457: The Cooling Effect and Water Use Efficiency of Urban Landscape Strategies in a Hot Dry Climate

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Abstract

This paper describes a climatic analysis of landscape strategies for outdoor cooling in a hot arid region, accounting for the efficiency of water use. Six landscape strategies were studied, using different combinations of trees, lawn, and an overhead shade-mesh. The effects of these treatments were tested in two adjacent courtyards at Sde-Boqer, in the Negev Highlands of southern Israel, during summer (July-August). On average, air temperature in the non-vegetated exposed courtyard reached a maximum of about 34ºC in mid-afternoon. Compared to this base case, a configuration with shade trees and grass yielded a daytime temperature depression of up to 2.5°C, while shading the courtyard with a fabric shading mesh, counter-intuitively, caused a relative increase of nearly 1°C. Unshaded grass was found to provide only a small air temperature depression and had the highest water requirement. However when the grass was shaded, either by the trees or by the shade mesh, a synergic effect produced greater cooling as well as a reduction in total water use of over 50%. The "cooling efficiency" of these strategies was calculated as the ratio between the sensible heat removed from the space and the latent heat equivalent of the evaporated water. This measure is proposed as a criterion for evaluating landscape strategies in arid regions, where the water resource is scarce.

Keywords: Landscaping, cooling, efficient water use, hot arid regions

1. Introduction

Many studies have demonstrated the cooling effect of irrigated vegetation in urban open spaces, though usually irrespective of the cost of water. In hot arid regions, however, water availability is a limiting factor and must be considered.

Despite this limitation, outdoor evaporative cooling is becoming increasingly recognized as a means for moderating the urban heat island, reducing building energy demand and improving pedestrian comfort [1,2]. In many hot arid regions, intense solar radiation and high air temperatures have an impact on even the most basic human activities.

The landscape strategies examined in this study are based on irrigated grass and shade trees, which are compared with a dry overhead shading-mesh commonly used in public areas such as playgrounds. Several studies have indicated that vegetation moderates air temperature not only through shading and reduction of surface temperatures, but also due to evaporative cooling. The “Park Cool Island” (PCI) is a well-known phenomenon [3] by which vegetation in parks and streets generates localized cooling, with temperature reductions up to 3-4°C observed at mid-day during summer [4-8]. As opposed to shade trees, grass reduces temperatures mainly through evapotranspiration at ground level. Its ultimate contribution to thermal comfort may in fact be limited since it does not affect the incoming radiation, which has such a dominant impact on the daytime thermal stress in hot-dry urban spaces [9]. As an intentional design strategy, shading can be achieved not only by trees but also by shading elements such as a lightweight mesh. Such shading elements regulate not only solar radiation but also the evapotranspiration rate of plants under their shade, thus leading to potential water savings [10].

As indicated by the aridity index [11], the mean annual precipitation (*P*) in desert regions is significantly less than the mean potential evapotranspiration (*PET*), a condition that necessitates irrigation for urban landscaping. This study addresses the issue of water scarcity by focusing on the water consumption of several combinations of shade and vegetation, in relation to the cooling effect they produce in an urban context. The strategies studied here are compared by empirical measurements, and in a subsequent stage of the work these measured data are further interpreted using analytical models for microclimate and thermal comfort.

2. Methodology

2.1 Sites and Observations

The microclimate of open spaces within a complex urban setting is influenced by a variety of factors related to building geometry and surface properties, anthropogenic heat release, and vegetation [12]. This complexity makes it difficult to identify comparable urban sites in which the effects of individual parameters such as landscape treatments may be analyzed empirically. Comparisons are further complicated because the cooling effect of vegetation is interrelated with other building effects [13].

The present study addresses these problems by establishing a controlled experiment in two adjacent courtyard spaces, which are similar in their geometry and material attributes and differ only in their landscape treatments (Fig. 1).

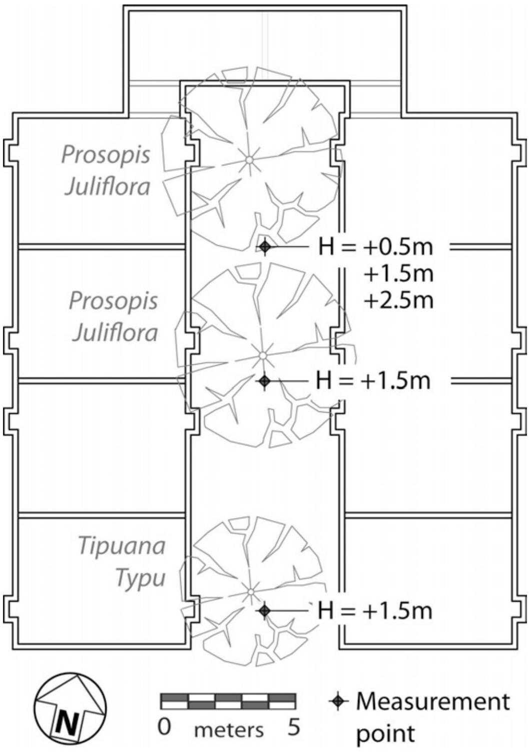

Fig 1. Courtyard plan showing measurement points (in both courtyards), and trees (in one courtyard only)

Six different landscape strategies were studied in the courtyards, using different combinations of trees, grass, and shade-mesh. The effects of these treatments were tested through on-site climatic monitoring in the courtyards, which are located at the Sde-Boqer campus in the arid Negev Highlands region of southern Israel (30.8 °N latitude, 500m altitude). The region is characterized by hot dry summers and cool, sunny winters [14]. One courtyard was planted with three existing shade trees, while the other was initially devoid of vegetation. Otherwise, the two elongated courtyards were similar in geometry, both orientated along an approximately N-S axis and with a H/W ratio of about 0.5 (Figs. 1-2).

Irrigated grass was introduced at different stages in each of the courtyards, and the space without trees was intermittently covered with a fabric mesh.

The six study cases are summarized in Table 1, and two of the cases, "Mesh-Bare" and "Trees-Grass", are illustrated in Figure 2.

Table 1: The six landscape strategies analyzed

		Ground surface	
		Bare	**Grass**
Top cover	**Exposed**	Exposed Bare	Exposed Grass
	Trees	Trees Bare	Trees Grass
	Mesh	Mesh Bare	Mesh Grass

Fig 2. Case study courtyards with bare pavement and shading mesh (top), and with grass and trees (bottom).

The bare ground in the two courtyards consisted of light grey concrete pavement (70% coverage) and 30% exposed soil. One of the courts had three trees along its length, two of which were *Prosopis-Juliflora* and the third *Tipuana Typu*. Both species are common in hot arid regions and are considered economical water consumers [15]. On a daily basis in summer, the water consumption coefficient (ratio to Class A pan evaporation) is 0.3 for of Tipuana Typu and 0.2 for the Prosopis-Juliflora. Both species have a medium leaf density that allows ventilation and sufficient solar penetration for the grass to grow in their shade. The fabric mesh was made from black polyester netting with a 70% opacity, providing a similar density of shade as the trees.

The grass subsequently planted in the two courtyards was Durban grass with a pan water consumption coefficient ranging from 0.4 to 0.55, depending on its maintenance. This type of grass was selected mainly for its ability to grow under heavy shade, with a minimum requirement of only three hours of direct sun a day. The grass sod units were placed on a polyethylene sheet covering 80% of the 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 for several hours at a time. Water sprinklers for the grass were located in each court and activated each morning at 6:00, for approximately 12 minutes. The two irrigation systems were programmed to provide each type of vegetation with enough water to allow unrestricted evapotranspiration.

The courtyards were monitored over a 45-day period during July-August 2007, by taking comprehensive measurements of climatic variables and of water consumption. Typical ambient temperatures during this period ranged from 20-33°C, with an average relative humidity of 35% at 14:00 and up to 90% at night. Wind speed ranged from a maximum of 6 m/s in late afternoon to a minimum of less than 1 m/s during the night. Prevailing wind directions ranged from north to northwest, with a light southwest breeze during early morning hours.

The two courtyards are protected from the dominant wind directions during the day, such that in the exposed court (without tree or mesh cover), wind speeds were reduced to about half of those in the surrounding open space.

Each landscape configuration was monitored for a period of at least 3-4 successive days. To account for minor differences in ambient conditions between periods, measured data were normalized relative to a common reference dataset. Courtyard air temperature at each given hour was adjusted proportionally based on the ratio between the simultaneously measured ambient temperature and the average ambient temperature for that hour over the entire study period. Water consumption was normalized for the same temperature ratios, as the rate of evapotranspiration under well-irrigated and calm conditions is mainly affected by solar radiation and ambient air temperature [16], and thus is proportional to their variations during the day.

2.2 Measurement setup

In each of the two courtyards, dry- and wet-bulb temperatures were measured using copper-constantan thermocouples in aspirated psychrometers at five observation points set up on instrument masts (maximum error estimated at 0.1 °C). For the horizontal profile, three points were situated along the long axis of the courtyard at a height of 1.5 m. On the "main" mast located midway between the two Prosopis-Juliflora trees, two more points were situated at different heights, creating a vertical profile from 0.5 to 2.5 m. Data were sampled at 10-second intervals and recorded as 10-minute averages using Campbell Scientific CR-21X dataloggers, and temperature trends were then processed as hourly averages.

Wind velocity was measured using a Campbell 014A cup anemometer (with a sensor accuracy of ±0.11 m/s) in the bare court, and with a Young 81000 ultrasonic anemometer in the court with trees. Surface temperatures of the various built and vegetated surfaces were measured in the two courtyards using shielded ultra-fine thermocouples and an IR thermometer.

Besides the *in-situ* measurements, climatic data corresponding to the measurement days were obtained from the nearby meteorological station for comparison and analysis purposes.

Water use for grass irrigation was estimated using custom-made mini-lysimeters, which were designed to ensure representative measurement of evapotranspiration (ET) from the grass-soil surface [17]. The instruments consisted of rectangular metal pans (5 x 10 x 3 cm), embedded in the grass-soil layer. The evapotranspiration rate was determined from the periodic change in the 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 [18]. The method uses pairs of cylindrical probes inserted in the sapwood, with the upper probe heated by the Joule effect at a constant rate and the lower (reference) probe unheated.[1] The overall estimate of representative tree transpiration was calculated from the average of three pairs of probes located in each tree at the same height (about 0.8 m), at equal intervals around the trunk.

3. Empirical Findings

The climatic effects of the landscape strategies studied were analyzed under relatively uniform building and environmental effects. The findings presented in this section focus on individual microclimatic parameters measured within the courtyards.

3.1 Air temperature pattern

Table 2 summarizes the air temperature data for the various landscape strategies at a height of 1.5 m, at hours representing early morning, noon, afternoon and night time. The data are normalized relative to the average of the measurement period (July 1 – August 15).

Table 2: Normalized air temperature [°C] for the six study strategies ("main" observation point, 1.5 m height), Sde-Boqer data, July-August 2007

Case study	600	1200	1400	2400
Exposed Bare	21.4	31.6	33.7	21.3
Exposed Grass	20.3	31.2	33.3	21.3
Mesh Bare	21.5	33.1	34.6	21.7
Mesh Grass	20.6	32.6	34.0	21.3
Trees Bare	21.2	30.8	32.0	21.8
Trees Grass	20.5	30.2	31.7	21.4

The strategy providing the greatest temperature depression (measured at 14:00) was the combination of trees over grass, which registered

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[1] The probes were built according to a method developed by Oren, Lab & Phillips (Duke University) and S. Cohen (Volcani Institute, Israel).

a maximum temperature of (31.7°C). The highest (normalized) maximum temperature was recorded in the mesh-covered courtyard ("mesh bare"), which at 34.6°C was nearly a full degree higher than the daily maximum in the same courtyard when exposed to the sky ("exposed bare"). The diurnal air temperature patterns of the six study strategies are illustrated in Figure 3. In the horizontal and vertical temperature profiles, only minor differences (up to 0.5°C at noontime) were found between the different locations and heights, indicating a high rate of mixing of air within the courtyards.

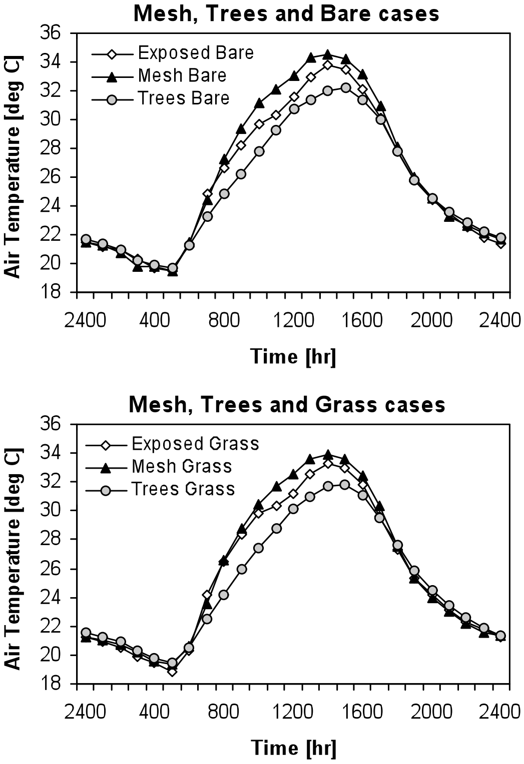

Fig 3. Normalized diurnal air temperature series for the six landscape strategies, "main" observation point, 1.5 m height

3.2 Humidity pattern

The relative humidity was typically about 35% at noon, rising up to 80-90% at night (with a vapour pressure range of 14-15 mmHg) in the exposed bare case. No noticeable differences in this humidity pattern were found among the different landscape strategies.

As with the air temperature profile patterns, only small differences were recorded for the horizontal and vertical profile of relative humidity and vapor pressure, which reinforces previous observations [5] that the effects of transpiration from trees are felt mostly immediately *above* the canopy rather than in the volume below.

3.3 Wind speed

Table 3 summarizes the average wind speed in the courtyards at a height of 1.5 m, for three situations in which the wind speed pattern changed significantly: the bare exposed court, the court with shade mesh coverage, and the court with trees. The data in Table 3 indicate that the shading strategies tend to reduce the wind speed inside the space substantially relative to that of the exposed court, by about 50% in the case of mesh coverage and by 80% in the case of trees.

Table 3: Normalized wind speed [m/s] in three courtyard situations ("main" observation point, 1.5 m height), Sde-Boqer data, July-August 2007

Case study	600	1200	1400	2400
Exposed Bare	0.4	2.5	3.1	1.0
Mesh Bare	0.3	1.1	1.3	0.4
Trees Bare	0.2	0.3	0.4	0.2

3.4 Ground temperature

An important element affecting both air temperature and human thermal comfort is the radiant temperature of solid surfaces within the courtyard. Table 4 summarizes the ground surface temperatures for the different landscape strategies. The main point to notice in this table is the high midday temperature of the pavement in the exposed bare court (reaching a maximum of 55°C), compared to the maximum air temperature of 33.5°C. The pavement temperatures under the mesh and under the trees are reduced substantially, reaching maxima of 39°C and 37°C respectively, while those for grass exposed and shaded under the mesh are about the same as the air temperature. The grass under the trees was much cooler – only 27°C.

Table 4: Normalized ground surface temperatures [°C] for the six study strategies ("main" location)

Case study	600	1200	1400	2400
Exposed Bare	21.9	52.8	54.5	24.1
Exposed Grass	18.7	37.6	35.7	19.8
Mesh Bare	23.2	36.6	39.4	24.7
Mesh Grass	19.6	31.6	33.3	21.1
Trees Bare	24.1	32.2	36.5	25.4
Trees Grass	20.2	26.8	27.4	21.0

4. Results and discussion

4.1 Cooling effect

The cooling effect is estimated firstly as the difference in air temperature between a given landscape strategy and that of the base case ("exposed bare"). These differences are shown in Fig. 4, which illustrates the diurnal pattern of these cooling effects. The negative sign indicates cooling and the positive sign indicates relative heating. It can be seen that the maximum cooling effect is reached by the strategy with trees over grass.

Compared to the base case, an average reduction of 1.7°C was observed in normalized T_{max} at 14:00 due to the shade trees, whereas the shade mesh, counter-intuitively, caused an increase in T_{max} of 0.9°C. The irrigated lawn reduced T_{max} by 0.5°C when added to the exposed courtyard, and contributed to a total reduction of 2.2°C when combined with the trees. The grass also reduced the relative heating effect of the shade-mesh to 0.2°C. Maximum cooling effects occurred at 10:00, reaching as much as 2.5 °C in the courtyard with trees and grass.

The mean daytime (6:00-18:00) cooling effect for the different treatments is shown in Table 5, which illustrates that while the purely vegetative strategies yield a net temperature depression (negative values), those incorporating the shade mesh lead to a net daytime *heating* effect.

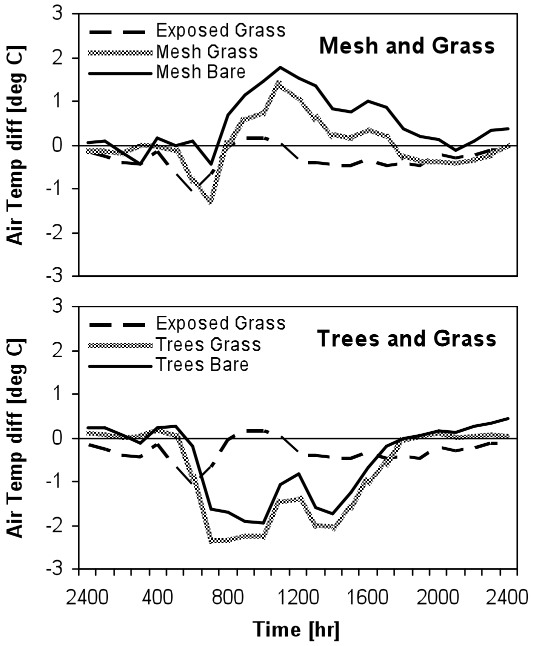

Fig. 4. Hourly air temperature differences between each treatment and the base case ("exposed bare")

4.2 Cooling with respect to water use

Compared to standard pan evaporation values recorded at the nearby meteorological station for the period of July and August, the water consumption values (evapotranspiration) of the trees studied are relatively low. For the Prospis-Juliflora, the ratio is 0.1, and 0.05 for Tipu-Tipuana, as compared to their "potential" pan coefficient of 0.2 and 0.3 respectively. The low coefficients may be due to trees young of age with a less developed canopy than of typical mature tree of the same species. As for the grass, when fully exposed its water consumption coefficient was found to be 0.55, which is within the range given in agricultural guidelines for the region [15].

Table 5 summarizes the total daily water use of the various landscaping strategies. It was found that under the given conditions in the courtyards, exposed grass requires a relatively large amount of water (5.71 kg/m²) while its cooling effect is negligible (0.3 ºC). Grass under trees required only 2.75 kg/m² per day, and when combined with the trees' transpiration (1.06 kg/m²), yields a total of 3.81 kg/m² day. Thus, adding trees over grass reduces the total water consumption of the vegetation when compared to exposed grass alone. A similar reduction appears in the case of the shade mesh over grass (3.76 vs. 5.71 kg/m²). The reduction in water use thus resulted in a saving of 34% in the case of grass under a shade mesh and of 52% under trees.

Adding shade not only reduced the water consumption of grass, but also increased its cooling effect, from 0.3°C (when used alone) to 0.5°C (when added under trees) and to 0.7°C (when added under the mesh).

The "cooling efficiency" of the landscaping strategies was calculated as the ratio between the sensible heat removed from the space (ΔQ_H) and the amount of water supplied to it, with the latter expressed as its equivalent latent heat of evaporation (ΔQ_E) – both given in MJ/m^2 (Table 5). The sensible heat was calculated from the difference in air temperature (with respect to the base case), its heat capacity, the volume enclosed by the courtyard walls and the volumetric exchange rate of the courtyard air (estimated as 20 ACH). The latent heat was calculated from the total amount of water (per unit of landscaped area) evaporated, estimated from the lysimeter and sap flow measurements, and the latent heat of vaporization.

It should be emphasized here that although the cooling efficiency is given as a percentage, the actual values are very sensitive to the assumption of 20 air changes per hour. The main benefit of using this indicator is therefore as a means of *comparing* the relative cooling obtained from evaporating a given amount of water in each of the different landscaping strategies – and *not* as an absolute datum.

It is clear from Table 5 that shade trees provide the highest cooling efficiency by far, and that shading can improve the cooling efficiency of grass, which is otherwise poor under the studied conditions.

Table 5: Cooling efficiency calculated for the six landscape strategies, based on the ratio between the daily average cooling effect and water use for the total daytime period (6:00-18:00), Sde-Boqer data, July-August 2007

Case study	**Cooling effect**		**Water use**		**Cooling efficiency** [%]
	ΔT [^oC]	**ΔQ_H** [kJ/m^2]	**ET** [kg/m^2]	**ΔQ_E** [kJ/m^2]	
(1) Mesh Bare	+0.9	+739	--	--	--
(2) Mesh Grass	+0.2	+178	3.76	6375	-2.8
(3) Trees Bare	-1.1	-960	1.06	1797	53.4
(4) Trees Grass	-1.6	-1333	3.81	6459	20.6
(5) Exposed Grass	-0.3	-289	5.71	9681	3.0
(2)-(1) Grass under mesh	-0.7	-561	3.76	6375	8.8
(4)-(3) Grass under trees	-0.5	-374	2.75	4662	8.0

5. Summary and conclusions

This study deals with empirical findings regarding the cooling effect and water use of six landscaping strategies in an arid region. The study introduces a criterion for judging the merits of a landscape strategy in an arid region by computing on a daily basis its cooling efficiency with respect to water consumption per unit of ground area.

The main findings are:

1. The combination of shade trees over grass was predictably found to be the most effective landscape strategy in terms of the cooling provided, with T_{max} reduced by up to 2°C.
2. Somewhat unexpectedly, a shade mesh providing the same amount of shade as the trees did not cool the courtyard air, but rather caused a noticeable heating effect (of up to 0.9 °C).
3. Planting grass gave very little cooling of the air above, yet consumed large amounts of water. Shading the grass, either by trees (preferably) or by a shade mesh, had the synergetic effect of increasing the cooling effect and reducing water consumption.
4. Both trees and mesh have the potential to improve outdoor thermal comfort in areas where they provide shade, as indicated by the fact that in both cases the surface temperature of the shaded ground was reduced substantially. Introducing grass under trees or under the mesh further reduces the ground temperature, thus contributing even more to thermal comfort.
5. Trees provide by far the most efficient means of reducing outdoor air temperature, relative to their water consumption. Adding grass resulted in only slightly more cooling, at the expense of much greater water consumption.

6. Acknowledgements

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