The Moderating Effect of Desert Ground Cover Plants on Pedestrian Thermal Sensation

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Pedestrians' thermal sensation is affected by their exchange of energy with their surroundings, mainly through radiation and convection. In the case of cities, the properties of ground-cover vegetation can have an important influence on this energy exchange, particularly in terms of radiation. Although vegetated surfaces have a low albedo, they can maintain lower temperatures than typical paved areas because they are cooled by evapotranspiration – which can be crucial in a desert environment. The purpose of this research is to examine the cooling efficiency of surface cover plants which are adapted to arid climates. The research site, in the Negev desert of southern Israel, consists of several small test plots with different species of succulents, creepers, grass, artificial turf and bare ground. Measurements of surface temperature and albedo provided input for comprehensive pedestrian thermal comfort modelling using the Index of Thermal Stress, assuming an open space scenario with various surface cover treatments. The results indicate great differences between the vegetated surfaces and the other surface treatments, and broad similarities between the cooling properties of the different plants. Differences in cooling efficiency, therefore, depend on the water requirements of the different species.

Key words: thermal stress, vegetation, desert, albedo, water requirement

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ABSTRACT: Pedestrians' thermal sensation is affected by their exchange of energy with their surroundings, mainly through radiation and convection. In the case of cities, the properties of ground-cover vegetation can have an important influence on this energy exchange, particularly in terms of radiation. Although vegetated surfaces have a low albedo, they can maintain lower temperatures than typical paved areas because they are cooled by evapotranspiration – which can be crucial in a desert environment. The purpose of this research is to examine the cooling efficiency of surface cover plants which are adapted to arid climates. The research site, in the Negev desert of southern Israel, consists of several small test plots with different species of succulents, creepers, grass, artificial turf and bare ground. Measurements of surface temperature and albedo provided input for comprehensive pedestrian thermal comfort modelling using the Index of Thermal Stress, assuming an open space scenario with various surface cover treatments. The results indicate great differences between the vegetated surfaces and the other surface treatments, and broad similarities between the cooling properties of the different plants. Differences in cooling efficiency, therefore, depend on the water requirements of the different species.

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INTRODUCTION

Vegetation has significant cooling properties which can contribute to human thermal comfort in the built environment [1, 2, 3]. However, effective use of urban vegetation to achieve desired microclimatic effects requires systematic study of the costs and benefits of different types of plants, seeking species that can contribute to human comfort with minimal strain on environmental resources. In this experimental study, surface cover plants with known irrigation requirements were examined in terms of their ability to contribute to improved thermal sensation in the built environment in a desert climate.

The geometry of the built environment creates microclimatic niches which have a direct effect on pedestrians. These niches may occur in street 'canyons' and they are influenced by radiant exchange, wind flow and surface materials [4, 5]. The radiant properties of surrounding surfaces is an important component in the overall sensation of thermal comfort, and this is expressed in the Index of Thermal Stress (ITS) – which was proposed by Givoni [6] and further developed by Pearlmutter et al. [5] to assess the thermal sensation induced in pedestrians by different urban environments. The ITS model is used in this study to assess possible differences in thermal stress engendered by different surface conditions. When solar radiation strikes a ground surface, some of it is reflected and some is absorbed in the material, depending on the surface albedo. The absorbed radiation heats the surface and some of this heat energy is emitted as long wave radiation. A pedestrian is exposed to both the reflected short-wave and to re-emitted long-wave radiation, which impose a thermal load on the body.

Integrating vegetation within the urban fabric may affect the modes of heat transfer and potentially moderate pedestrian thermal stress. The physical characteristics of vegetation can reduce surface reflectivity, while absorbing much of the short-wave radiation, which is converted into latent heat due to evapotranspiration – thereby reducing surface temperature and potentially also air temperature. Previous studies located in the Negev desert showed reduction of thermal stress [8, 9] and an increase in latent heat values [7]. However, while differences in the ITS between a vegetated and non-vegetated surface were significant, differences in air temperature throughout the day were less than 1°C [8, 9]. Moreover, a study located in a hyper-arid environment found that while subtropical irrigated vegetation reduced air temperature throughout the day, native vegetation had a mild cooling effect during the night and a warming effect during the day [10]. The process of evapotranspiration is of course dependent on the availability of water to sustain evaporation from the soil surface and transpiration from the plant leaves.

Plants in arid regions develop mechanisms to increase their water use efficiency (WUE) by closing their stomata during the day, and opening them during the night. This allows for the fixation of CO_2 without the losses of water, through a process called Crassulacean acid metabolism (CAM). Succulents are CAM plants which have adapted to aridity by preserving water in their thick leaves [11], and they are often recommended for use on green roofs as well as ground surfaces.

MATERIALS AND METHODS

The study made use of small test plots with several different types of plant species. Measurements of radiant surface temperature, short wave radiation balance (albedo) and water consumption were taken at the study site during the summer months. Hourly averages of relative humidity and direct and diffuse radiation were taken from an adjacent meteorological station. The data collected provided input for comprehensive microclimatic modelling of energy balance and pedestrian thermal stress in hypothetical urban spaces.

Selection of Plant Species

Six species of ground cover plants were selected (Table 1) according to their suitability for use in arid conditions. The choice was based on previous research [15] and local landscaping firms' experience: three succulent species and in addition one type of grass and two other creeping plants with relatively thin leaves, provided a broad comparison among different types of leaves and different evapotranspiration properties. In addition to the plants, an artificial turf and bare ground were examined.

Table 1: Characteristics of the plant species used for the experiment. Data for irrigation indicate the annual water requirement (mm) to complement an annual precipitation of 250mm in a semi-arid Mediterranean climate (Koepen BSh) [12, 13, 14].

Plant species	Origin	Life form	Irrig. (mm/year)
Aptenia *Aptenia Cordifolia*	S. Africa	succulent	200
Convolvulus *Convolvulus Arveuvnsis*	N. Africa	climber	350
Drosanthemum *Drosanthemum Hispidum*	S. Africa	succulent	< 200
Kikuyu grass *Pennisetum Clandestinum*	E. Africa	grass	1200
Lippia *Phyla Nodiflora*	Americas	creeper	>400*
Malephora *Malephlora Crocea*	S. Africa	succulent	100

*An estimated value based on local landscaping firms' experience.

Site Setup

The research was carried out at the Sde Boqer campus in the Negev. It consisted of six planted test plots, $4m^2$ each, and additional areas artificial plastic turf and bare ground for control measurements. The test plots were arranged in a row perpendicular to the prevailing north-west wind, and fully exposed to solar radiation all throughout the day in the summer (Fig 1). This setup allowed for a direct comparison among the plant species as they were all being examined under near-identical environmental conditions.

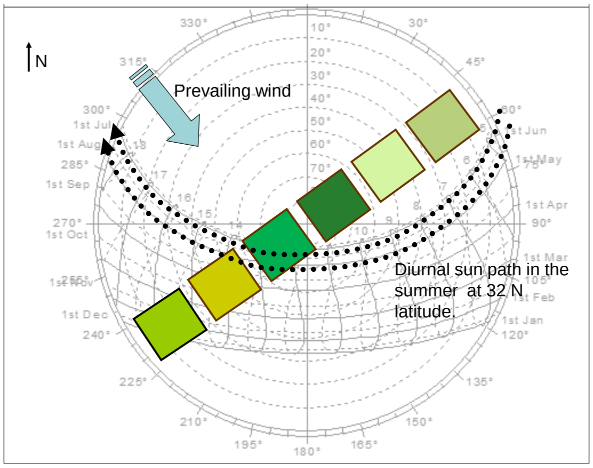

Fig 1: A diagram of the six planted test plots with respect to the prevailing north-west wind (thick arrow) and to sun position in the summer months, July and August (dotted arrows).

Measurements

Albedo - Albedo is defined as the ratio between incoming and reflected solar radiation. In order to assess the albedo of each planted surface in the experiment, two pyranometers (Kipp & Zonen) were attached opposite to one another: an upward-facing pyranometer was used to measure incoming global radiation and an identical downward facing pyranometer was used to measure reflected short wave radiation from each plot. The pyranometers were mounted above the center of the 2m x 2m plot, and moved between the plots every 2-3 days. An initial measurement height of 1m was used, but preliminary results indicated that more accurate results could be obtained by lowering this height and thereby reducing the effects of extraneous reflections from surrounding bare soil within the instrument's angle of view. Midday albedo averages (11:00-13:00) of each plot were calculated in order to highlight the critical effect of each surface cover.

Radiant surface temperature - The surface temperature of each plot was measured using a thermal imaging IR camera (LAND Infrared Ltd.) which senses the long wave radiation (L) emitted from the surface and provides a spatial mapping of surface temperature (T_s) according to defined emissivity values. The temperature calculation is based on the following equation:

$$L=\sigma\varepsilon T_s^4 \qquad [1]$$

Where σ is the Stefan-Boltzmann constant (5.67×10^{-8} W /m^2 K), and ε is the emissivity of the surface, which is provided as input for the camera. Images of each plot were taken three times a day (09:00, 13:00 and 16:00) during six representative days during July and August 2012. Surface temperature images were downloaded using 'WIN-LIP' software (LAND Infrared Ltd.). Data in each image were analyzed by using three representative rectangular areas to give an average temperature of 1) the whole plot area; 2) a fully vegetated patch; and 3) a bare soil patch. Comparisons were made to assess the specific differences of the albedo and surface temperature as independent parameters.

Ambient conditions - Weather data including ambient dry bulb temperature (ultrafine thermocouple) and wind speed (Met-One cup anemometer, 1.5m above ground) were measured continuously throughout the experiment and compiled using a Campbell 23x data logger. These variables are not significantly affected by the presence of irrigated ground-cover vegetation when measured at screen height within defined urban spaces [9]. Data of relative humidity and diffused radiation were taken from a local meteorological station [17].

Thermal Sensation Model

The measured raw data, supplemented by climatic data from the local meteorological station [17], was fed into an energy exchange model [5], which computes the total radiation balance between a standing, rotationally-symmetric pedestrian and the surrounding space. In order to isolate the effects of variations in exposed ground surface properties, the geometric attributes in this experiment were defined to represent a space with negligible building height relative to its width.

The output of the model is an energy value (W) based on the equation:

$$ITS = (M-W+R_n+C)/f \qquad [2]$$

Where R_n is the net radiation, C is convection, M-W express the body heat by its metabolism and its work and f is the efficiency of sweat evaporation [5, 9]. The ITS expresses the equivalent latent heat of sweat evaporation (in watts) that is required to maintain thermal equilibrium between the body and the environment under warm conditions. In addition to the energy values, the ITS model correlates with a subjective thermal sensation scale based on data from surveys. A "comfortable" zone defines a total energy flux of <160W between a pedestrian and the environment. Between 160-480W the sensation is defined as "warm" and between 480-800W it is "hot". Over 800W the sensation definition is "very hot" [16].

RESULTS

Albedo - Measurements of albedo and surface temperature were taken during the summer months (2012). Average mid-day albedo results (Fig. 2) indicate similarities between the vegetated plots, ranging between 0.26-0.27 in all cases, compared with a slightly lower value of 0.24 for artificial turf. These values may be compared with the significantly higher albedo of 0.39 for bare loess soil.

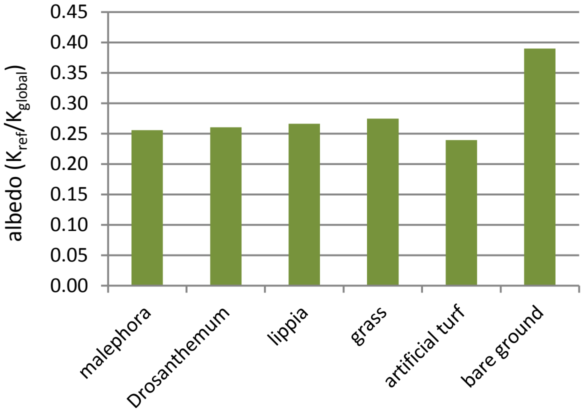

Figure 2: Mid-day average albedo in each plot, as measured during July-August 2012.

Surface temperature - Surface temperature images were taken from each plot on different dates. Some plots took longer to reach a full surface cover along the experiment period. An interesting scenario was demonstrated on the slower growing plants. The thermal images enabled to use surface temperature data from surfaces which were not fully covered, and evaluate the negative contribution of bare spots. Figure 3 gives an example for surface temperature differences which can reach over 20°C. The bare spots can affect the total surface temperature significantly. While the temperature of a random vegetated area (2) is 38.4°C, with some additional bare spots the total surface temperature (1) can rise up to 42.1°C. The surface temperature values which were used for the ITS were from the fully vegetated areas.

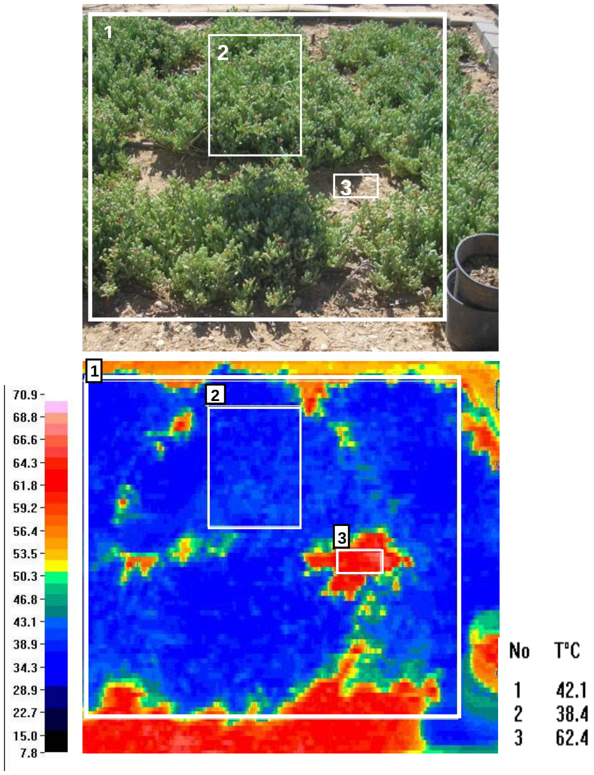

Figure 3: The malephora plot on 27/8/2012 midday (top). A thermal image (bottom) of the plot on the same day with three rectangles demonstrating the average temperature on a: (1) the entire plot, (2) vegetated area, and (3) bare area.

Surface temperatures of the different plants were broadly similar (Fig. 4), but the temperatures of the three succulents were higher than the *kikuyu grass* and *lippia* by 3-5°C at midday. Bare ground temperature was some 20°C warmer, reaching over 55°C, and the artificial turf mat measured over 70°C in the middle of the day.

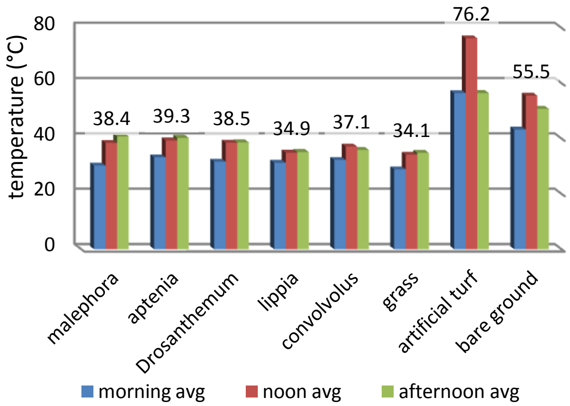

Figure 4: Average temperatures (°C) of each planted surface, as measured during July-August 2012 in the morning, at noon and in the afternoon. Labels refer to noon averages.

Thus both the albedo and surface temperature results show significant differences between vegetated ground cover and bare soil or artificial turf. However, initial results indicate broad similarities between the cooling properties of the different plants, despite the significant differences in their water requirement.

Index of Thermal Stress

The computerized model was run with hourly data from three representative days. An average thermal stress (W) of the three days indicates close similarities between the trends of all the vegetated surfaces with no significant differences (Fig. 5). The results show that in Sde Boqer, a person standing on a vegetated surface in an open space in the summer will be warm for most of day, except from 13:00-16:00 when the ITS rises over 480W, which is defined as hot.

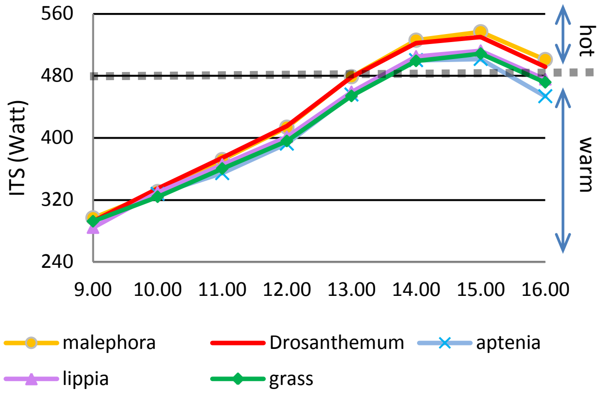

Figure 5: ITS results presented as the change of energy flux throughout the day, comparing five different vegetated surfaces. The arrows on the right indicate thermal sensations.

Figure 6 presents the average trend of all the vegetated surfaces in comparison to bare ground and artificial turf. Unlike people standing on a planted surface, who are exposed to 'hot' conditions for only three hours, people standing on bare ground or on artificial turf, which are not cooled by evapotranspiration, will be exposed to thermal stress exceeding the 480W threshold for most of the day, from between 9:00 and 10:00 in the morning until well after 16:00.

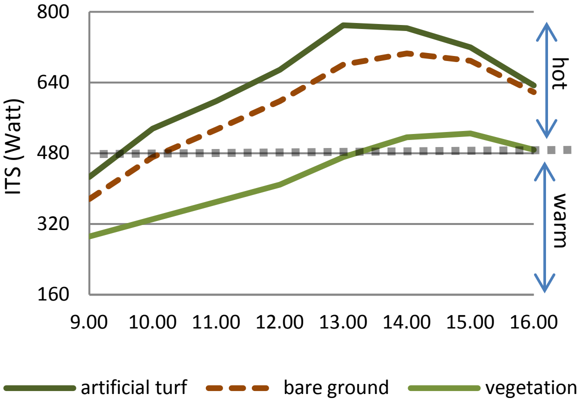

Figure 6: ITS results presented as the change of energy flux throughout the day, comparing vegetated surfaces to artificial turf and bare ground over the course of the summer daytime hours. The arrows on the right indicate thermal sensations.

DISCUSSION

The analysis above accounts for the effect of vegetation on thermal stress that is manifested through radiant exchange: Vegetated surfaces have a very low albedo, but are also cooler than most other surfaces: Thus they reflect less solar radiation but also emit less infrared radiation. It is important to mention that the artificial turf measured in this study was detached from the surface it was laid on. This may have affected the extremely high temperatures records as the turf itself consists of a fairly thin and dark polymer with very low thermal mass. However, vegetation also has an indirect effect on thermal comfort, if evapotranspiration results in lower air temperature and higher humidity. The magnitude of this effect has been variously estimated at 0.5 degrees to 3 degrees or more [8, 10].

Although it may be assumed that plants that require extensive irrigation have a greater effect on air temperature and moisture than water conserving varieties, it was not possible to measure this effect directly in the small vegetated plots established for the experiment. The potential effect of such modification on thermal stress was thus analysed numerically, assuming that differences among different cover plants could lead to adiabatic cooling of 2°C, though in reality, such differences are most likely much smaller. Table 2 shows the effects on thermal stress from a temperature reduction of 2 degrees and a concurrent increase in humidity, resulting from evapotranspiration at a grass-covered surface. Although a 2°C decrease in air temperature due to evaporation is rather high, the resulting reduction in thermal stress is fairly modest - only 40-50W- compared to differences of 200-300W between vegetated and non-vegetated surfaces (Fig. 6).

Table 2: ITS calculated for a grass surface cover based on hourly data from August 13, 2012 and a hypothetical evaporative cooling of 2°C *with a concurrent increase in RH.*

	hourly data (13/8)			DBT reduction (-2°)		
time	DBT (°c)	RH (%)	ITS (W)	DBT (°c)	RH (%)	ITS (W)
10.00	33.1	25.4	370	31.1	31.1	336
11.00	34.6	21.8	388	32.6	27.0	348
12.00	36.0	21.2	414	34.0	26.0	369
13.00	36.8	18.4	467	34.8	22.8	418
14.00	37.8	18.1	516	35.8	22.2	467
15.00	37.7	20.5	510	35.7	25.0	457
16.00	36.3	24.0	430	34.3	29.1	379

SUMMARY OF THE FINDINGS

Vegetation can be a valuable contributor to human outdoor thermal comfort, and the ground surface cover component has great importance. As shown, a planted surface can reduce the energy load on a pedestrian by over 200W compared to bare ground. The water-saving alternative of artificial turf is seen to be problematic, with differences of up to 300W between real grass and artificial turf at mid-day. The different types of vegetation cover did not reveal any significant differences at this stage of the analysis. Albedo measurements were all over 0.25 and midday surface temperatures (under full exposure to summer sun) ranged between 34°-39°C, while the succulents were at the top of this range and grass was at the bottom. The primary contribution of cover plants to thermal comfort is manifested through radiant exchange rather than a reduction in air temperature. Despite differences among plants in irrigation requirements, their contribution to thermal comfort is similar.

CONCLUSIONS

The main goal of this study was to assess whether ground-cover plants other than typical grass lawns can contribute to a meaningful improvement in thermal comfort, despite their significantly lower water requirements. The results show that differences in the effect of cover plants on thermal sensation are small, and hardly reflect the fact that the nominal water requirement of grass (which is irrigated by sprinklers) is several times higher than that of the other species (all of which are drip-irrigated). This means that in terms of "cost-benefit", succulents may be expected to have a higher cooling efficiency than *kikuyu grass* or *lippia*. Additional experimentation will include detailed measurements of evapotranspiration in order to compare the irrigation requirements of the selected plant types and to confirm the validity of recommendations provided by local landscape developers and gardeners.

ACKNOWLEDGMENTS

The study is funded by the Badler Fund for Desert Architecture. A preliminary survey of desert plants was conducted at the Arava Institute (AIES) under the guidance of Dr. Eli Groner. The first stages of the experiment were assisted by Ms. Yeela Gundar. The study made use of the professional gardening consultancy and assistance of Mr. Gilead Michaeli. A very big thanks to Mr. Wolfgang Motzafi-Haller who was responsible for all the technical work and maintenance and contributed valuable knowledge and ideas.

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