INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **31**: 1498–1506 (2011)
Published online 2 June 2010 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.2177

The influence of trees and grass on outdoor thermal comfort in a hot-arid environment

Limor Shashua-Bar, David Pearlmutter* and Evyatar Erell
Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Beersheba, Israel

ABSTRACT: The effects of vegetation on human thermal stress in a hot-arid region were tested in two semi-enclosed urban spaces with various combinations of mature trees, grass, overhead shading mesh and paving. The index of thermal stress was calculated hourly from measured meteorological data in the studied sites to evaluate thermal comfort in the different spaces based on radiative and convective pedestrian–environment energy exchanges and sweat efficiency, and expressed on a thermal sensation scale ranging from 'comfortable' to 'very hot'. The efficiency of water use in providing improved comfort was gauged for each of the vegetative landscaping treatments by comparing the total evapotranspiration with the reduction in thermal stress, both expressed in terms of their values in equivalent energy. While conditions in a paved, unshaded courtyard were found to be uncomfortable throughout the daytime hours (with half of these hours defined by severe discomfort), each of the landscape treatments made a clear contribution to improved thermal comfort. With shading, either by trees or mesh, discomfort was reduced in duration by over half and limited in maximum severity when the shading was placed above paving. When combined with grass, both shading mechanisms yielded comfortable conditions at all hours. In both cases, the effect of trees was more pronounced than that of the mesh, but by a small margin. With unshaded grass, 'hot' conditions in the courtyard were restricted to a short period in mid-afternoon, a considerable improvement over unshaded paving, attributable mainly to the lower radiant surface temperatures. Copyright © 2010 Royal Meteorological Society

KEY WORDS urban microclimate; evapotranspiration; thermal comfort; vegetation

Received 17 September 2009; Revised 10 March 2010; Accepted 29 April 2010

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 (UHI). However, in arid regions, this situation may theoretically be reversed, with a relative abundance of irrigated landscaping within the built-up area creating 'cool islands' in the midst of sparsely vegetated natural surroundings. Observations in desert cities have shown that such urban cool islands 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* (i.e. a combination of evaporation from wet surfaces and transpiration from plant leaves), 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 A_v and the complete three-dimensional urban surface area A_c (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. Modelling results also showed that canopy layer air is progressively cooled with the addition of evaporating area, with temperature reductions under the experimental conditions ($A_v/A_c = 0.2$) reaching nearly 3 K. It is clear, however, that vegetation in actual cities is not evenly distributed and that the effects of trees and vegetated ground cover may in fact be concentrated in distinct patches such as parks, courtyards or tree-lined streets.

This 'park cool island' effect has been identified in several other studies, with reductions in air temperature of up to 3–4 K observed at mid-day during summer in the case of trees in streets and parks (Bernatzky, 1982; Oke, 1989; Spronken-Smith and Oke, 1998; Shashua-Bar and Hoffman, 2000; Chen and Wong, 2006; Potchter *et al*., 2006) and of up to 2 K in the case of vegetated surfaces such as urban lawns (Bonan, 2000; Spronken-Smith *et al*., 2000) and green walls and roofs (e.g. Onmura *et al*., 2001; Takebayashi and Moriyama, 2007; Alexandri and Jones, 2008).

The causes of these air temperature reductions include not only the direct cooling and humidification of air through transpiration and surface evaporation but also

* Correspondence to: David Pearlmutter, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Beersheba, Israel. E-mail: davidp@bgu.ac.il

the moderation of radiant and convective surface-to-air heat exchange due to the lower temperatures of shaded and/or vegetated ground and building elements. While it has been suggested that parks and other green spaces may serve as sources of cooling for the larger urban terrain, particularly in the downwind direction (Ca *et al.*, 1998; Dimoudi *et al.*, 2003), in many cases the cooling of air may be highly localized – with individual cool islands of limited spatial extent forming within an otherwise overheated built-up area (Saito *et al.*, 1990–1991). 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 (Schiller and Karchon, 1974), even if the effects of shading and cooler surfaces moderate significantly the overall thermal stress experienced by pedestrians (Pearlmutter *et al.*, 1999). It has been observed repeatedly that due to the dominance of radiation in hot-arid settings, air temperature alone is not necessarily a robust indicator of overall thermal comfort for pedestrians in the urban space (Ali-Toudert and Mayer, 2006; Johansson, 2006; Pearlmutter *et al.*, 2006).

Thus, the actual microscale effects of urban vegetation on human comfort are complex and interrelated with the effects of other built elements in the city, whose geometry and surface properties may vary widely (Stabler *et al.*, 2005; Shashua-Bar *et al.*, 2006; Erell and Williamson, 2006). One implication of this complexity is that some UHI mitigation strategies, such as the use of high-albedo surfaces (e.g. Rosenfeld *et al.*, 1995, 1998), may result in lower surface temperatures but more intense reflected radiation, which also contributes to pedestrian discomfort (Pearlmutter *et al.*, 2007).

An additional concern related to the microscale effects of landscaping is the use of water resources, which in many arid regions are scarce (Ferguson, 2007; Perry, 2007). Aridity is characterized by precipitation levels that are significantly less than the potential evapotranspiration (Bruins and Berliner, 1998), meaning that while evaporative cooling may be especially effective, requirements for irrigation may outstrip available water sources. The balance between water consumption and the moderation of urban heating is examined in the present study, which examines the microscale influence of vegetative landscape treatments on pedestrian thermal stress within the confines of a well-defined urban space.

2. Methodology

The effects of different landscape configurations on thermal stress are evaluated using measured data from two adjacent, semi-enclosed courtyard spaces. By computing the energy exchange between the urban environment and a hypothetical pedestrian in the space, the reductions in physiological thermal stress, and in turn perceived thermal discomfort, are estimated and compared with the rate of irrigation required by each vegetative treatment to achieve them.

2.1. Experimental setup

The observational study was conducted at the Sede-Boqer campus of Ben-Gurion University, located in the Negev Highlands of southern Israel (30°50′N, 34°40′E; 475-m elevation). Daily temperatures during the summer period (measurements were conducted during July to August) range on average from an early morning minimum of 20 °C to an afternoon peak of 33 °C, with relative humidity averaging 35% at 14 : 00 and increasing to about 90% at night. Prevailing winds are consistently from the northwest, reaching maximum velocity in the late afternoon and evening (Bitan and Rubin, 1994).

The experiment was designed to compare a number of different landscape treatments under relatively controlled conditions, such that their microscale effects could be identified and distinguished from the background effects of the larger built-up area. For this purpose, two adjacent courtyard spaces were selected which had virtually identical geometry and material properties (Meir *et al.*, 1995); one, however, had been planted with three mature trees, whereas the other was devoid of vegetation. Both spaces were surrounded by single-story buildings and elongated in plan along an approximately north–south axis, with a cross-sectional aspect ratio of approximately $H/W = 0.5$ (Figure 1).

In addition to their original disposition, the courtyards were modified in two ways: a ground cover treatment consisting of grass sod on a shallow soil underlayment was placed alternately in each of the two spaces, and an overhead shading mesh was installed in the courtyard without trees. This yielded a total of six distinct landscape configurations which could be monitored over the course of the summer period, each combining one of the three overhead treatments ('trees', 'exposed' and 'mesh') with one of two ground treatments ('grass' and 'bare'). The six study cases and their parameters are summarized in Tables I and II, respectively.

The ground surface in the two courtyards initially consisted of light grey concrete paving tiles (covering about 70% of the area) and exposed loess soil occupying the remainder. One of the courts had three trees planted along its centre line, two of which were *Prosopis-Juliflora* (a variety of mesquite) and the third *Tipuana-Typu* (rosewood). Both species are common in hot-arid regions and are considered economical water consumers: the nominal pan coefficient (defined as the ratio between the tree's evapotranspiration per unit horizontal area and evaporation from a Class A pan) is 0.2 for *Prosopis-Juliflora* and 0.3 for *Tipuana-Tipu* (Kremmer and Galon, 1996). Both tree species have a medium leaf density that allows ventilation and sufficient solar penetration for grass to grow in their shade.

The grass subsequently planted in the two courtyards was Durban grass with a measured pan evaporation coefficient of approximately 0.8, which is typical of values for short-cut grass cited in previous studies (Brutseart, 1982; Pearlmutter *et al.*, 2009). Durban grass was selected mainly for its ability to grow in the shade,

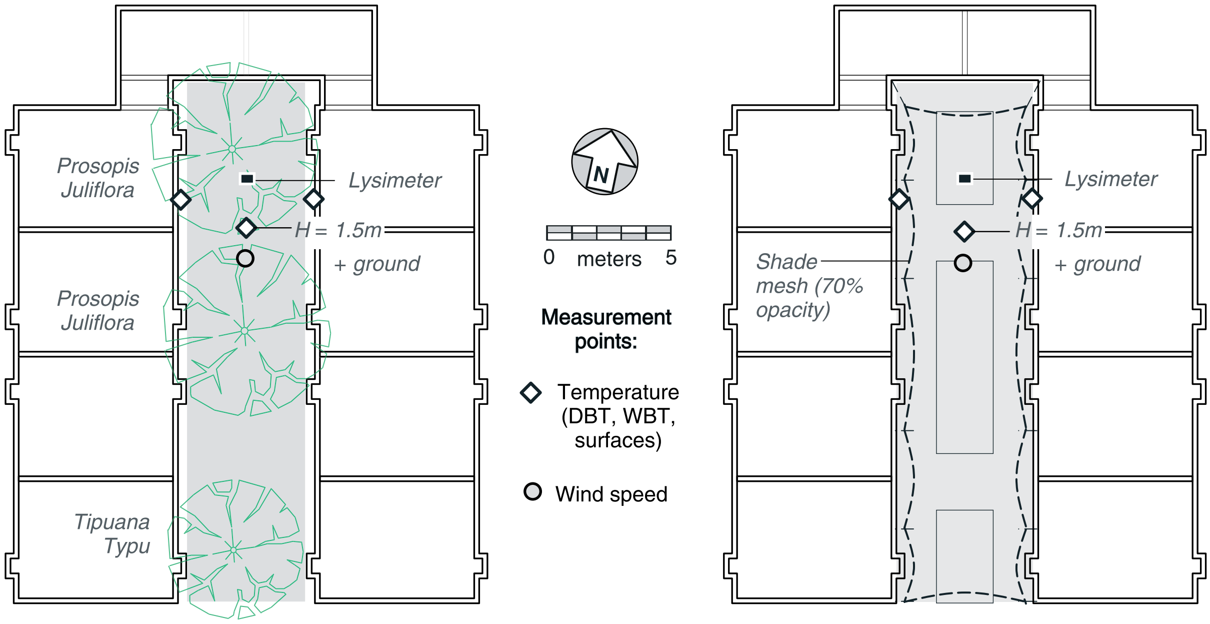
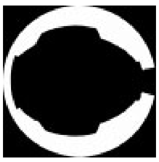
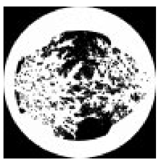


Figure 1. Plan of courtyard configurations showing location of measurement points and of trees in west courtyard (left) and shading mesh in east courtyard (right). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Table I. The six landscape configurations analysed.

		Ground surface treatment	
		Bare paving and soil	Irrigated grass
Overhead treatment	Exposed Trees Shade mesh	'Exposed-bare' 'Trees-bare' 'Mesh-bare'	'Exposed-grass' 'Trees-grass' 'Mesh-grass'

Table II. Physical parameters of the various landscape elements.

Parameter	Ground surfaces		Overhead treatments	
	Bare	Grass	Trees	Shade mesh
SVF	exposed court  0.62	court with trees  0.37	court with mesh  0.29	
Area ratios	30% soil, 70% pavement	90% grass	70% coverage	70% coverage
Albedo	0.60 (walls), 0.55 (ground)	0.22	–	–
Transmissivity	–	–	0.3	0.3

with a minimum requirement of only 3 h of direct sunlight per day. This variety also has especially shallow roots, which made it suitable for planting in the form of sod units on a thin soil layer approximately 3 cm in depth. The grass and underlayment were placed on polyethylene sheeting, covering about 90% of the total ground area of each court.

The trees and the grass were irrigated separately: a drip irrigation system was installed around each tree trunk, providing water to the root zone in the surrounding soil but isolated from the grass layer. Water sprinklers for the grass were located in each court and activated each morning at 6:00. The duration and rate of watering by the two irrigation systems were determined on the basis of preliminary experiments, with the objective of providing an amount of water sufficient to compensate for daily water loss through evapotranspiration (as detailed in Section 3.2). The impermeable polyethylene sheeting under the grass ensured that spray from the sprinklers would not reach the tree roots and that drip irrigation around the trees would not be available to the grass.

Micrometeorological variables and water consumption were monitored in the two courtyards over a 45-day period during July to August 2007, with each landscape configuration monitored for a period of at least 3–4 consecutive days. Instruments were located at the mid-point of each of the two canyon-like spaces, between the two *Prosopis-Juliflora* trees in the west courtyard and at the same relative location in the east court. Dry-bulb and wet-bulb temperatures were measured using copper-constantan thermocouples in aspirated psychrometers, placed at a height of 1.5 m. Wind velocity was measured using a Campbell 014A cup anemometer in the bare court, and with a Young 81 000 3-D ultrasonic anemometer in the court with trees. Radiant temperatures of the various built and vegetated surfaces were measured in the two courtyards using shielded ultra-fine thermocouples (attached to wall, paving, soil, lower tree branch and roof surfaces) and an IR thermometer (for the grass surface). Incoming solar radiation was measured with a Kipp and Zonen CM5 pyranometer and net all-wave radiation was recorded with an REBS Q7.1 net radiometer, both located at a height of 1 m above the adjacent building's flat roof. All readings were recorded with Campbell CR21X and CR23X data loggers. Reference climatic data for the given measurement days were obtained from the nearby meteorological station.

Evaporation from the grass was estimated using custom-made mini-lysimeters, whose dimensions and material were optimized to ensure representative measurement of evapotranspiration from the grass–soil volume (Grimmond *et al*., 1992). The instruments consisted of rectangular (5 × 10 cm) galvanized metal pans with a vertical depth of 3 cm embedded in the grass–soil layer, which was of similar thickness. The evapotranspiration rate was determined from the periodic change in lysimeter weight, measured hourly with a high-resolution electronic scale starting immediately following the daily irrigation at 6 : 00.

Transpiration from the trees was measured by the sap flow (thermal dissipation) method, which relates transpiration to the rate of sap flow in the tree trunk (Gash and Granier, 2007). The method uses a pair of cylindrical temperature probes inserted into the sapwood, with the upper probe heated by the Joule effect at a constant rate and the lower (reference) probe unheated, with the rate of sap flow calculated as a function of the difference in temperature between the two probes. To account for variations in sap flow among different parts of the tree, transpiration was calculated from the average temperature difference of three pairs of probes located in each tree at the same height (approximately 0.8 m), at equal intervals around the trunk.

2.2. Computation of thermal stress

A variety of models have been used to assess outdoor thermal comfort, often through the use of a hypothetical, 'physiologically equivalent' temperature (e.g. Hoppe, 1993, 1999). Such measures typically portray radiant effects using the mean radiant temperature (MRT), which is difficult to quantify in an outdoor urban context due to the multiplicity of radiating surfaces together with the high intensity of solar and atmospheric radiation. Although the measurement of MRT using globe thermometers of varying diameters and materials has received wide attention in recent studies (Ali-Toudert and Mayer, 2006, 2007; Thorsson *et al*., 2007; Kenny *et al*., 2008), this approach is still subject to uncertainties given the extreme variability of air flow and convective heat transfer that is typical in the urban canopy layer.

In the present study, pedestrian thermal stress is quantified using the index of thermal stress (ITS), originally developed by Givoni (1963) and implemented in urban canyon-type settings by Pearlmutter *et al*. (2007). Rather than deriving a hypothetical temperature, the ITS directly 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 to maintain thermal equilibrium, accounting for radiation R_n and convection C as well as for 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:

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

The instantaneous exchange of energy by radiation and convection is computed in W/m^2 of body surface using a vertical cylinder to represent a standing pedestrian in the centre of the space (Pearlmutter *et al*., 1999). The body's net radiation balance R_n is composed of absorbed direct (K_{dir}), diffuse (K_{dif}) and reflected (K_{ref}) short-wave components; long-wave absorption from the sky and other downward-radiating elements (L_{d}), from horizontal ground surfaces (L_{h}) and from vertical wall surfaces (L_{v}); and long-wave emission from the body to the environment (L_{s}):

$$R_{\mathrm{n}} = (K_{\mathrm{dir}} + K_{\mathrm{dif}} + K_{\mathrm{h}} + K_{\mathrm{v}})(1 - \alpha_{\mathrm{s}}) + L_{\mathrm{d}} + L_{\mathrm{h}} + L_{\mathrm{v}} - L_{\mathrm{s}} \qquad (2)$$

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 (Table II) and of the body itself (α_s). Long-wave absorption from surfaces (including the ground, walls, tree canopy, and shading mesh) is calculated on the basis of view factors, measured surface temperatures and estimated emissivity values for all relevant materials, whereas emission from the body is based on a constant skin-clothing temperature of 35 °C. Absorption of downward long-wave emission from the sky dome is calculated from measured meteorological values and relevant sky view factors. A detailed description of the calculation of individual radiation components is given by Pearlmutter *et al.* (2006).

Convective energy exchange (in W/m^2 of body area) is a function of the skin–air temperature differential ($T_s - T_a$) and an empirical heat transfer coefficient h_c based on wind speed V:

$$C = h_c(T_s - T_a) \tag{3a}$$

$$h_c = 8.3V^{0.6} \tag{3b}$$

In nearly all cases, C represents a net dissipation of heat from the body since courtyard air rarely reaches a temperature above 35 °C, which was taken as a constant for T_s.

To calculate the level of thermal stress from the environmental loads R_n and C, component flux densities in W/m^2 are multiplied by the DuBois body surface area to yield fluxes in watts, and summed with the net metabolic heat gain (taken as a constant 70 W for a standing person). The evaporative cooling efficiency f is computed from an empirical relation based on the vapour pressure of the surrounding air (as well as wind speed and a clothing coefficient), as detailed by Pearlmutter *et al.* (2007).

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 about 120 W each (Table III).

Table III. Correlation between ITS and thermal sensation level (Pearlmutter *et al.*, 2007).

Index of thermal stress (W)	Thermal sensation
<160	Comfortable
160–280	Warm
280–400	Hot
>400	Very hot

While climatic conditions were relatively consistent throughout the summer monitoring period, minor differences were accounted for by normalizing the ITS 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 (ITS_{ref}) and the average of reference values for that hour over the set of selected days:

$$ITS_{norm} = ITS \times \left(\frac{\overline{ITS}_{ref}}{ITS_{ref}}\right) \tag{4}$$

Daily water consumption was normalized according to the same procedure, based on Class A pan evaporation at the meteorological station.

3. Results and discussion

3.1. Pedestrian thermal stress

In Figure 2, normalized hourly daytime (6 : 00–20 : 00) values of calculated 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

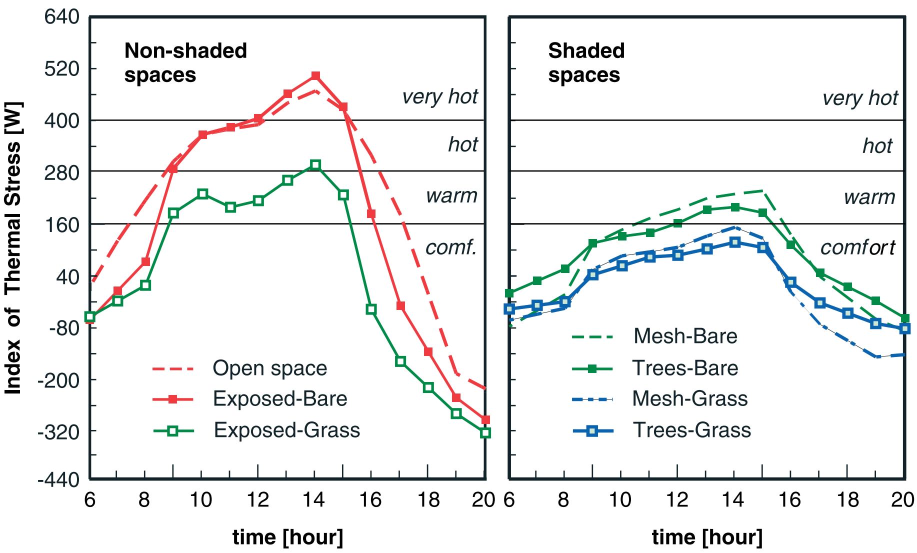


Figure 2. Normalized index of thermal stress (ITS) values during summer daytime hours (LST) for non-shaded spaces (left) and for courtyard configurations with overhead shading by either trees or mesh (right), with corresponding levels of thermal sensation. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

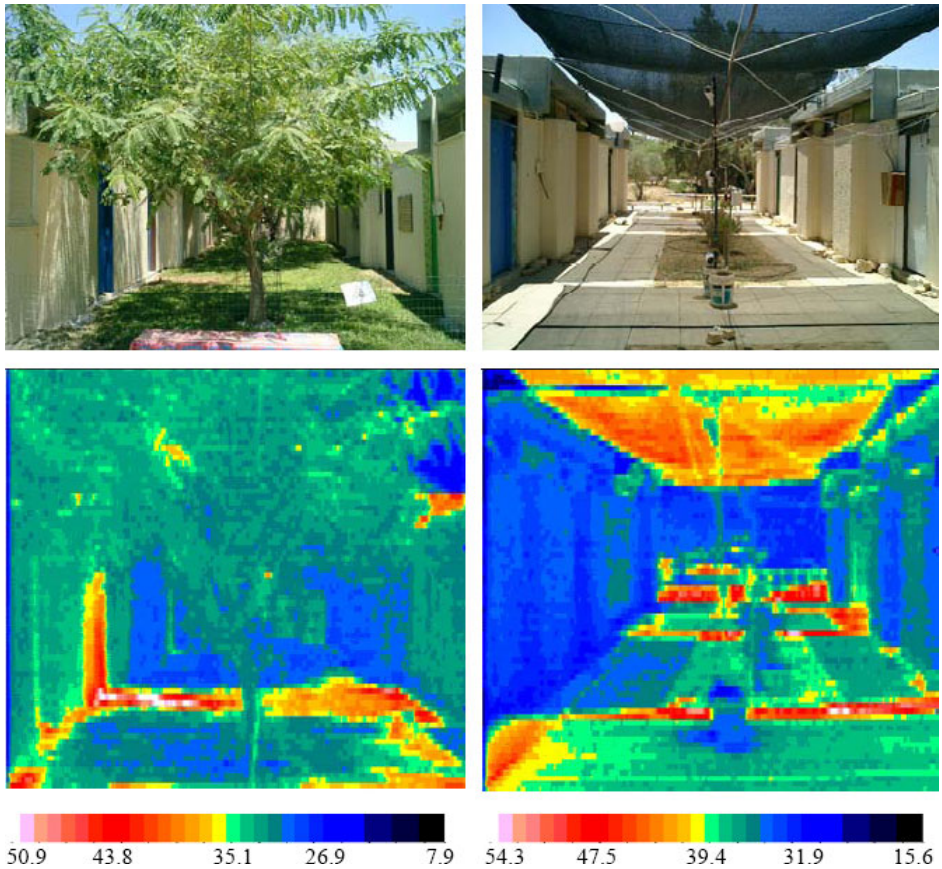


Figure 3. Visual and corresponding infrared thermal images of courtyard configurations with grass and trees (left) and with bare pavement and shading mesh (right), at approximately 12 : 20 LST on 17 July 2007. Thermal images show radiant surface temperatures (in °C) based on a long-wave emissivity of 0.92 (note separate temperature scales). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

of measured data (air and ground temperatures, short-wave radiation, wind speed and vapour pressure) from the adjacent meteorological station.

In this 'open' situation, ITS values representing thermal discomfort (>160 W) prevail for nearly all daytime hours, between approximately 8 : 00 and 18 : 00. In the non-treated courtyard ('exposed-bare'), the duration of discomfort is only about 2 h shorter than this, and in fact is more severe at mid-day, reaching a higher peak of about 520 W (well above the limit of 'very hot').

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 confined to the 'warm' category throughout the mid-day hours. This overall result is mainly due to the lower radiative surface temperature (see sunlit spots in Figure 3) 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).

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. This is primarily due to the sharp reduction in short-wave radiation absorbed directly by the body (reduced from a peak of about 200 W/m^2 to a relatively constant 50 W/m^2) but also to the shading of surfaces which reduces both short-wave reflection and long-wave emission due to their reduced radiant temperature. 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 radiative temperatures (45–50 °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 °C; Figure 3). At the same time, the overhead shading treatments introduced effects which decrease convective heat loss: the trees restricted air flow by up to 80%, and the mesh increased air temperature by up to nearly 1 °C (Shashua-Bar *et al*., 2009).

Adding grass under the trees or under the mesh produces a modest further reduction in stress, but a crucial one as these combinations of shading and vegetative 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-grass', meaning that the fully 'green' space is the one in which the daytime pedestrian stress is lowest. In this fully vegetated courtyard, air temperature at peak daytime hours was lower than in the bare exposed courtyard by up to 2.5 °C (Shashua-Bar *et al*., 2009). Interestingly, neither the presence of grass nor the presence of trees introduced any significant change in the cooling efficiency

Configuration	Hour [LST]														
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Open space	4	4	5	6	6	6	6	7	7	7	6	5	4	4	4
Exposed Bare	4	4	4	6	6	6	7	7	7	7	5	4	4	4	4
Exposed Grass	4	4	4	5	5	5	5	5	6	5	4	4	4	4	4
Mesh Bare	4	4	4	4	4	5	5	5	5	5	4	4	4	4	4
Trees Bare	4	4	4	4	4	4	5	5	5	5	4	4	4	4	4
Mesh Grass	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Trees Grass	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

Figure 4. Thermal sensation levels by summer daytime hour, for all spatial configurations (4 = comfortable, 5 = warm, 6 = hot, 7 = very hot). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

of sweating, as differences in vapour pressure at head height among the various studied cases were minor.

The basic relationship between configurations observed for daytime ITS values is generally reversed at night, with the lowest values occurring in the spaces which are the most exposed and the least vegetated. This opposite pattern is observed, however, during hours when 'comfortable' conditions prevail in all cases, regardless of landscape treatment. An hour-by-hour summary of daytime thermal sensation levels for all of the spatial configurations is given in Figure 4. This 'snapshot' shows clearly that thermal stress is concentrated in the mid-day hours and is insubstantial from early evening (18:00) until early the following morning (8:00).

3.2. Thermal comfort with respect to water use

As mentioned previously, the daily irrigation of grass and trees was designed to offset as closely as possible the water loss due to evapotranspiration (ET) over the same daily period. In Figure 5, which compares the water use for each of the vegetative treatments both in terms of the water volume provided (metered separately for grass sprayers and tree drippers) and the water volume lost (measured with lysimeters and sap flow probes, shown here before normalization), it can be seen that a close match between irrigation and ET was in fact achieved for the tree transpiration as well as for the grass ET, when the grass was shaded by either trees or mesh. An exception to this correlation is seen in the case of exposed-grass, which was under-irrigated relative to its actual evapotranspiration of about 650 l/day.

In Table IV, a summary of the normalized daily water use for each landscape treatment is given in terms of the equivalent latent heat Q_E (in kWh) represented by evapotranspiration from the vegetation, derived as the product of the water volume evaporated ET (in kg) and the latent heat of vapourization ($L_V = 2.43$ MJ/kg at 30 °C and 100 kPa):

$$Q_E = L_v \mathrm{ET} \quad (5)$$

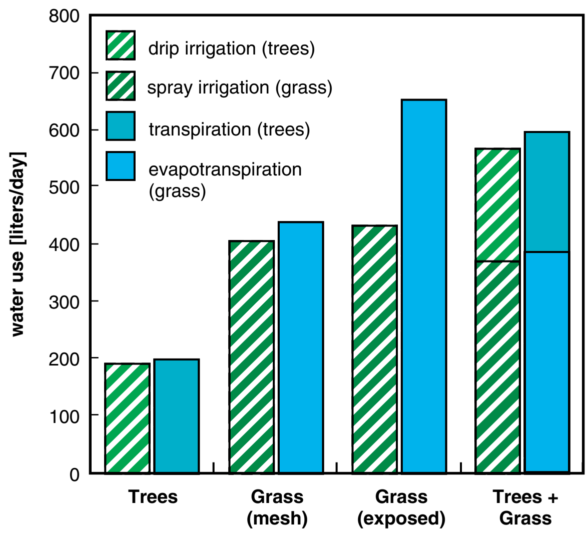


Figure 5. Total daily (non-normalized) water use in the courtyard for each of the vegetative treatments, in terms of irrigation provided and actual water loss through evapotranspiration from grass and transpiration from trees. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

It can be seen that the normalized latent heat of water loss in the case of exposed-grass was higher than that of any other configuration (332 kWh), including the total of trees and shaded grass combined. It is notable that overhead shading lowered the total water loss by 25–35%, to the equivalent of 242 kWh in the case of grass shaded by mesh and to 218 kWh in the case of grass shaded by trees. The lowest water use is seen for the treatment with drip-irrigated trees only, whose transpiration energy was only 55 kWh/day, on average.

Moreover, in Table IV, the landscape strategies are compared in terms of their effect on thermal comfort, which is evaluated by calculating the hourly difference between each courtyard's associated ITS value and that of the non-treated base case courtyard ('exposed-bare'). This 'cooling effect' (Δ ITS) is computed in kWh as a daily total (in this case during daytime hours only, from 6:00 to 18:00).

Table IV. Summary of daytime reduction in thermal stress, daily water loss and cooling efficiency for each of the landscape treatments relative to the 'exposed-bare' configuration.

Landscape treatment	Daytime cooling ΔITS (kWh)	Daily water use Q_E (kWh)	Cooling efficiency $\Delta ITS/Q_E$ (%)
Mesh-bare	1.53	0	NA
Exposed-grass	1.75	332	0.53
Mesh-grass	2.47	242	1.02
Trees-grass	2.42	218	1.11
Trees-bare	1.50	55	2.72

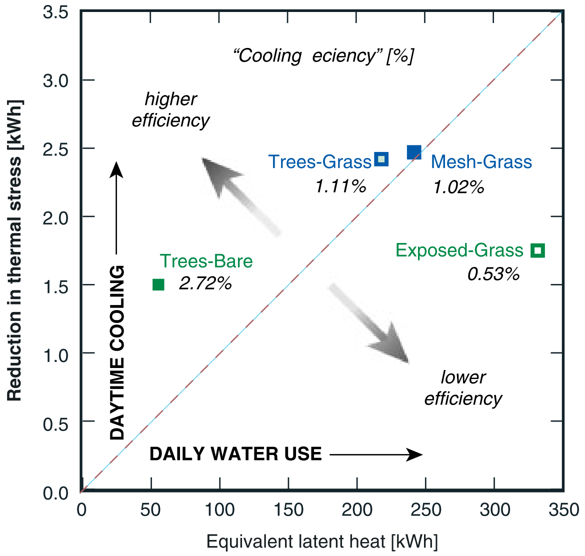


Figure 6. Scatter plot of daytime cooling versus daily water use, showing relative cooling efficiency for each landscape treatment. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

By taking the ratio between the pedestrian cooling energy provided (quantified here for one pedestrian) 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 Table IV. It is clear from the relative values that the deployment of shade trees (only) achieves by far the highest efficiency of any vegetative treatment, followed by the two variations of shaded grass. While exposed-grass does have a significant cooling effect, its high water consumption gives it the lowest efficiency. A depiction of all three parameters, water use, daily cooling and cooling efficiency, is given in Figure 6.

4. Conclusions

Findings from the controlled experiment, which compares several fairly common 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. Despite the tendency of many researchers to focus on air temperature, it is radiant exchange that is often the dominant factor affecting thermal comfort in deserts (as in many other environments). Vegetation thus contributes to comfort not only by directly shading a person but also by reducing long-wave emission from courtyard surfaces and by limiting the amount of solar radiation reflected from them.

Acknowledgements

Limor Shashua-Bar was a Blaustein Fellow during her tenure at the Jacob Blaustein Institutes for Desert Research (BIDR) and was also supported by a fellowship from the Planning and Grants Committee of the Israel Council for Higher Education. Mr Wolfgang Motzafi-Haller was responsible for the preparation, installation and ongoing maintenance of the experimental instruments, and meteorological data from the adjacent weather station were provided by Mr David Klepatch of the Energy and Environmental Physics Department of the Blaustein Institutes for Desert Research. The authors are grateful to Prof. Pedro Berliner of the Wyler Department of Dryland Agriculture at the Jacob Blaustein Institutes for Desert Research for his assistance and insight over the course of the study and to Dr Shabtai Cohen from the Department of Soil, Water and Environmental Sciences at the Agricultural Research Organization, Volcani Center for his advice on the experimental setup and his help in applying the sap flow method of measuring evapotranspiration in trees (including instructions for building the sap flow probes, obtained from R. Oren of Duke University, USA and N. Phillips of Boston University, USA).

References

Alexandri E, Jones P. 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment* **43**: 480–493.

Ali-Toudert F, Mayer H. 2006. Numerical Study on the effects of aspect ratio and orientation on an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment* **41**: 94–108.

Ali-Toudert F, Mayer H. 2007. Thermal comfort in an east-west oriented street canyon in Freiburg (Germany) under hot summer conditions. *Theoretical and Applied Climatology* **87**: 223–237.

Bernatzky A. 1982. The contribution of trees and green spaces to a town climate. *Energy and Buildings* **5**: 1–10.

Bitan A, Rubin S. 1994. *Climatic Atlas of Israel for Physical and Environmental Planning and Design*. Ramot Publishing Company, Tel-Aviv University: Tel-Aviv.

Bonan GB. 2000. The microclimates of a suburban Colorado (USA) landscape and implications for planning and design. *Landscape and Urban Planning* **49**: 97–114.

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.

Bruins HJ, Berliner PR. 1998. Aridity, climatic variability and desertification. In: *The Arid Frontier: Interactive Management of Environment and Development*, Bruins HJ, Lithwick H (eds). Kluwer: Dordrecht.

Brutseart W. 1982. *Evaporation into the Atmosphere: Theory, History and Applications*. Kluwer Academic Publishers: Dordrecht, Holland.

Ca V, Asaeda T, Abu E. 1998. Reductions in air conditioning energy caused by a nearby park. *Energy and Buildings* **29**: 83–92.

Chen Y, Wong NH. 2006. Thermal benefits of city parks. *Energy and Buildings* **38**: 105–120.

Dimoudi A, Nikolopoulou M. 2003. Vegetation in the urban environment: microclimate analysis and benefits. *Energy and Buildings* **35**: 69–76.

Erell E, Williamson T. 2006. Simulating air temperature in an urban street canyon in all weather conditions using measured data from a reference meteorological station. *International Journal of Climatology* **26**: 1671–1694.

Ferguson BK. 2007. Water conservation methods in urban landscape irrigation: an exploratory overview1. *Journal of the American Water Resources Association* **23**: 147–152.

Gash JHC, Granier A. 2007. Granier (1985) – a new method of sap flow measurement in tree trucks. In: *Evaporation*, Gash JHC, Shuttleworth J (eds). IAHS Press: Wallingford; 61–63.

Givoni B. 1963. Estimation of the effect of climate on man – development of a new thermal index. PhD thesis, Technion-Israel Institute of Technology [in Hebrew].

Grimmond CSB, Isard SA, Belding MJ. 1992. Development and evaluation of continuously weighting mini-lysimeters. *Agricultural Forest Meteorology* **62**: 205–218.

Hoppe P. 1993. Heat balance modeling. *Experientia* **49**: 741–746.

Hoppe P. 1999. The physiological equivalent temperature- a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology* **43**: 71–75.

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.

Kenny NA, Warland JS, Brown RD, Gillespie TG. 2008. Estimating the radiation absorbed by a human. *International Journal of Biometeorology* **52**: 491–503.

Kremmer O, Galon I. 1996. *Water Consumption Coefficients for Gardening and Landscape Irrigation*. SHAHAM, Ministry of Agriculture: Israel [in Hebrew].

Meir I, Pearlmutter D, Etzion Y. 1995. On the microclimatic behavior of two semi-attached courtyards in hot dry region. *Building and Environment* **30**: 563–572.

Oke TR. 1989. The micrometeorology of the urban forest. *Philosophical Transactions of the Royal Society* **B324**: 335–349.

Onmura S, Matsumoto M, Hokoi S. 2001. Study on the evaporative cooling effect of roof lawn gardens. *Energy and Buildings* **33**: 653–666.

Pearlmutter D, Berliner P, Shaviv E. 2006. Physical modeling of pedestrian energy exchange within the urban canopy. *Building and Environment* **41**: 783–795.

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, Bitan A, Berliner P. 1999. Microclimatic analysis of 'compact' urban canyons in an arid zone. *Atmospheric Environment* **33**: 4143–4150.

Pearlmutter D, Krüger EL, 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.

Perry C. 2007. Efficient irrigation; inefficient communication; flowed recommendations. *Irrigation and Drainage* **56**: 367–378.

Potchter O, Cohen P, Bitan A. 2006. Climatic behavior of various urban parks during hot and humid summer Mediterranean city of Tel Aviv, Israel. *International Journal of Climatology* **26**: 1695–1711.

Rosenfeld AH, Akbari H, Bretz S, Fishman BL, Kurn DM, Sailor D, Taha H. 1995. Mitigation of urban heat islands: materials, utility programs, updates. *Energy and Buildings* **22**: 255–265.

Rosenfeld AH, Romm G, Akbari H, Pomerantz M. 1998. Cool communities strategies for heat island mitigation and smog reduction. *Energy and Buildings* **28**: 51–62.

Saito I, Ishihara O, Katayama T. 1990–1991. Study of the effect of green areas on the thermal environment in an urban area. *Energy and Buildings* **15–16**: 493–498.

Schiller G, Karchon K. 1974. Microclimate and recreational value of tree planning in deserts. *Landscape Planning* **1**: 329–337.

Shashua-Bar L, Hoffman ME. 2000. Vegetation as a climatic component in the design of an urban street: an empirical model for predicting the cooling effect of urban green areas with trees. *Energy and Buildings* **31**: 221–235.

Shashua-Bar L, Erell E, Pearlmutter D. 2009. The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape and Urban Planning* **92**: 179–186.

Shashua-Bar L, Hoffman ME, Tzamir Y. 2006. Integrated thermal effects of generic built forms and vegetation on the UCL microclimate. *Building and Environment* **41**: 343–354.

Spronken-Smith R, Oke TR. 1998. The thermal regime of urban parks in two cities with different summer climates. *International Journal of Remote Sensing* **19**: 2085–2104.

Spronken-Smith R, Oke TR, Lowry WP. 2000. Advection and the surface energy balance across an irrigated urban park. *International Journal of Climatology* **20**: 1033–1047.

Stabler LB, Martin CA, Brazel AJ. 2005. Microclimates in a desert city were related to land use and vegetation index. *Urban Forestry and Urban Greening* **3**: 137–114.

Takebayashi H, Moriyama M. 2007. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Building and Environment* **42**: 2971–2979.

Thorsson S, Lindberg F, Eliasson I, Holmer B. 2007. Different methods for estimating the mean radiant temperature in an outdoor setting. *International Journal of Climatology* **27**: 1983–1993.

