cooling effects of latent heat exchange resulting from evapotranspiration should be of the same order as the vertical extent of the urban heat island effect. Thus, favorable modification of the microclimates of high-rise structures should obtain in vegetated cities, indicating that some reduction in high-rise building space-cooling energy consumption may accrue from large-scale landscape design and implementation.

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