MICROSCALE VEGETATION EFFECTS ON OUTDOOR THERMAL COMFORT IN A HOT-ARID ENVIRONMENT

Limor Shashua-Bar, David Pearlmutter, Evyatar Erell
Blaustein Institutes For Desert Research, Ben Gurion University of the Negev, Israel

Abstract

The effect of irrigated vegetation on human thermal stress in a hot-arid region was tested in two semi-enclosed urban spaces with varying combinations of mature trees, shading mesh, lawn and paving. The Index of Thermal Stress was calculated hourly from measured data to evaluate thermal comfort in the spaces, and was expressed on a scale of thermal sensation. While thermal stress in a paved unshaded courtyard was severe during mid-day hours, both grass and shading, either by trees or by mesh, contributed significantly to thermal comfort. A combination of the two strategies resulted in comfortable conditions at all hours – though trees alone provided more efficient cooling in terms of water use, as measured by the rate of evapotranspiration. The main effect of both grass and shade was to reduce radiant loads, while differences in air temperature were small.

Key words: thermal stress, evapotranspiration, microclimate, landscape, urban design

1. INTRODUCTION

Irrigated vegetation may have a profound impact on the climate of urban areas, and the relative lack of vegetation in many cities has been cited as one of the main causes of the urban heat island. Yet in arid regions this situation may theoretically be reversed, with a relative abundance of irrigated landscaping within the built-up area creating a "cool island" in the midst of sparsely vegetated natural surroundings. Observations in desert cities have shown that such an urban cool island may indeed develop, though largely as a daytime, rather than as a nocturnal, phenomenon (Brazel *et al*. 2000).

The primary mechanism to which this type of urban cooling is attributed is evapotranspiration, by which radiant energy driving the surface energy balance is converted into latent, as opposed to sensible heat. Recent studies in Israel's Negev desert using an open-air scaled urban surface (the OASUS model) showed that the proportion of dissipated latent heat is directly related to the 'complete vegetated fraction,' or the ratio between the total vegetated area and the complete three-dimensional urban surface area (Pearlmutter *et al.* 2009). This indicates that evaporative cooling depends not only on the extent of urban green spaces, but also on the height and density of buildings within the urban fabric. In addition, the thermally moderating effect of vegetation is not just evaporative but also radiative, due to the lower temperatures of shaded and vegetated ground surfaces – and the direct shading of pedestrians. Thus the cooling effects of urban vegetation may be highly localized, with individual cool islands of limited spatial extent forming within an otherwise overheated built-up area. When the vegetated area is small and turbulent mixing of air in the urban canopy is efficient, air temperature reductions within the green patch may in fact be negligible – though it has been shown repeatedly that the effects of shading and cooler surfaces moderate significantly the overall thermal stress experienced by pedestrians (Pearlmutter *et al*., 1999; Ali-Toudert and Mayer, 2006; Johansson, 2006).

Notwithstanding its benefits, the use of vegetative landscaping in arid regions relies on water resources for irrigation, which in many cases are scarce since precipitation is far outweighed by potential evapotranspiration. This balance between water consumption and the amelioration of urban heating is examined in the present study, which employs observations in a well-defined urban space to model the micro-scale influence of various landscape treatments on pedestrian thermal stress.

2. EXPERIMENTAL SETUP

The landscape strategies examined include six combinations of ground cover (dry paving and irrigated grass) and overhead treatment (exposed, shade trees, and shading-mesh). A controlled experiment was conducted in two adjacent courtyard spaces (Fig. 1), which are nearly identical in their material attributes and geometry (15 x 6 m; long axis N-S; H/W = 0.5) but differentiated by the existence of three mature trees in one of the spaces (grass sod units were added to each space subsequently). The site is located at the Sde-Boqer campus in the arid Negev Highlands of southern Israel (30.8°N, 500m elevation). The courtyards were monitored in hot-dry conditions during July-August 2007, with measurements made in each landscape configuration for a period of at least 3-4 successive days. Ambient temperatures were typically in the range of 20-33°C, with low daytime relative humidity and strong northwesterly winds in late afternoon.

Dry- and wet-bulb temperatures were measured in each courtyard (between two *Prosopis Juliflora* trees in the planted courtyard and at the same central point in the exposed one) using copper-constantan thermocouples in aspirated psychrometers. Temperatures of the various built and vegetated surfaces were measured in both

Corresponding author: David Pearlmutter, Jacob Blaustein Institutes for Desert Research, Ben Gurion University of the Negev – Sde Boqer Campus, 84990 Israel. E-mail: davidp@bgu.ac.il

courtyards using shielded ultra-fine thermocouples and an IR thermometer. Wind speed was measured within the courtyards, and other climatic data corresponding to the measurement days were also obtained from a nearby meteorological station for comparison and analysis purposes.

Water use for grass irrigation was estimated using custom-made mini-lysimeters, which consisted of rectangular metal pans embedded in the grass-soil layer. The evapotranspiration rate was determined from the periodic change in lysimeter weight, measured hourly with a high-resolution electronic scale starting from the daily time of irrigation. Transpiration from the trees was measured by the sap flow method, which relates the transpiration rate to the rate of sap flow in the tree trunk. The method uses pairs of cylindrical temperature probes inserted in the sapwood, with the upper probe heated by the Joule effect at a constant rate and the lower (reference) probe unheated. A more detailed description of the monitoring setup is given by Shashua-Bar *et al.* (2009a; 2009b).

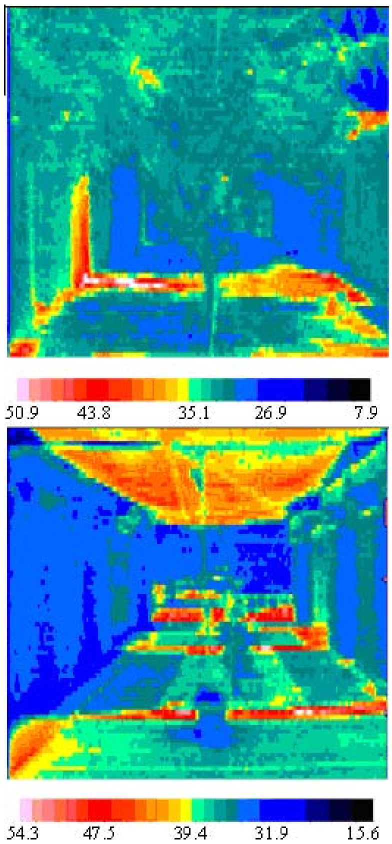

Figure 1. Thermal images of courtyards with trees and grass (top) and with paving and mesh (bottom).

3. MODELING THERMAL STRESS AND THERMAL SENSATION

Pedestrian thermal stress was quantified using the Index of Thermal Stress (ITS), which expresses the overall energy exchange between a pedestrian's body and its surroundings under warm conditions. Expressed in watts of equivalent latent heat, the index is a measure of the rate at which the body must secrete sweat in order to maintain thermal equilibrium – accounting for radiation R_n and convection C as well as the body's internal heat generation (based on metabolism M and work W) and the efficiency of sweat evaporation f, as limited by atmospheric humidity:

$$ITS = [R_n + C + (M-W)] / f \qquad [1]$$

The instantaneous exchanges of energy by radiation and convection are computed in W m^{-2} of body surface using a vertical cylinder to represent a standing pedestrian in the center of the space (Pearlmutter *et al.* 1999). The body's net radiation balance is composed of absorbed direct, diffuse and reflected short-wave components, long-wave absorption from the sky and other downward-radiating elements, horizontal ground surfaces and vertical wall surfaces, and long-wave emission from the body to the environment. The absorption of short-wave radiation is based on measured global and diffuse radiation, shading and view factors (a function of courtyard geometry), and the albedo of built and vegetative surfaces and of the body itself. Long-wave absorption from surfaces is calculated on the basis of view factors, measured surface temperatures, and estimated emissivity values for all relevant materials. Downward long-wave emission from the sky dome was taken as the residual in the measured net radiation balance above the building roof (with incoming short-wave measured, roof albedo estimated, and outgoing long-wave computed from the measured roof surface temperature and estimated emissivity) and emission from the body is based on a constant skin-clothing temperature. Convective energy exchange is a function of the skin-air temperature differential and of an empirical heat transfer coefficient based on wind speed, which was measured along with air temperature in the courtyards.

To calculate the level of thermal stress from the radiative and convective environmental loads, component flux densities are multiplied by the DuBois body surface area to yield fluxes in watts, and summed with the net metabolic heat gain. The evaporative cooling efficiency is computed from an empirical relation based on the vapor pressure of the surrounding air, as well as on wind speed and a clothing coefficient. The level of physiological stress represented by the ITS has also been correlated with subjective thermal discomfort, on a thermal sensation scale ranging from "comfortable" to "very hot" (Givoni 1963; Pearlmutter et al. 2007). According to this scale, a limit to comfort is found at an ITS value of approximately 160 W, with the thresholds for "warm" and "hot" conditions occurring at successive increments of 120 W each.

While climatic conditions were relatively consistent throughout the summer monitoring period, minor differences were accounted for by normalizing the results from individual days relative to a reference dataset taken from the adjacent meteorological station. For each landscape configuration, a representative daily cycle was selected and hourly ITS values were adjusted proportionally based on the ratio between the equivalent value computed from simultaneous measurements at the 'open' site of the meteorological station, and the average of reference values for that hour over the set of selected days.

4. RESULTS AND DISCUSSION

In Figure 2, normalized hourly daytime (6:00-20:00) values of thermal stress are shown for the six courtyard configurations as well as for a pedestrian in an 'open space', with the latter calculated on the basis of measured data (air and ground temperatures, short-wave radiation, wind speed and vapor pressure) from the adjacent meteorological station. In this 'open' situation, ITS values representing thermal discomfort (>160 W) prevail for nearly all daytime hours. In a paved courtyard with no shading (Exposed-Bare), heat stress is only slightly shorter than this in duration – and in fact is more severe at mid-day, reaching a higher peak of about 520 W.

The introduction of irrigated ground cover (Exposed-Grass) in place of paving and bare soil reduces the level of thermal stress significantly, such that it is nearly confined to the "warm" category throughout the mid-day hours. This overall result is mainly due to the lower radiative surface temperature of the grass and reduced emission of long-wave radiation, and only in small part to its lower albedo (moderating reflected short-wave radiation) and evaporative cooling of the air above (slightly increasing convective heat removal).

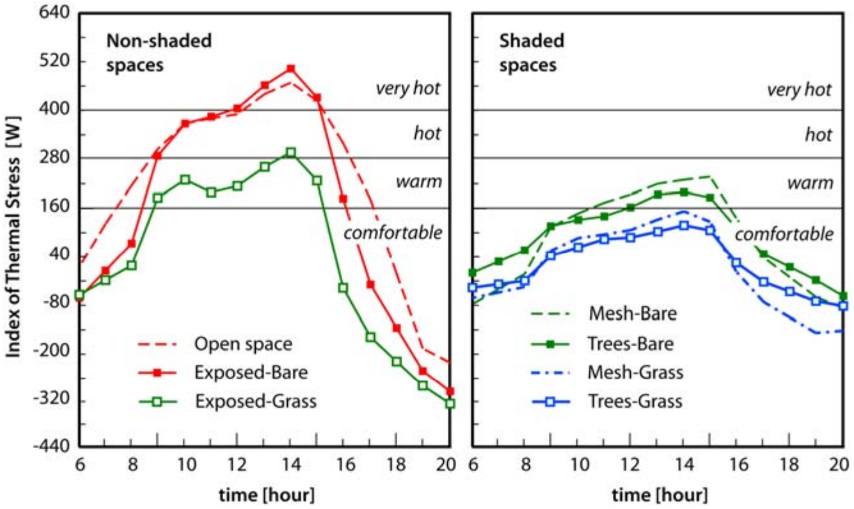

Figure 2. Normalized ITS values during summer daytime hours for non-shaded spaces (left) and for courtyard configurations with overhead shading by either trees or mesh (right), with corresponding levels of thermal sensation.

In the cases with overhead shading – either by trees or mesh – but without grass, the attenuating effect on pedestrian thermal stress during mid-day hours is more pronounced than that observed with exposed grass. It may also be seen that the vegetative shading treatment (Trees-Bare) results in fewer hours of discomfort than Mesh-Bare, owing largely to the high radiant temperatures (45-50^{o}C) of the mesh's bottom surface relative to the underside of tree canopy, which remained close to the courtyard air temperature of up to about 35^{o}C (see Fig.1).

Adding grass under the trees or under the mesh produces a modest further reduction in stress, but a crucial one since these combinations of shading and green ground cover result in a thermal state defined as "comfortable" during all hours of the day. Once again a small advantage is seen during daytime for the purely vegetative configuration (Trees-Grass) compared with Mesh-Bare, meaning that the fully 'green' space is the one in which the peak pedestrian thermal stress is lowest. It is of interest to note that a substantial reduction of thermal stress was obtained with all landscape treatments in spite of a relatively small reduction in air temperature – the shade mesh alone even created a small increase in temperature (Shashua-Bar *et al.*, 2009a) – and a significant decrease in wind speed that was created by the trees (and to a lesser extent, by the mesh). This highlights the importance of radiant exchange in thermal comfort in outdoor spaces, especially in hot-dry climates.

The daily irrigation of grass and trees (metered separately for grass sprayers and tree drippers, with polyethylene sheeting for mutual isolation between the two types of irrigated soil) was designed to offset as closely as possible the water loss due to evapotranspiration over the same daily period. Figure 3, which compares the water use for each of the vegetative treatments both in terms of the water volume provided and the water volume lost (i.e. ET, measured with lysimeters and sap-flow probes), shows that that a close match between irrigation and actual (non-normalized) ET was in fact achieved for the tree transpiration as well as for the grass, when the grass was shaded by either trees or mesh. Exposed grass was under-irrigated relative to its actual evapotranspiration of about 650 liters per day, through oversight rather than design. This rate was higher than that of any other configuration, including the total ET of trees and shaded grass combined. It is notable that overhead shading lowered the grass ET by about one third – to just over 400 liters/day in the case of the mesh, and to just below that figure in the case of trees. The lowest water use is seen for the treatment with drip irrigated trees only, which transpired approximately 200 liters daily.

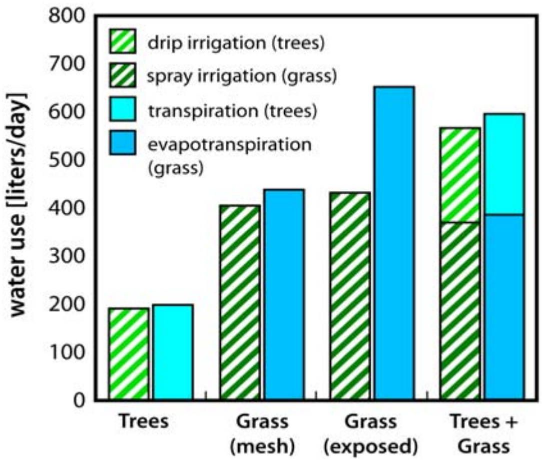

Figure 3. Daily water use for each of the vegetative treatments, in terms of irrigation provided and actual water loss through evapotranspiration (values not normalized).

Table 1 gives a summary of the daily water use for each landscape treatment – normalized relative to pan evaporation at the reference site – in terms of the equivalent latent heat represented by evapotranspiration from the vegetation. This value (Q_E, in kWh) is derived as the product of the water volume evaporated and the latent heat of vaporization. Also in Table 1, the landscape strategies are evaluated in terms of their daily cooling effect (ΔITS). This calculation is based on the hourly difference between each courtyard's associated ITS value and that of the non-treated base case courtyard (Exposed-Bare), and is computed in kWh as a daytime total (from 6:00 to 18:00). By taking the ratio between the reduction in heat load on a pedestrian (quantified here for one person only) and the water required to provide it (i.e. the latent heat energy of evapotranspiration), a measure of 'cooling efficiency' is generated as a percentage for each landscape treatment, as shown in the last column of Table 1.

Table 1. Summary of daytime reduction in thermal stress, latent heat of daily water loss and cooling efficiency for each of the landscape treatments.

Landscape treatment	**Daytime cooling ΔITS** [kWh]	**Daily water use Q_E** [kWh]	**Cooling efficiency** [%]
Mesh Bare	1.53	0.0	- NA -
Exposed Grass	1.75	331.7	0.53
Mesh Grass	2.47	241.6	1.02
Trees Grass	2.42	217.7	1.11
Trees Bare	1.50	55.2	2.72

It is clear from the relative values that the deployment of shade trees achieves by far the highest efficiency of any vegetative treatment – with a value that is 2.5 times as high as that of the tree-shaded grass (which in turn is slightly higher that of mesh-shaded grass). While exposed grass does have a significant cooling effect, its high water consumption gives it the lowest efficiency, only half that of the shaded grass.

5. CONCLUSIONS

Findings from the controlled experiment, which compares a series of urban-space landscape configurations in terms of pedestrian thermal comfort and cooling efficiency of vegetation, lead to a number of general conclusions:

- Each of the landscape treatments made a clear contribution to improved comfort, with the greatest reduction in mid-day thermal stress provided by a combination of shade trees and grass.
- The vegetative treatment achieving the highest cooling efficiency in terms of water usage was the configuration of shade trees alone. The additional cooling provided by irrigated grass was far outweighed by its high water demand, which was much higher still when exposed to the sky rather than shaded by either trees or mesh.
- Intermediate-level moderations of thermal stress were made by single landscape elements (grass, trees or mesh) used in isolation – indicating their usefulness on the one hand, and on the other hand showing the synergetic value of *combined* strategies in terms of thermal comfort as well as water-use efficiency.
- Vegetation may make a substantial contribution to human thermal comfort even when its effect on air temperature is negligible.

ACKNOWLEDGEMENTS *- Dr. Shashua-Bar's work was supported by fellowships from the Blaustein Center for Scientific Cooperation at Ben-Gurion University of the Negev and from the Planning and Grants Committee of the Israel Council for Higher Education. The authors thank Wolfgang Motzafi-Haller for his dedicated effort in installing and maintaining the experimental setup.*

References

Ali-Toudert, F., Mayer, H., 2006. Numerical study on the effects of aspect ratio and solar orientation on outdoor thermal comfort in hot and dry climate, *Building and Environment*, 41, 94-108.
Brazel, A., Selover, N., Vose, R., Heisler, G., 2000. The tale of two climates–Baltimore and Phoenix urban LTER sites, *Climate Research*, 15, 123–135.
Givoni, B., 1963. Estimation of the effect of climate on man – development of a new thermal index. PhD thesis, Technion - Israel Institute of Technology.
Johansson, E., 2006. Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco, *Building and Environment*, 41, 1326-1338.
Pearlmutter, D., Bitan, A., Berliner, P., 1999. Microclimatic analysis of 'compact' urban canyons in an arid zone, *Atmospheric Environment*, 33, 4143-4150.
Pearlmutter, D., Berliner, P., Shaviv, E., 2007. Integrated modeling of pedestrian energy exchange and thermal comfort in urban street canyons, *Building and Environment*, 42, 2396-2409.
Pearlmutter, D., Krüger, E.L., Berliner, P., 2009. The role of evaporation in the energy balance of an open-air scaled urban surface, *International Journal of Climatology*, 29, 911-920.
Shashua-Bar, L., Erell, E. and Pearlmutter, P., 2009a. Water use considerations and cooling effects of urban landscape strategies in a hot dry region. *International Conference on Urban Climatology*, Yokohama, 2009.
Shashua-Bar, L., Erell, E. and Pearlmutter, P., 2009b. The cooling efficiency of urban landscape strategies in a hot dry climate, *Landscape and Urban Planning* (in press).