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Research paper

The moderating effect of water-efficient ground cover vegetation on pedestrian thermal stress

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HIGHLIGHTS

- We examine the effect of different ground cover plants on pedestrian thermal stress.
- Thermal differences between different plant types are small compared to dry surfaces.
- Non-succulents are slightly less stress-inducing but with higher water requirements.
- Succulents are more efficient in terms of their ratio between cooling and irrigation.

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ABSTRACT

The level of thermal stress experienced by pedestrians in an urban environment is affected by their exchange of energy with their surroundings, and 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 and thus absorb a large part of the solar radiation incident upon them, they can maintain lower temperatures than typical paved surfaces because they are cooled by evapotranspiration. The purpose of this research is to examine the cooling effect of "succulent" surface cover plants that are adapted to arid climates, in comparison to plants such as grass that require substantially more irrigation. The research site, in the Negev desert of southern Israel, consists of several small test plots with different species of succulents and other plants, along with dry ground surfaces. Measurements of surface temperature and albedo provide input for comprehensive pedestrian thermal comfort modeling using the Index of Thermal Stress, assuming an open space scenario with various surface cover treatments. Water requirements of the different plant are examined through an irrigation experiment. Results indicate that although there are thermal differences between the different plant types, these differences are small when compared with non-vegetated surfaces. While the non-succulents are slightly cooler and less stress-inducing than the desert-adapted plants, their water requirements are higher, making them less efficient in terms of the ratio between cooling "benefits" and water "costs"—both of which are expressed in terms of their equivalent energy.

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1. Introduction

Ground-cover vegetation has significant thermal benefits that can contribute to human comfort in the built environment (Oke, 1987; Bonan, 2000; Arnfield, 2003; Home, Bauer, & Hunziker, 2009; Erell, Pearlmutter, & Williamson, 2011). However, the effective use of urban vegetation to achieve desirable 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.

This is especially true in hot-arid regions, where climatically harsh conditions are intensified by local heat islands and compounded by regional and global changes. These effects can make outdoor activity thermally stressful and deepen residents' reliance on energy-intensive air conditioning in buildings and vehicles. Plants may contribute to climatic moderation, but water scarcity and difficult urban growing conditions highlight the importance of 'efficient' solutions that provide maximal environmental benefit with minimal use of scarce natural resources. There is a particular need to understand the role of surface cover plants that are used extensively in urban landscaping, in terms of both their ability to

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contribute to the reduction of thermal stress on a pedestrian and their irrigation requirements in a hot-arid environment (Potchter, Goldman, Kadish, & Iluz, 2008).

The properties of vegetated surfaces in the built environment create microclimatic niches which have a direct effect on pedestrians (Erell & Williamson, 2006). These niches occur in spaces such as streets or parks (Shashua-Bar & Hoffman, 2000; Potchter, Cohen, & Bitan, 2006), where radiant and convective energy exchanges impact the level of thermal stress to which a pedestrian's body is exposed, and in turn influence the degree of thermal discomfort which is perceived (Pearlmutter, Berliner, & Shaviv, 2007).

1.1. Indices of thermal stress

Different indices have been developed to assess the thermal environment experienced by a person. For example, the Physiological Equivalent Temperature (PET) model developed by Höppe (1999) represents the hypothetical air temperature under standard indoor conditions which would produce a level of heat exchange between the body and the environment that is equivalent to what occurs under the given conditions. A similar approach is taken in the Universal Thermal Climate Index (UTCI), defined by Jendritzky, de Dear, and Havenith (2012) as "the air temperature of the reference condition which would elicit the same dynamic response (strain) of the physiological model as the actual conditions". A central component of these indices is the Mean Radiant Temperature (T_{mrt}), which encapsulates the effects of radiation received by a person from multiple sources in the surrounding environment – and which can be difficult to quantify in a complex urban setting (Kántor & Unger, 2011; Pearlmutter, Jiao, & Garb, 2014).

The widespread use of thermal indices that characterize the environment in terms of an "equivalent temperature" has an intuitive logic, given our familiarity with degrees on a temperature scale as a measure of thermal states. At the same time, it is important to remember that the human body's thermal endings are not in fact sensors of temperature—but rather of heat flow, monitoring the rate of heat gain or loss from the body due to radiation, convection and evaporation (Heschong, 1979). When analyzing the thermal impacts of physical design attributes such as spatial geometry or surface cover materials, it is useful to separate these individual channels of energy exchange in order to understand their relative contribution to the microclimate which is sensed by an occupant of the space (Erell, Pearlmutter, Boneh, & Bar (Kutiel), 2014).

An alternative approach for assessing the thermal environment that recognizes and responds to these considerations is to model the man-environment energy balance directly—using the Index of Thermal Stress (ITS). Rather than attempting to portray the combined effects of climatic variables (including direct and indirect solar radiation, terrestrial and atmospheric long-wave radiation, the heat and water vapor content of the surrounding air, and the rate at which it flows) as a single point on an imaginary thermometer, the ITS is based on an accounting of the individual energy exchanges between a pedestrian's body and the surroundings (Givoni, 1963). The index is expressed in watts, rather than degrees, and essentially defines the rate of thermal regulation that is physiologically required for the body to maintain thermal equilibrium with the environment (Pearlmutter et al., 2007).

Calculated values of the ITS, based on measurements in a series of open spaces, have been found to correlate closely with subjective thermal sensation as expressed in questionnaire responses by pedestrians in the same set of locations. A study in the hot-arid Negev region of Israel (Pearlmutter et al., 2014) employed micrometeorological measurements to derive ITS in a series of urban spaces, and compared the results with those of a simultaneous survey in which the occupants of those spaces reported their level of thermal sensation on a 7-point scale ranging from "very cold" to "very hot." ITS alone was found to account for nearly 60% of the variance in pedestrians' thermal sensation, and over 70% was accounted for by models that included contextual variables in addition to ITS. The findings indicated that pedestrians experiencing variable outdoor conditions have a greater tolerance for incremental changes in thermal stress than they do under controlled indoor conditions, with a tapering of responses at high values of ITS. However, the thresholds of ITS corresponding to thermal 'neutrality' and thermal "acceptability" appeared to be quite consistent regardless of context. A subsequent study by Saaroni et al. (2015) compared thermal conditions and perceptions in a Mediterranean coastal park, and even despite the differences in the physical setting found a remarkably similar relationship between ITS and thermal sensation. In both cases, the increment of ITS producing a change of one level on the thermal sensation scale was equal to about 320 W, and in both cases the "neutral point" on the sensation scale corresponded with a physical situation in which the dissipation of heat from a person's body was precisely in balance with that person's internal metabolic heat production (ITS = 0). Thus while personal and experiential factors were clearly seen to have an impact on thermal perception, the basic utility of ITS for predicting thermal sensation and thermal neutrality was reinforced under in a variety of different circumstances.

At the same time, it should be emphasized that the sensation of thermal "neutrality" is not necessarily considered synonymous with a feeling of thermal "comfort." Empirical research over several decades has indicated that the experience of comfort is strongly related to people's expectations, and is often associated with relief from *un*comfortable conditions rather than simply a lack of hot or cold stimuli (Auliciems 1981; Fountain, Brager, & de Dear, 1996; de Dear & Brager, 1998). For example, Zhang and Zhao, 2008 found that while thermal acceptability and comfort are indeed correlated with thermal neutrality under uniform conditions, this is not the case when individuals are exposed to non-uniform stimuli over different parts of the body—as is often the case in an outdoor setting. Given the rapidly-changing, or 'transient' nature of the thermal environment in such spaces, a person may continuously alternate between a state of thermal comfort and discomfort (Hensen 1990). Thus while the ITS has been shown to be a good predictor of thermal sensation under outdoor conditions, such indices are undoubtedly limited in their capacity to predict what a particular person may prefer at a given time and place.

1.2. Thermal stress and vegetation

Shashua-Bar, Pearlmutter, and Erell (2011) made use of the ITS model in an experimental study to analyze the thermal effects of shade trees and grass in two semi-enclosed courtyard spaces, and to evaluate the "cooling efficiency" of irrigated landscaping by comparing its potential to reduce bodily heat gain with the water it requires for irrigation. The study showed that a grass-covered ground surface can significantly lower a pedestrian's level of thermal stress under hot summer daytime conditions, due to a combination of two mutually-reinforcing factors. On the one hand, its albedo is lower than that of typical paved surfaces or bare soil, and therefore reflects less short-wave radiation onto a person's body. On the other hand, this preferential absorption of sunlight is largely channeled into the release of latent heat through evapotranspiration rather sensible heat, and thus a green lawn tends to maintain a low surface temperature and emit less long-wave radiation. These processes change the fundamental energy balance of the surface, at the local and even the urban scale (Sailor, 1995; Santamouris, Synnefa, & Karlessi, 2011;Santamouris et al., 2012; Li, Harvey, & Kendall, 2013). However, this enhanced "cooling" performance must be maintained by replacing large quantities of water lost through transpiration. In a hot-dry atmosphere, the irrigation

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