

## **Cooling Urban Heat Islands with Sustainable Landscapes**

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### **Introduction**

The rapid urbanization of U.S. cities during the past fifty years has been associated with a steady increase in downtown temperatures of about 0.1° to 1.1°C (0.25° to 2°F) per decade. Because the demand of cities for electricity increases by about 3 to 4 percent for every increase of one degree Celsius (1.5 to 2 percent per degree Fahrenheit), about 3 to 8 percent of current electric demand for cooling is used just to compensate for this urban heat-island effect (Akbari et al. 1990). Other implications of growing urban heat islands include increases in carbon dioxide emissions from power plants, municipal water demand, concentrations of smog, and human discomfort and disease. Global warming, which may double the rate of urban temperature rise, could accentuate these environmental problems. Moreover, the accelerating world trend toward urbanization may expand the local influence of urban heat islands, as megalopolises begin to modify regional climate and airflow (Tyson et al. 1973).

This paper is directed to the policy-makers who are responsible for urban design and its climatological consequences. It summarizes our current knowledge on the structure, energetics, and mitigation of the urban heat island. Special attention is given to physical features of the environment that can be easily manipulated, particularly vegetation. Prototypical designs illustrate how concepts of sustainable landscapes and urban climatology can be applied to counteract urban warming in street canyons, parking lots, urban parks, and residential streets. In a previous study (McPherson 1990a), sustainable landscapes were defined as multifunctional, low maintenance, biologically diverse, and expressive of "place." Mitigation of urban heat-islands by landscapes can contribute to the sustainability of our cities. Because most electric utilities experience peak demands during summer because of air-conditioning loads, this paper addresses mitigation of summertime heat islands, while recognizing that winter heat islands can be beneficial in cities with cool climates.

### Urban Heat Islands

Warmer air temperatures in cities compared to air temperatures in surrounding rural areas is the principal diagnostic feature of the urban heat island. Alterations of the urban surface by people result in diverse microclimates whose aggregate effect is reflected by the heat island (Landsberg 1981). Buildings, paving, vegetation, and other physical elements of the urban fabric are the active thermal interfaces between the atmosphere and land surface. Their composition and structure within the urban canopy layer, which extends from the ground to about roof level, largely determine the thermal behavior of different sites within a city (Goward 1981; Oke 1987a). Thus, urban heat islands can be detected at a range of scales, from the microscale of a shopping center parking lot to the mesoscale of an urbanized region.

#### Structure of Urban Heat Islands

The structure of urban heat-islands has been well documented from climatological studies of cities around the world (see Chandler 1965; Landsberg 1981; Oke 1986). Urban and rural temperature differences are greatest and the spatial and temporal qualities of these anomalies most apparent during clear and calm summertime conditions. The horizontal structure of a hypothetical heat island is characterized by a "cliff" that follows the city's perimeter and is steepest along the windward boundary (Oke 1982). This sharp temperature gradient leads to pulses of cool air flowing into the city at night. Intraurban heat islands and "cool islands" reflect localized effects of differences in building density and surface cover. Temperatures in mid-latitude parks can be 1° to 3°C (1.8° to 5.4°F) cooler than outside, and their influence can extend several hundred meters beyond the park boundary (Chandler 1965; Herrington et al. 1972; Oke 1989). Differences in urban and rural temperatures usually are greatest (3° to 8°C) in early evening near the city core. However, daytime temperatures often are warmest outside the core in a zone with lower buildings and more exposed pavement (Tuller 1973). Winds carry the warmth of the city downwind.

Analysis of temporal differences shows that the intensity of the urban heat-island is greatest at night, primarily due to differences in urban-rural cooling (Oke 1982). Nocturnal urban air-temperature anomalies of 3° to 5°C are typical, as compared with 1°C daytime anomalies (Goward 1981). At sunset, rural areas begin to cool rapidly while urban areas remain warm and then cool at a slower rate. Different urban-rural cooling rates at sunset produce maximum heat-island intensities three to five hours later. At sunrise, urban areas begin to warm relatively slowly, sometimes producing urban "cool islands" during the morning.

Under calm conditions, a rural/urban breeze system develops at night that modifies the heat island's vertical structure by creating an urban heat dome. Downwind heat plumes can extend over rural areas for considerable distances. The vertical extent of air temperature anomalies at night is only two to three times building height, compared with more than 1 kilometer during the day. Increased turbulent mixing of the atmosphere during daytime is primarily responsible for this urban impact on the atmosphere (Duckworth and Sandberg 1954).

#### Energetics of Urban Heat Islands

Radiation and anthropogenic sources of energy are partitioned into latent, sensible, and stored energy within the urban environment. Flows (or fluxes) of energy for each of these terms are expressed in the energy balance equation for an urban surface as:

$$Q_F + K^* + L^* = Q_F + Q^* = Q_E + Q_H + Q_S$$

where

$Q_F$  is anthropogenic heat release,

$K^*$  is net shortwave radiation (direct, diffuse, and reflected),

$L^*$  is net longwave radiation,

$Q^*$  is the net allwave radiation,

$Q_E$  is latent heat-flux density,

$Q_H$  is sensible heat-flux density, and

$Q_S$  is net storage heat-flux density.

The magnitude of these energy fluxes ranges widely within and among cities depending on factors such as city size, population, latitude, urban morphology, and land cover characteristics. As a general guide for assessing the relative importance of each flux along the urban-rural gradient, Oke (1988a) listed hypothetical flux densities based on existing observations. These data, reproduced in table 1, refer to clear summer conditions at noon for a mid-latitude city with 1 million inhabitants. Unfortunately, typical values for nocturnal conditions, when the urban heat island is most intense are unavailable.

The relative importance of anthropogenic heat is small except during winter in high-latitude cities. At noon during summer, anthropogenic heat-flux densities typically range from twenty to fifty watts per square meter (table 1), depending on population density and energy use per capita (Oke 1988a).

Surprisingly, differences in net all-wave radiation ( $Q^*$ ) between rural and urban environments are relatively small because of offsetting the effects of urban atmosphere, albedo, and geometry (table 1). On average, smog attenuates urban short-

**Table 1** Radiation and Energy Balances for Hypothetical Midlatitude City at Noon During Clear Summer Conditions. All Values in  $\text{W m}^{-2}$  (after Oke, 1988a).

| <i>Available Energy</i> | <i>Rural</i> |  | <i>Suburban</i> |  | <i>Urban</i> |  |
|-------------------------|--------------|--|-----------------|--|--------------|--|
| $K\downarrow$           | 800          |  | 776             |  | 760          |  |
| $K\uparrow$             | -160         |  | -116            |  | -106         |  |
| $L\downarrow$           | 350          |  | 357             |  | 365          |  |
| $L\uparrow$             | -455         |  | -478            |  | -503         |  |
| $Q^*$                   | 535          |  | 539             |  | 516          |  |
| $Q_F$                   | 0            |  | 15              |  | 30           |  |
| Total                   | 535          |  | 554             |  | 546          |  |

| <i>Partitioned Energy</i> | <i>Rural</i> | <i>%</i> | <i>Suburban</i> | <i>%</i> | <i>Urban</i> | <i>%</i> |
|---------------------------|--------------|----------|-----------------|----------|--------------|----------|
| $Q_S$                     | 80           | 15       | 122             | 22       | 148          | 27       |
| $Q_H$                     | 150          | 28       | 216             | 39       | 240          | 44       |
| $Q_E$                     | 305          | 57       | 216             | 39       | 158          | 29       |
| Total                     | 535          | 100      | 554             | 100      | 546          | 100      |

wave radiation by about 10 percent, but a lower urban albedo (15 percent versus a rural albedo of 20 to 25 percent) results in relatively more absorption than in rural surroundings. Longwave radiation is primarily a function of surface temperature and exposure to the sky. Warmer air temperatures above cities result in greater incoming longwave radiation, but this is offset by increased outgoing longwave radiation due to warmer urban surface temperatures. However, it is important to recognize that urban heat-island intensity is greatest in urban canyons, partly because of the effect of tall buildings on radiation exchange. These buildings shade the street and wall surfaces during the day, reducing absorption of shortwave radiation and in some cases creating daytime "cool islands." However, the rate of heat loss to the sky at night is reduced because the sky in the city core is a less accessible sink for longwave heat loss compared with the sky in more open rural or suburban settings. Thus, although net allwave radiation in urban and rural environments is similar when averaged over a day, the geometry of cities results in diurnal differences in flux densities that can have important effects on the timing and intensity of the heat island.

Available energy ( $Q_F + Q^*$ ) is partitioned into three fluxes,  $Q_S$ ,  $Q_H$ , and  $Q_E$ . Net storage heat flux ( $Q_S$ ) depends on the thermal properties and arrangement of elements within the urban canopy layer. The thermal properties of typical urban materials such as asphalt, brick, and concrete are similar to those of rural materials such as bare soils. Higher urban net storage heat-flux densities are attributed to

differences in the composition and structure of these materials rather than their thermal properties per se (Goward 1981). For instance, unshaded, vertical building walls in the urban core can absorb larger amounts of radiant energy per unit of ground surface area than flatter rural surfaces can. Much of this energy is returned to the air as sensible heat because the low thermal mass of honeycomb-structured buildings results in relatively little heat storage. Paving materials have high thermal inertias that delay the time of peak surface temperature and reduce temperature ranges compared with those for surfaces of unshaded buildings with similar albedos. For the hypothetical mid-latitude city at noon, net storage heat flux typically accounts for about 15 and 27 percent (80 and 148 watts per square meter) of the available energy in rural and urban areas, respectively (Oke 1988a). Most importantly, daytime heat storage by the urban fabric delays the onset and retards the rate of nocturnal cooling.

Partitioning of the remaining energy into sensible ( $Q_H$ ) and latent energy ( $Q_E$ ) fluxes depends largely on available atmospheric, surface, and soil moisture. Moisture availability in urban environments exhibits great diversity in both space and time, whereas spatial diversity is less in rural areas (Oke 1988a). Lakes, irrigated fields, and forests of rural areas transform incoming energy into latent energy through evapotranspiration. Because less energy remains as sensible heat, air temperatures are lower. Hence, at noon in rural areas, 50 to 60 percent of the available energy is consumed as latent heat flux, and about 30 and 15 percent become sensible and subsurface heat fluxes (table 1). Vegetation cover accounts for from 5 to 20 percent of the surfaces in cities, 15 to 50 percent in suburbs, and 75 percent or more in rural areas (Rowntree 1984). Because cities have less vegetation and more impervious surfaces than rural areas, more energy is available to warm the air. Latent heat flux typically consumes only 30 percent of the incoming energy in the irrigated hypothetical city at noon, about half that consumed in the country. Hence, in urban areas, nearly 45 percent of the incoming energy warms the air as sensible heat (table 1).

It should be recognized that in the previous discussion "ideal" conditions were assumed. When conditions are calm and clear, microclimatic differences are enhanced and the relative importance of radiation and heat storage is increased. As windspeed and cloud cover increase, convection becomes relatively more important and net radiation and storage heat fluxes are dampened.

#### Implications of Urban Heat Islands

Urban temperatures have been increasing in cities around the world. Comparisons of temperature data from paired urban and rural weather stations suggest that the

recent warming trends are due to the urban heat island effect rather than to changes in regional weather. For example, data from thirty-one California cities show a warming rate of  $0.4^{\circ}\text{C}$  ( $0.7^{\circ}\text{F}$ ) per decade since 1965 (Akbari et al. 1992). Additionally, scientists project a "greenhouse" warming rate of about  $0.3^{\circ}\text{C}$  ( $0.5^{\circ}\text{F}$ ) per decade, which could exacerbate urban heat-island effects. This section reviews some of the significant economic and social implications of continued urban warming.

Peak cooling loads occur on the warmest days when air conditioning demand is greatest. They increase by about 1 percent for every increase in temperature of  $10^{\circ}\text{C}$  in U.S. cities with populations larger than one hundred thousand. Approximately 3 to 8 percent of the current U.S. electricity used for air conditioning is needed to compensate for the heat island effect caused by an increase in city temperatures of about  $1^{\circ}$  to  $2^{\circ}\text{C}$  since 1950. Scientists at the Lawrence Berkeley Laboratory (Akbari et al. 1988) estimate total national costs for offsetting the effects of summer heat islands on electricity at about \$1 million per hour or more than \$1 billion per year (5 percent of total air-conditioning costs).

Urban heat islands can contribute to global warming because warmer temperatures result in greater demands for cooling. Coal-burning power plants release about 0.45 kilograms (1 pound) of carbon per kilowatt-hour of electricity they generate. Therefore, mitigating urban heat islands can indirectly reduce carbon dioxide emissions at power plants and concentrations of atmospheric  $\text{CO}_2$ .

Large-scale plantings of urban trees and the use of light-colored surfaces can conserve about 2 percent of the total U.S. carbon production (Akbari et al. 1988).

Concentrations of urban ozone are increased by increases in ambient temperature (Cardelino and Chameides 1990). One study found that the incidence of smoggy days increased by 1 percent for each degree Celsius increase in temperature (Akbari et al. 1992). Because many large cities have smog problems and smog concentrations are sensitive to small increases in temperature, controlling urban heat islands is one means of improving air quality.

Urban heat islands can have numerous other adverse effects on the physical and psychological well-being of city dwellers. Heat-aggravated illness and death are related to increased cardiovascular diseases that weaken resistance to heat. Unnaturally high heat loads can directly and indirectly reduce life expectancy (Weihe 1986).

#### Mitigation of Urban Heat Islands

The thermal behavior of cities is largely a by-product of urban morphology or, more specifically, the composition and three-dimensional structure of materials

that constitute the urban canopy layer. This section reviews mitigation potential and the problems associated with urban geometry, surface color, and vegetation, elements that are commonly manipulated during the development process.

*Urban geometry.* Oke (1988b) stated that designs for street canyons in high- and mid-latitude cities should (1) maximize shelter from wind for pedestrian comfort, (2) maximize dispersion of air pollutants, (3) maximize urban warmth to reduce the need for space heating, and (4) maximize solar access. For warm-climate cities, objective 3 could be modified to read: minimize urban warming to reduce the need for space cooling. In either case, there can be a conflict between objectives promoting shelter, which imply narrow streets and compact forms, and objectives promoting dispersion, which imply separation and low building density. No design can maximize all objectives but it is possible to meet all objectives to a degree that is minimally acceptable.

Oke's analysis of urban geometry in relation to air-flow patterns, radiation exchange, and thermal behavior resulted in a range of canyon geometries and building densities that achieve a "zone of compatibility" wherein the worst aspects of not providing shelter, dispersion, warmth, or solar access are avoided. For instance, aspect ratios (building height/canyon width) of 0.4 to 0.6 and building densities (roof area/total surface area) of 0.2 to 0.4 satisfied all four objectives. The deep canyons and high building densities of many European cities result in geometries that more frequently fall within Oke's zones of compatibility compared to those many North American cities whose settlement patterns are more dispersed (Oke 1988b).

Numerical models and computer simulations have been used to evaluate the climatic impacts of urban design features. Arnfield's (1990) calculations of irradiances on urban canyon walls and floors provide quantitative guidelines on street geometry. He found that irradiance values generally were smaller for canyon walls than for floors, and that controlling canyon-floor irradiance was more critical at lower latitudes because of higher solar angles. North-south street orientation provided less summer and more winter canyon-floor irradiance than east-west street orientation, though the latter provided more favorable seasonal irradiance on canyon walls. Using their Cluster Thermal Time Constant model, Swaid and Hoffman (1990) found that in hot regions, cities with north-south streets have weaker urban heat-island intensities ( $0.8^{\circ}\text{C}$ ) than cities with east-west streets. Their sensitivity analysis illustrated how increasing aspect ratios (canyon height to width) results in a stronger daytime "cool island" due to increased shade, and a weaker nocturnal heat island due to appreciably reduced maximum temperature.

Although manipulation of aspect ratio, building density, and street orientation might reduce urban heat island effects substantially, the opportunity to exercise

this control is limited to new town planning and redevelopment projects. The urban geometry of most cities is well established and large-scale change is unlikely. In these circumstances, the use of vegetation and light-colored surfaces are more feasible mitigation options.

*Light-colored surfaces.* Increasing the albedo of building surfaces by whitewashing reduces solar heat gain and resulting heat storage. Additionally, increasing the albedo of large areas of the city by using light-colored dyes or sand in paving materials will lower air temperature by reducing the absorption of shortwave radiation. According to data from computer simulations for Sacramento, California, a temperature drop of one to four degrees Celsius can be achieved by increasing citywide albedo from 25 to 40 percent (Taha et al. 1988). Whitewashing residential buildings (albedo change from 9 to 70 percent) reduced annual cooling energy 19 percent and peak cooling demand by 14 percent (Taha et al. 1988). The combined effects of modifications in urban and building albedo resulted in savings of up to 62 percent for annual cooling and 35 percent for peak cooling. However, because the effect of the increased solar load on buildings from lighter surroundings was not incorporated in the model, predicted savings may exceed actual savings.

Albedo modification is a promising strategy for heat island mitigation because of the relatively quick payback period. Once light surfaces are applied, benefits begin to accrue. Many surfaces need to be recoated, so there is the opportunity for large-scale implementation. Using data for Sacramento, Akbari and others (1987) calculated that urban albedo could be increased from 20 to 30 percent by changing the albedo of rooftops (15 to 40 percent) and streets (14 to 30 percent). Increased glare and the desire of some designers and property owners for unrestricted color selection are potential obstacles to implementation. Also, some materials (e.g., tar roofing) do not lend themselves to painting and others may require regular recoating and cleaning (Akbari et al. 1987). Large-scale tree planting could counteract the effectiveness of color change by shading light surfaces and reducing citywide albedo. The extent to which the energy absorbed in this way would influence urban warming depends on its partitioning into latent and sensible heat fluxes.

*Vegetated surfaces.* The energy-saving potential of trees and other landscape vegetation has been documented (Heisler 1986; Meier 1991; Parker 1990). Vegetation can mitigate urban heat islands directly by shading heat-absorbing surfaces, and indirectly through evapotranspirational (ET) cooling. In a review of studies that measured temperature reductions, Meier (1991) reported that vegetation consistently lowered wall surface temperatures by about seventeen degrees Celsius and reduced air-conditioning costs by 25 to 80 percent. The extent to which measured reductions in surface temperature and savings in cooling costs can be attributed to

direct building shade versus ET cooling is not clear. In most circumstances, the impact of one or several trees on ambient temperatures and cooling load are small compared to the shading effect. Cool air produced in the tree crown is dissipated by the much larger volume of air moving through the tree. However, large numbers of trees and expansive greenspaces can reduce local air temperatures by one to five degrees Celsius, and the advection of this cool air can lower the demand for air conditioning (O'Rourke and Terjung 1981; Oke 1989).

Computer simulations (Huang et al. 1987) of the cooling effects of three trees around a residential home in Sacramento showed that shade alone reduced annual and peak cooling energy use by 16 and 11 percent, respectively. The combined effects of shade and ET cooling resulted in savings of 53 and 34 percent, respectively. Thus, ET cooling accounted for 70 percent of the annual energy savings and 68 percent of the peak savings. This finding may reflect the modeling assumption that ET is not limited by soil moisture. Trees in urban environments can experience drought stress due to limited soil moisture and large heat gains from absorbed and reflected radiation (Oke 1989). Theoretically, for stressed plants ET cooling is least during mid- to late afternoon when water vapor deficits are greatest and stomata are closed. Therefore, actual ET cooling effects may be less than projected, especially with regard to peak savings. The relative importance of ET cooling has been disputed by Lowry (1988), who calculated an ET cooling rate of  $0.3^{\circ}\text{C}$  per hour and a sensible heating rate of  $1.0^{\circ}\text{C}$  per hour along ten meters of street canyon containing six mature trees.

The selection and location of trees around buildings to minimize the peak demand for air conditioning is particularly important to electric utilities because the marginal cost of peak power is generally 20 to 30 percent greater than the cost of base load power (about \$0.10 versus \$0.075 per kilowatt-hour). Parker (1987) described a methodology for determining the optimal location of vegetation to reduce peak loads. "Peak load landscaping" requires that plants be positioned to provide maximum shade several hours before the time when the local utility typically experiences peak demand. In south Florida peak demand usually occurs between 5 and 6 P.M. in early August when temperatures are warmest. To account for the delay before heat on the exterior walls transfers inside and affects the air-conditioning load, Parker recommended plantings for maximum shading of south- and west-facing surfaces between 3 and 4 P.M. in early August. Large-scale implementation of "peak load" landscaping also could reduce urban heat-island intensity because this intensity often is greatest (6 to 11 P.M.) during the period of peak demand for most summer-peaking electric utilities (3 to 10 P.M.). How effectively this landscaping can "shave" and shift peak demand for electricity depends on factors such as the utility's demand profile and regional climate.

**Table 2** Summary of Impacts of Vegetation on Electricity Use in Arizona Annual Cooling Savings (kWh) and Peak Demand Savings (kW)

| Study                      | House Type                                 | Planting Type                            | Shade |      | ET Cool   |      | Total/Tree |      |
|----------------------------|--------------------------------------------|------------------------------------------|-------|------|-----------|------|------------|------|
|                            |                                            |                                          | kWh   | kW   | kWh       | kW   | kWh        | kW   |
| Huang et al. 1987          | 143 m <sup>2</sup> wood Phoenix            | 1 tree west side 50 m <sup>2</sup>       | 208   | 0.47 | 665       | 0.33 | 873        | 0.80 |
| McPherson & Dougherty 1989 | 137 m <sup>2</sup> wood Tucson             | 1 olive tree west side 46 m <sup>2</sup> | 292   | 0.39 | —         | —    | 292        | 0.39 |
| McPherson 1990b            | 137 m <sup>2</sup> wood Phoenix and Tucson | xeriscape 8 trees                        | 1673  | 0.97 | (Phoenix) |      | 209        | 0.12 |
|                            |                                            | 50 shrubs                                | 1353  | 0.94 | (Tucson)  |      | 169        | 0.12 |
| McPherson 1991             | Tucson                                     | 500,000 mesquite                         | 61    | —    | 277       | —    | 338        | —    |

Additional measurements and modeling studies are needed to quantify the potential savings in annual and peak load electricity to be gained through landscaping.

Water is becoming increasingly expensive in many cities, and the cooling value of trees that use little water has been questioned in desert cities. Shading with little ET cooling, as with desert trees, results in the conversion of most absorbed radiant energy into sensible heat that warms the air. However, because net storage heat flux can be substantial in hot, arid cities (Grimmond & Oke 1990), shading alone can reduce urban heat-island intensity by reducing surface temperatures and the amount of energy stored and later reradiated from paving and buildings (Swaide and Hoffman 1990). Findings from a study using quarter-scale buildings (McPherson et al. 1989) suggest that ET cooling from turf can provide cooling savings equivalent to the savings gained from the dense shade of shrubs and trees requiring little water. These results indicate that the microscale effects of vegetation in hot, arid regions can be more significant than was commonly thought. Landscaped mini-oases with small turf areas that provide ET cooling and desert trees that shade buildings can effectively balance the need to conserve energy and water (McPherson 1990b).

Results of several field studies and computer simulations designed to quantify the effects of trees on electric use in Arizona are summarized in table 2. Annual cooling energy and peak demand savings ranged from 169 to 873 kilowatt-hours and 0.12 to 0.80 kilowatts, respectively. Other findings suggest that:

- (1) Shading of windows and west-facing walls provides the most savings in cooling energy (McPherson and Dougherty 1989).
- (2) On trees selected for shade, crown shape can be more important than crown density (McPherson and Dougherty 1989).
- (3) Annual water costs for certain tree species can be twice as much as the energy savings from their shade (McPherson and Dougherty 1989).
- (4) Energy and water prices determine the extent to which it is economical to substitute ET cooling for electric air conditioning (McPherson and Woodard 1990).
- (5) Effects of tree shade on winter heating demand can be substantial (Thayer and Maeda 1985; Heisler 1986; McPherson et al. 1988).

The Arizona Corporation Commission (1990) recommended that utilities fund the development of consumer guides on energy-efficient landscaping and programs offering rebates for tree planting. These recommendations were based upon the results of a benefit-cost analysis that found that the present value of net benefits for planting 180,000 trees is \$2.9 million. The analysis assumed planting costs of \$45 per tree, annual water costs of \$4 to \$6 per tree, a 7 percent discount rate, and a twenty-year planning horizon. Each tree was assumed to shade the west-facing wall and provide annual and peak savings of 250 kilowatt-hours and 0.33 kilowatts, respectively, after the fifth year. The study showed that trees were an economical conservation measure because they met the need for electric energy services at a cost lower than the cost of generating electricity.

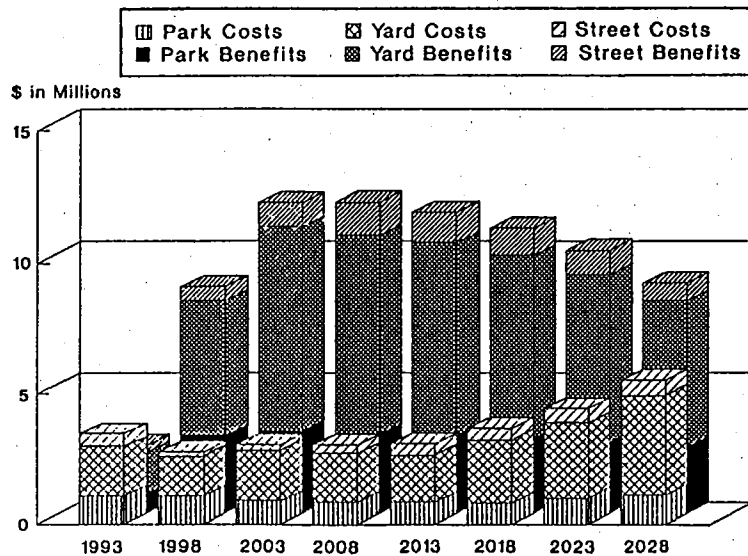
A benefit-cost analysis (fig. 1) for the planting of 500,000 trees in Tucson, Arizona, projected net benefits of \$236.5 million for the forty-year planning horizon (McPherson 1991). The benefit-cost ratio and the internal rate of return for all trees were 2.6 and 7.11, respectively. Yard trees provided the highest rate of return (14 percent) and street trees the lowest (2 percent). Average annual costs and benefits per tree were estimated as \$9.61 and \$25.09, respectively. Cooling savings provided the greatest benefits, and removal costs were the largest management expense. Projected average annual benefits in cooling energy per tree were 61 kilowatt-hours (\$4.39) for shade and 227 kilowatt-hours (\$16.34) for ET cooling. Carbon savings averaged 185 kilograms (408 pounds) annually per tree. An important conclusion was that investment in tree planting by the public sector may be warranted because economic, environmental, and aesthetic benefits extend beyond the site where individual trees are planted.

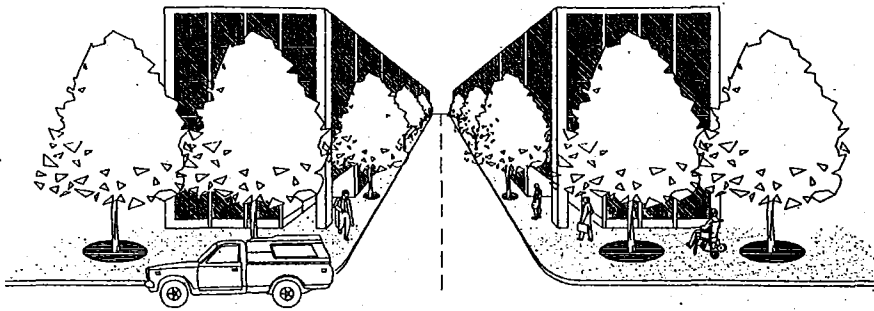
The value of trees for energy conservation has also been evaluated at the national level. Projections from computer simulations indicate that 100 million mature trees in U.S. cities (three trees for every other single-family home) could

reduce energy use for heating and cooling by 30 billion kilowatt-hours and reduce CO<sub>2</sub> emissions by as much as 8 billion kilograms (9 million tons) per year (Akbari et al. 1988). Increasing vegetation was more cost-effective in mitigating heat island effects than other fuel-saving measures such as using energy-efficient appliances and cars.

Although the potential for planting trees in U.S. cities is great and considerable mitigation of urban heat-island effects is possible, there are problems associated with tree planting. First, trees can be a serious liability if they become a public hazard, interfere with aboveground or belowground utilities, or require excessive maintenance. Second, trees can adversely affect the urban climate by blocking solar access in winter, by trapping pollutants within the urban canopy layer and by increasing aerodynamic roughness, thereby reducing country-city air flow and convective heat loss. Third, trees can be relatively expensive to plant and slow to provide a return on investment. Fourth, increased tree planting can increase the amount of pollen that affects allergy sufferers, the use of scarce water supplies, and the amount of solid waste that goes into landfills. However, these problems can be minimized through careful planning, wise selection of species, and designs that fully use the hydrologic, ecologic, atmospheric, restorative, and aesthetic benefits that vegetation can provide.

**Figure 1** Projected average annual costs and benefits from proposed planting of 500,000 desert trees during 1990 to 1995 in parks, yards, and streets of Tucson, Arizona (from McPherson 1991)





**Figure 2** Tall, narrow deciduous street trees shade the canyon walls and sidewalks, reduce downdrafts, and provide ET cooling. Pollution dispersion by down-canyon breezes and vertical mixing of buoyant air is achieved because the crowns do not cover the entire canyon. Bare branches in winter enhance solar heat gain.

### Design Examples

Several design examples illustrate how climatological information is applied to urban heat-island mitigation in a northern hemisphere city (approximately thirty degrees north latitude) with a hot climate. These examples focus on the use of vegetation in situations that are typical of urban canyons, parking lots, parks, and single-family residential neighborhoods. Each design addresses objectives defined for street canyons and restated here for hot-climate cities.

- 1) Promote summertime cooling and the conservation of air-conditioning energy by reducing irradiance and increasing heat loss through latent heat flux, convection, and longwave radiation.
- 2) Allow for the dispersion of air pollutants by promoting down- and cross-canyon circulation and mixing with air moving above the city.
- 3) Provide for solar access during the winter by increasing irradiance.
- 4) Shelter pedestrians from extreme winds, turbulence, and downdrafts near buildings.

### Street Canyons

Various techniques have provided a salubrious street-canyon environment by balancing the needs for solar protection and atmospheric dispersion (fig. 2). A high aspect ratio reflects the importance of reducing the irradiance of canyon floors at lower latitudes. Light-colored roof, wall, and paving surfaces further reduce the amount of absorbed radiation. Tall, narrow trees reduce canyon wall irradiance, shade sidewalks, and lessen downdrafts at the base of buildings. Down-canyon

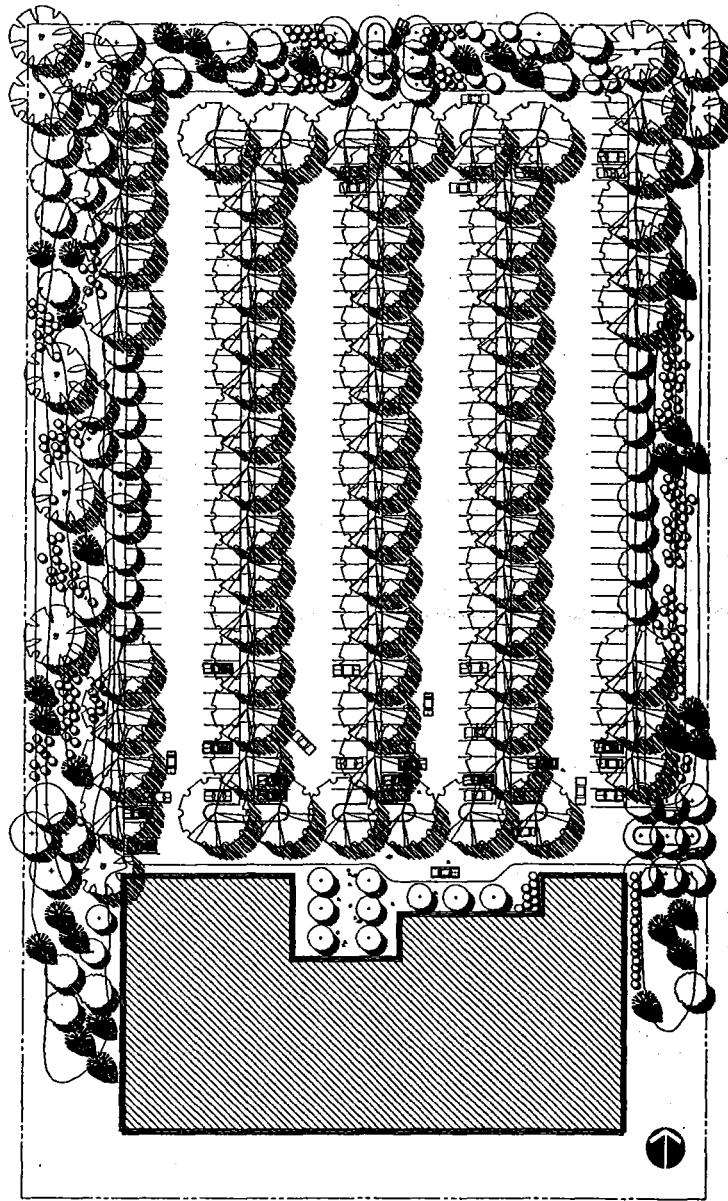
ventilation is not entirely obstructed since the trees do not cover the street. This arrangement also allows for some longwave heat loss from street to sky and perhaps for pollution dispersion through the ascension of hot air parcels. Amply irrigated deciduous trees lower summertime temperatures through ET cooling and provide increased winter irradiance when they drop their leaves. The trees also furnish other benefits such as absorbing gaseous pollutants and carbon dioxide, emitting oxygen, intercepting particulates, reducing noise, and enhancing scenic beauty. On the negative side, the trees reduce convective heat loss from the building skin and pollution dispersion from cross-canyon circulation.

#### Parking Lots

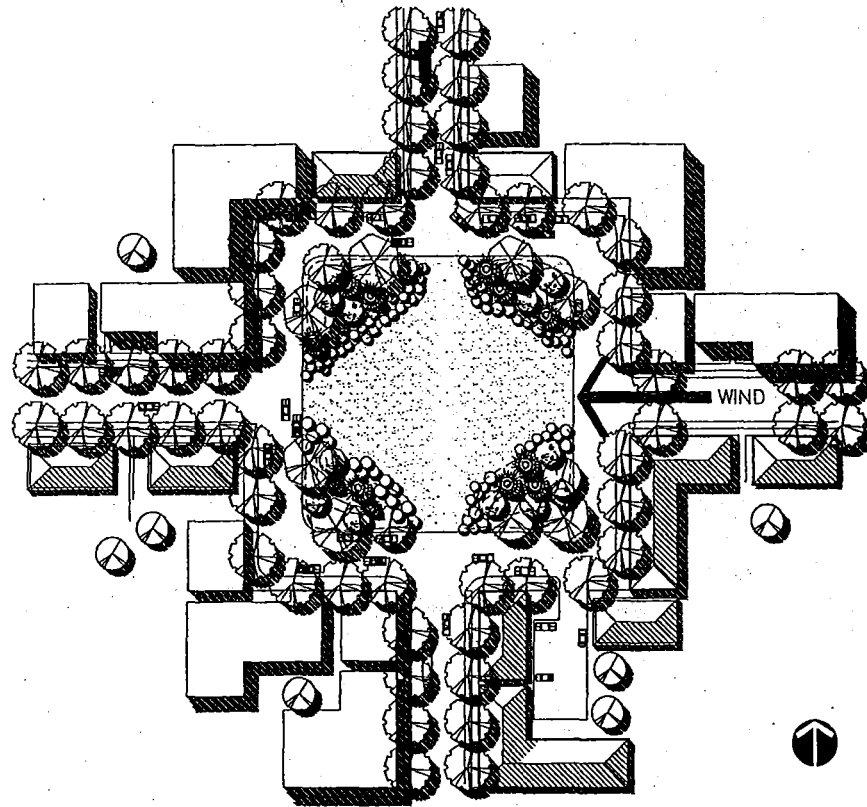
Parking lots are ubiquitous features of commercial strips and shopping malls that surround the urban core. Issues of visibility, safety, screening, and access are central to traditional parking-lot design. The design in figure 3 incorporates these concerns as well as the needs for shade, buffering, and water harvesting (Beatty 1990). Trees are aligned in north-south rows to shade as much pavement as possible during the summer. Dense, broad-spreading tree crowns increase the amount of shade. Ample growing space and soil moisture enhance tree survival, growth, and ET cooling effects. Trees are pruned high enough for safe visibility and truck clearance. Pruning also promotes subcanopy circulation for cooling and pollution dispersion. Rainfall runoff drains into the buffer plantings along the perimeter, where it is detained. These buffer plantings exhibit structural diversity, with a variety of species in several strata. Harvested rainfall supplements irrigation, and the plantings function to reduce sound, particulates, and gaseous pollutants. Vertical accents articulate entryways to enhance the safety and legibility of the parking lot.

#### Urban Parks

Parks can be important sources of fresh cool air in the city. The park in figure 4 is designed to increase nocturnal cooling and the advection of cool air into the warmer surrounding neighborhood. Much of the park is well-irrigated turf without trees. Transpiring turf shades the ground and cools the air. Although trees in turf can increase the ET cooling effect, they also can reduce radiant heat loss to the sky and convection/advection. This trade-off has not been studied sufficiently to permit us to know whether the addition of trees provides net benefits. Multi-layered plantings of drought-tolerant species create a buffer along berms that define the park perimeter. The use of native-looking plants in forms that reflect the



**Figure 3** Trees in the parking lot are arranged in north-south rows to provide maximum shade on pavement during the summer. Sufficient soil volumes and irrigation promote rapid growth and ET cooling. Stormwater runoff is harvested in basins along the periphery, where structurally diverse plantings filter particulates, intercept rainfall, and screen the parking lot.



**Figure 4** The open turf area in this urban park is a source of cool air that is carried into the surrounding area by prevailing breezes. Buffer plantings along the park boundary reflect the complex structure of the region's native plant associations.

structure of native plant communities promotes a sense of place. The buffer planting is multifunctional and an important symbol of "naturalness" in the heart of the city. The berms and buffer plantings disappear at street intersections to facilitate the flow of cool air through downwind openings and into adjacent street canyons.

#### Residential Streets

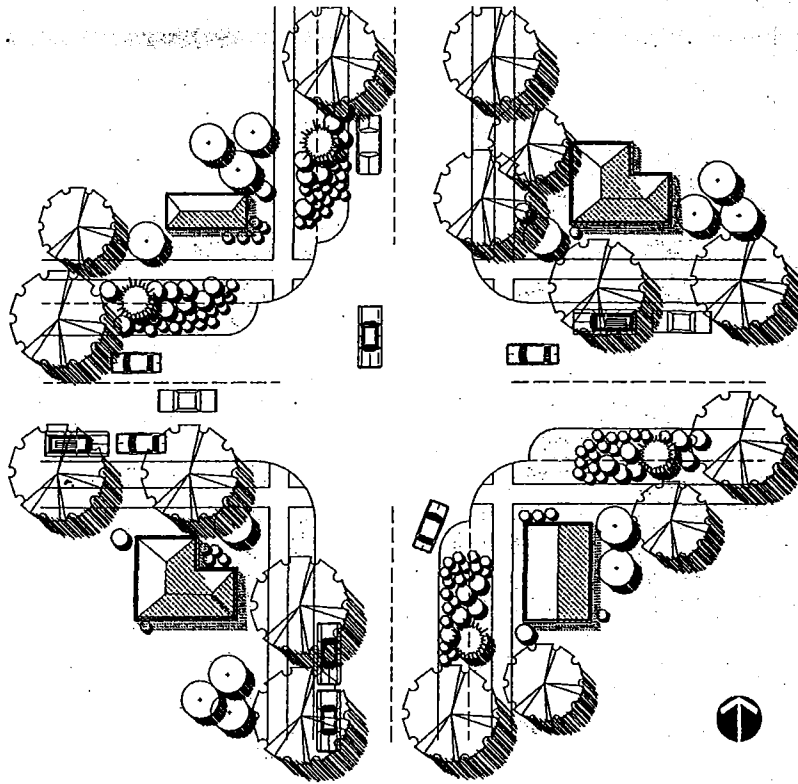
Most residential streets in the United States have paving that is too wide and planting strips that are too narrow. The design in figure 5 "reclaims" the right-of-way for people, plants, and animals. Narrowed traffic lanes force cars to travel

slowly through residential neighborhoods yet allow access for emergency vehicles. Parking for residents and guests is provided along intrablock alleys. Large roadside trees shade the pavement and promote pedestrian travel within a more comfortable microclimate. Reclaimed irrigation water and stormwater harvested off the surrounding areas nourish a complex association of plants and animals. Smaller drought-tolerant trees shade adjacent residences, conserving energy and water.

### Conclusion

Although urban climatologists have made many measurements of urban heat-island effects, there are relatively few predictive models for use by those who design

**Figure 5** Reclaimed greenspaces along residential streets provide areas for naturalistic plantings that enhance biodiversity by creating riparianlike habitats. Runoff harvested from streets and sidewalks reduces flooding downstream and conserves irrigation water. Small trees that use little water shade nearby buildings.



our cities (Oke 1988a). Most existing models do not adequately consider all fluxes of energy and matter or incorporate the spatial and temporal variability within the urban canopy layer (Martien et al. 1990). There is need for numerical models that are based on the physical processes at work in cities (Grimmond and Oke 1986). The output from microclimatic or canopy layer models that function at the scale of a homesite could be input for mesoclimatic models that integrate microscale effects over the area of a neighborhood or city. Once these models have been validated in different climatic regions, they should be simplified and integrated with existing geographic information systems to facilitate implementation by urban planners.

Studies are needed to determine the most cost-effective method for obtaining land-surface information for modeling purposes. Remotely sensed information seems appropriate for mesoscale modeling but may not provide the resolution needed for microscale simulation. Field surveys might be needed to identify plant species and size as well as building construction types, and to collect other detailed information. This will require the development of appropriate sampling and survey techniques.

Environmental planners are asking many practical questions related to urban heat-island mitigation that we cannot answer now. For instance, policy-makers in Arizona want to know the trade-offs between ET cooling and water demand. Elsewhere, utility and urban planners want to know how much savings in cooling energy can be achieved by increasing the amount of urban vegetation by a specified amount. Designers are asking how best to locate and manage vegetation in parks, streets, and residential areas to improve urban climate. Urban foresters want to know which tree species will provide the greatest long-term net benefits.

Clearly, there is a need for further development of urban climate models, as well as for climatological and urban forestry research that can be used to validate and verify the models. Equally important is the development and application of "user-friendly" planning and design tools. The cooling of our urban heat islands depends on the timely development and implementation of reliable predictive models, and the guidelines, regulations, and incentives that can be generated from the information they provide.

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