Watts in a comfort index: Evaluating pedestrian energy exchange and thermal stress in urban environments

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1. Introduction

The thermal environment that is experienced by pedestrians in cities is commonly, and habitually, described in terms of *temperature*. In some cases it is the near-surface air temperature that is used, and in others it is a mean radiant temperature, often embedded within a physiologically equivalent temperature or similar comfort index which is used to quantify, in degrees on a temperature scale, the thermal effects of the environment on a person.

While temperature is indeed our most familiar and intuitive measure of thermal states, 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 (and to a lesser extent, conduction).

This paper describes the validation and implementation of an alternative approach for assessing the thermal environment in urban spaces, using the Index of Thermal Stress (ITS). Rather than attempting to portray the effects of sun, wind, temperature and humidity as a single point on an imaginary thermometer, the ITS is based on an assessment of the individual energy exchanges between a pedestrian's body and the surroundings – expressed in *watts* – and the physiological response that is required for the body to maintain thermal equilibrium.

2. The Index of Thermal Stress

In outdoor environments, radiation fluxes often dominate the energy balance of the human body – especially solar radiation under clear daytime conditions. Rather than expressing these radiant energy fluxes as an "equivalent" mean radiant temperature, they may be calculated directly as flux density values, in watts per square meter of the body surface. In this way, they may be quantified in the same units as heat exchange by convection, which is a function of the speed at which air flows across the body and the temperature difference between the two. A thermal index that is based on a direct energy balance of this sort is the Index of Thermal Stress (ITS), which expresses the equivalent latent heat of sweat evaporation required for the body to maintain thermal equilibrium under warm environmental conditions. This index incorporates a direct calculation of all components of the energy balance, including short- and long-wave radiation, convection and metabolic heat production (in watts for the entire body). An important physiological aspect of the model is the recognition that not all sweat evaporates, and thus a sweat efficiency factor is included to express the limitation imposed on evaporative cooling of the body due to humidity. The index, originally developed by Givoni (1963) and adapted for urban spaces by Pearlmutter et al. (2007), may be computed (in total watts) as:

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

where R_n and C are energy exchanges due to net radiation and convection between the human body and the environment, M is the body's internal metabolic heat production, and f is a sweat efficiency factor. As seen in Figure 1, the exchange of energy through radiation and convection is typically calculated in W m^{-2} of body surface for a rotationally symmetrical person standing upright in given space (Pearlmutter et al. 1999; 2006). Net radiation R_n consists of short-wave components which are received as direct radiation from the sun (K_{dir}), diffuse from the sky (K_{dif}) and reflected from horizontal ground (K_h) and vertical surfaces (K_v), as well as long-wave radiation absorbed from the sky and other downward-radiating elements (L_d) and from horizontal ground surfaces (L_h) and vertical wall surfaces (L_v), and emitted to the environment by the body as a function of the skin-clothing surface temperature (T_s).

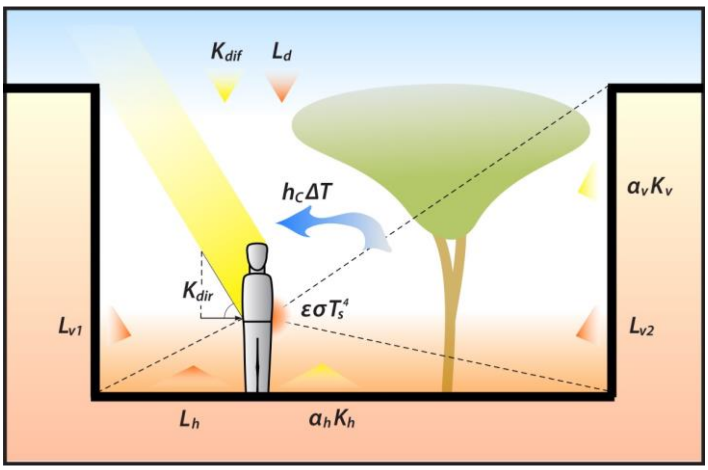

Figure 1. Schematic depiction of pedestrian energy exchanges in an urban space, for calculation of ITS.

The absorption of short-wave radiation is based on the measured intensity of incoming global radiation, incidence angles for direct radiation, angular view factors for indirect (diffuse from the sky and reflected from the ground) radiation, and the measured albedo of surrounding surfaces and of the body itself. Long-wave absorption from these surrounding surfaces is calculated on the basis of view factors, empirically measured (or estimated) surface temperatures, and emissivity values for the relevant materials, while emission from the body is typically based on a constant skin-clothing temperature of 35°C. The emission of downward long-wave emission from the sky dome is calculated from sky emissivity (as estimated from air temperature, humidity and clearness) and sky view factors. Each long-wave flux L (W m^{-2}) is computed as $L=\sigma\varepsilon T^4$ where σ is the Stefan-Boltzmann constant, ε is the emissivity of the emitting body and T is its temperature in Kelvin. A detailed description of the calculation of individual radiation components is given by Pearlmutter et al. (2006).

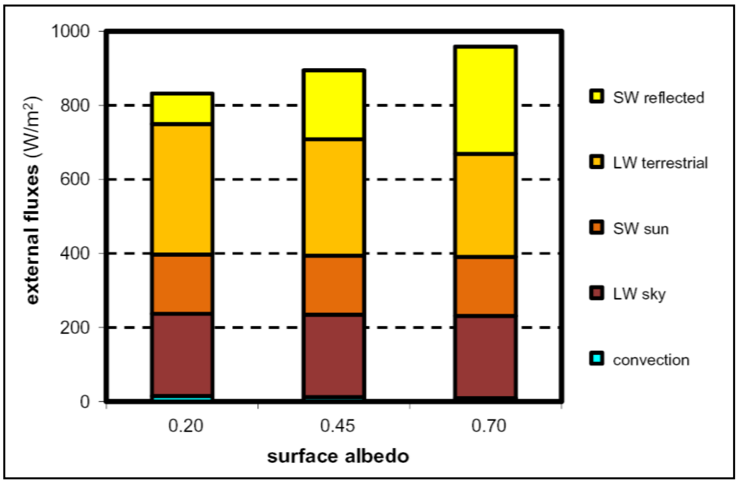

Figure 2. Breakdown of flux components and their variation with the albedo of surfaces surrounding a pedestrian in an urban space (Erell et al. 2014).

Energy exchange by convection C is calculated from the difference in temperature between the skin and the surrounding air, and a heat transfer coefficient which is an empirically-derived function of wind speed. To calculate the overall energy balance, radiative and convective flux densities in W m^{-2} are multiplied by the DuBois body surface area to yield fluxes in watts, to which is added the body's net metabolic heat production. The sweat efficiency f is calculated from an empirical relation based on the vapor pressure of the surrounding air (as well as wind speed and a clothing coefficient), as detailed by Pearlmutter et al. (2007).

One of the advantages of this modeling approach is that the relative impact of each individual flux on overall thermal stress can be evaluated separately. As illustrated in Fig. 2, for example, it is possible to evaluate the influence of variations in urban surface albedo not just on overall pedestrian thermal stress, but on the body's differential exposure to reflected short-wave and emitted long-wave radiation. This contrasts with the approach commonly taken when computing a thermal comfort index based on the mean radiant temperature, which is often measured with a globe thermometer and which aggregates the effects of solar and long-wave components into a single temperature value.

3. Correlation of ITS with subjective thermal sensation

In earlier studies, the pedestrian energy exchange model described above was used to examine the effects of urban street canyon geometry based on measurements in a compactly built residential neighborhood (Pearlmutter, 1999), and using an Open-Air Scaled Urban Surface (OASUS) model (Pearlmutter et al., 2006; 2007). The latter was subsequently used to analyze the effects of urban evaporation, and full-scale measurements were performed to gauge the effects of trees and grass on ITS in urban spaces (Shashua-Bar et al., 2011). In these studies, a correlation was introduced between the biophysical measure of ITS and a subjective measure of perceived thermal sensation, based on previous climate chamber experiments by Givoni (1963). While this provided a familiar "comfort scale" (ranging from "very cold" to "very hot") by which to evaluate the degree of thermal discomfort embodied in a given rate of energy exchange, it was calibrated using human subjects who were expressing their responses under controlled indoor conditions.

Figure 3. One of a series of urban open spaces used to compare biophysical thermal stress with subjective thermal sensation as perceived by pedestrians (Pearlmutter et al. 2014).

In an open urban environment, air flow and radiant fields may fluctuate rapidly and pedestrians' comfort expectations may differ markedly from those of occupants inside a room. Therefore we also examined the relationship between *outdoor* bioclimatic thermal stress and subjective thermal sensation, by comparing the results of physical environmental measurements and perceptual surveys conducted jointly in a series of urban spaces (Fig. 3) in a hot-arid climate (Pearlmutter et al. 2014). The micrometeorological data served as input for calculating the ITS in these spaces, while the Physiologically Equivalent Temperature (PET) was also derived as a comparative index. Simultaneously with the measurements, questionnaires were distributed to pedestrians in the urban spaces in order to gauge human perceptions of varying thermal stimuli.

The values of both ITS and PET were then compared with subjective thermal sensation votes, to examine the relationship of perceived comfort with these physical indices. An additional series of statistical analyses tested the degree to which behavioral and contextual variables could improve the predictive power of ITS.

The observed values of ITS were found to correlate fairly well with subjective thermal sensation, explaining nearly 60% of the variance in comfort vote responses (Fig. 4, left). It was found that the "neutral point" on the thermal sensation scale (with a value of 4, or "comfortable"), corresponded in a variety of different circumstances to 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). This finding reinforces the underlying premise of the model, which stipulates that people tend to feel most comfortable when their body is in thermal equilibrium with the surrounding environment. While the slope of the regression line is shallower than that found previously using climate chamber observations, the basic transition from category 4 ("comfortable") to category 5 ("warm") remained at a value of about 160 W – suggesting that while people's sensitivity to increasingly high heat stress is lower outdoors than indoors, their basic comfort threshold is largely consistent.

It may be seen in Fig. 4 (right) that PET values also correlated reasonably well, explaining over 50% of the variance in perceived thermal sensation. It should be emphasized that for the computation of PET using *RayMan* (www.urbanclimate.net/rayman), values of mean radiant temperature (T_{mrt}) were externally calculated from measurements with small gray-bulb globe thermometers, that were calibrated with precise wind speed measurements using a hot-wire anemometer adjacent to the globe. It was found that T_{mrt} is extremely sensitive to variations in wind speed, and can be decisively affected by the thermal inertia of the instrument. For the computation of ITS, this sensitivity was found to be more moderate since radiation fluxes were calculated individually from measured surface temperatures (for LW) and pyranometer readings (for SW) using the relevant thermal and optical properties of surrounding surface materials, and convective exchanges were calculated from in-situ measurements of wind speed and air temperature (for more detail see Pearlmutter et al. 2014).

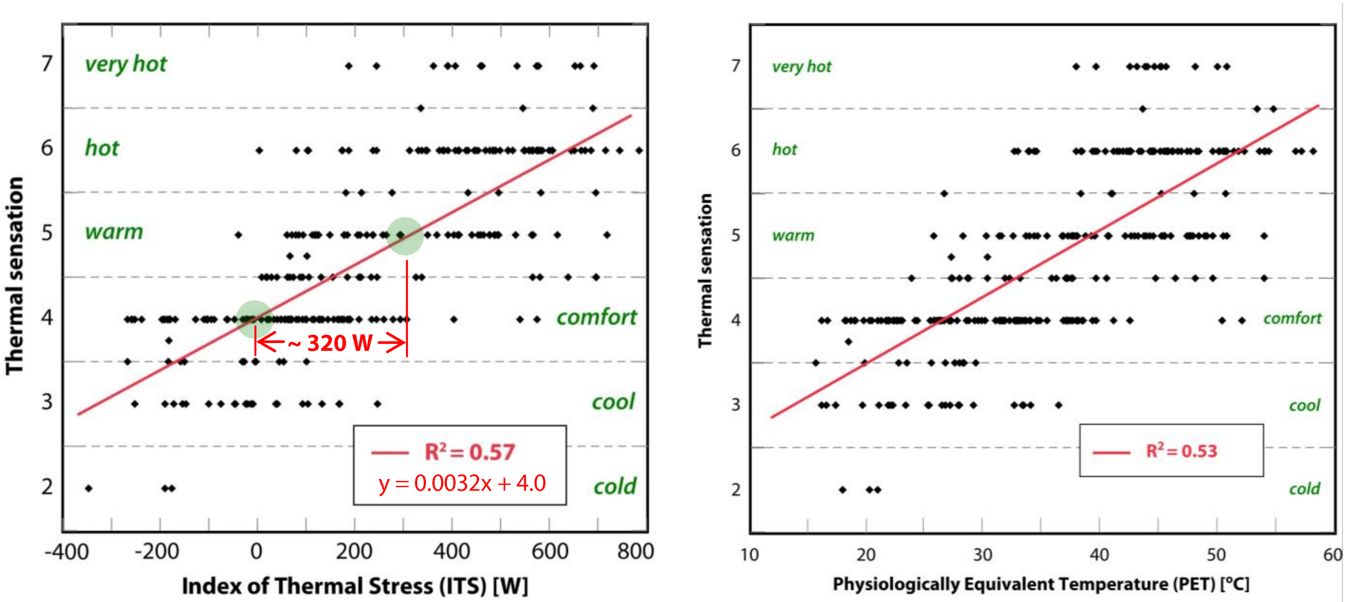

Figure 4. Correlation between perceived thermal sensation with ITS (left) and with PET (right). For more detail see Pearlmutter et al. (2014).

Through multivariate regression analysis, a number of personal and contextual factors were also found to impact thermal sensation, and when these factors were combined with ITS, the model was able to explain up to 70% of the variance in comfort responses.

Due to the unpredictable nature of personal factors like previous activity or long-term acclimation, it is useful to consider the *probability* that a certain value of environmental thermal stress will produce a given level of perceived thermal sensation. A probability distribution of this sort is shown in Fig. 5, and it can be seen that the thresholds between thermal sensation categories are similar but not identical to those derived by simple linear regression at increments of approximately 320 W (Fig. 4).

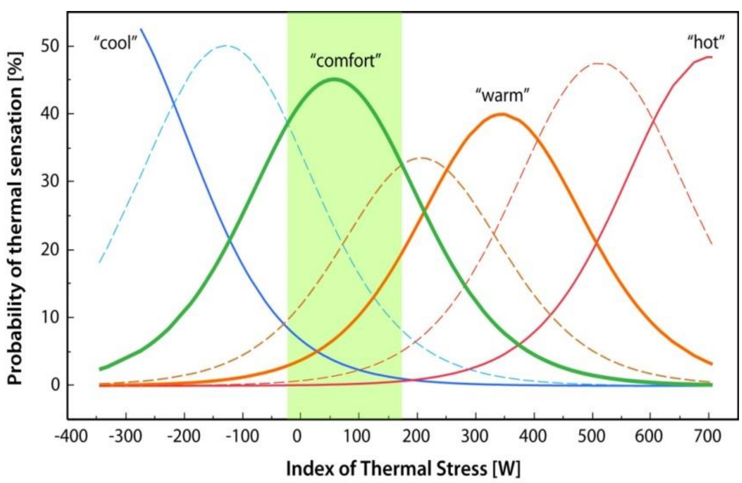

Figure 5. Probability distribution for different levels of thermal sensation over a range of ITS values.

4. Implementation of ITS in the urban environment

A series of recent experimental studies has made use of the ITS model to analyze the thermal effects of urban vegetation, and to evaluate the "cooling efficiency" of irrigated landscaping by comparing its potential to reduce bodily heat gain with the latent heat value of water loss through evapotranspiration.

4.1 The cooling efficiency of trees and grass

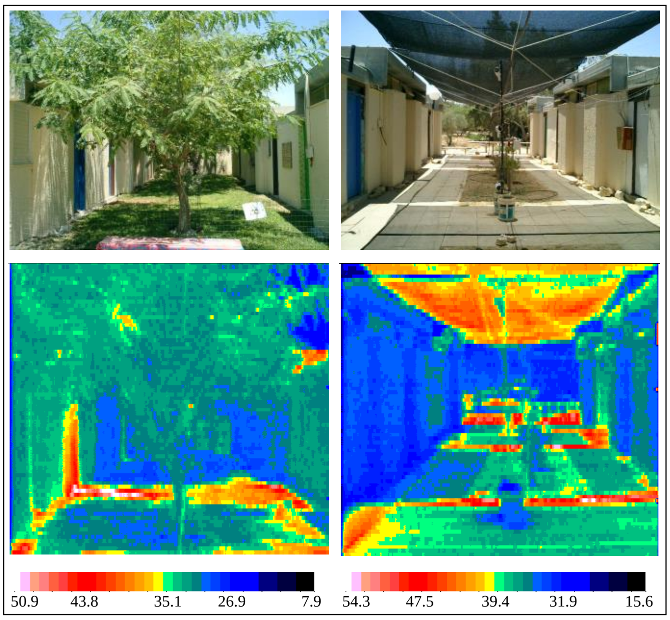

Figure 6. Visible (top) and thermal IR (bottom) images of semi-enclosed courtyard spaces with grass and trees (left) and shading mesh with bare pavement (right).

The combined effect of shade trees and vegetative ground cover on human thermal stress in urban spaces was observed in controlled outdoor experiments in the arid Negev region of Israel (Shashua-Bar et al. 2011). Measurements were made in two adjacent semi-enclosed courtyards with various combinations of mature trees, artificial shading, grass and paving (Fig. 6). For each landscape configuration, ITS was calculated from measured data to evaluate thermal comfort based on radiative and convective pedestrian-environment energy exchanges and sweat efficiency, and expressed on a thermal sensation scale. The "cooling efficiency" of each vegetative landscape treatment was gauged by comparing the reduction in thermal stress relative to an unplanted space (i.e., the "cooling" provided) with the consumption of water required to achieve this benefit (i.e., the "cost" of the improvement). The reduction in hourly ITS was totaled over the daytime hours of a summer day, and thus expressed in terms of total energy (in kWh). Likewise, the rate of irrigation required to replace daily water loss was quantified in terms of the equivalent latent heat of evapotranspiration, and thus also given as a total energy value (in kWh).

ITS results indicated that while conditions in a paved, unshaded courtyard were stressful throughout the summer daytime hours, each of the landscape treatments made a clear contribution to improved thermal comfort (Fig. 7, left). Shading by either trees or mesh reduced the duration of discomfort by over half and limited its maximum severity, and when combined with grass yielded comfortable conditions at all hours. The effect of trees was more pronounced than that of the artificial mesh, due to the latter's elevated radiative surface temperature (see Fig. 6 above). Thus in terms of daytime ITS values, the most effective treatment was a combination of tree and grass. In fact, was found that a combination of locally adapted shade trees and irrigated ground cover not only creates thermally comfortable conditions in otherwise stressful outdoor environments, but requires less total water for irrigation than exposed grass alone. This is a consequence of the extremely high rate of evapotranspiration from the grass to the atmosphere, which is moderated by protection from an overlying tree canopy. In terms of the "cooling efficiency" ratio between the reduction in thermal stress and equivalent latent heat of water loss, exposed grass is clearly the least efficient solution – while the highest efficiency by a vegetative landscape configuration is seen for shade trees alone (Fig. 7, right).

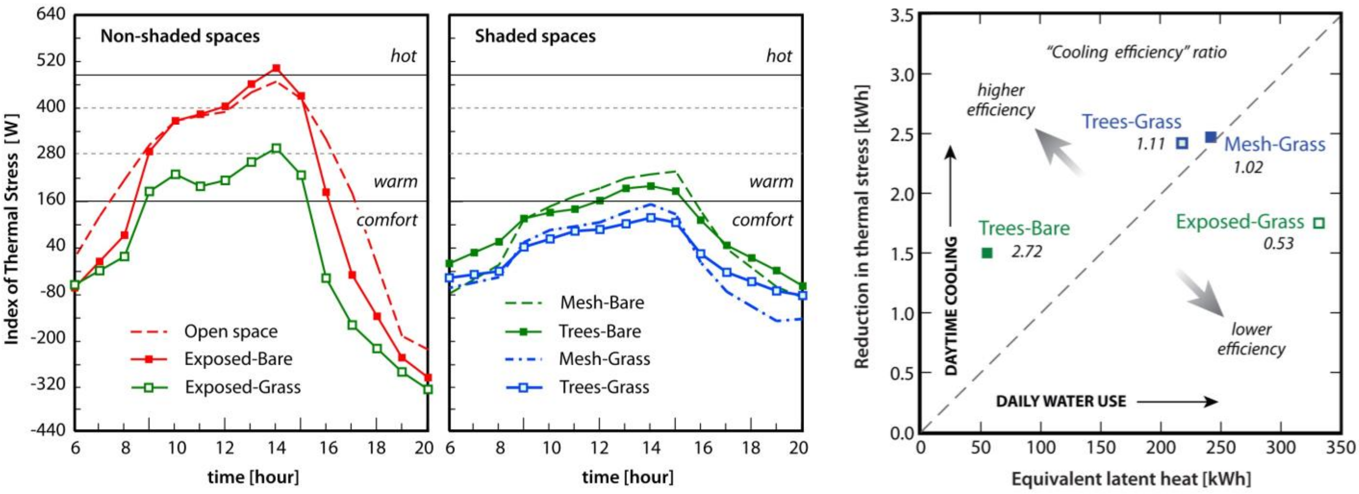

Figure 7. Left: Daily progression of ITS for different landscape treatments, based on Shashua-Bar et al. 2011 with thermal sensation thresholds updated according to Pearlmutter et al. 2014 (original thresholds of "hot" and "very hot" categories shown as dotted lines). Right: Cooling efficiency ratios for the different vegetative landscape treatments.

4.2 The cooling efficiency of water-efficient vegetation

Given the exorbitant water requirements of grass, a further experimental study investigated the potential of succulent plants for use as an alternative in urban landscaping (Snir et al. 2013). Small plots planted with a total of six species (Fig. 8) were used to compare the characteristic albedo and radiant surface temperature, as well as the water requirements, of different types of ground-cover vegetation. It was found that while the succulent varieties maintained slightly higher surface temperatures and ITS values than grass and other non-succulents (Fig. 9), their reduced water loss under conditions of limited irrigation endowed them with a higher cooling efficiency (Fig. 10). It was also found that a high price in terms of thermal stress is imposed by bare soil (due to its high albedo and intense reflected radiation) and artificial turf (due to its low albedo and high radiant surface temperature, exceeding 70°C).

Figure 8. Experimental plots planted with six types of succulent and other species, for measurement of albedo and surface temperature, as input for the calculation of ITS in urban spaces.

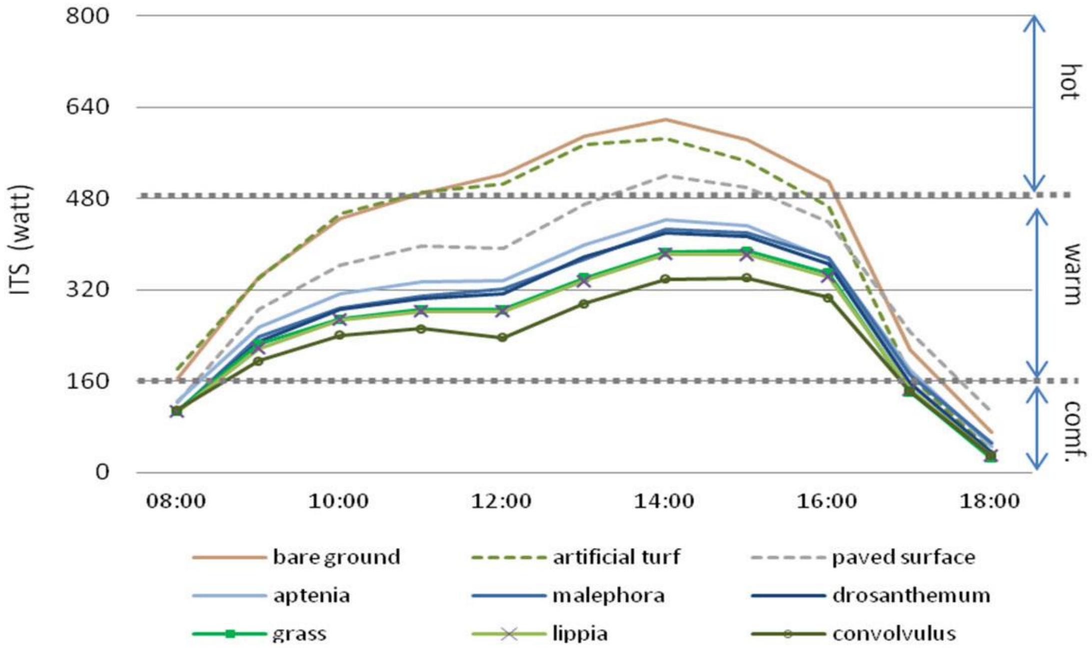

Figure 9.Calculated ITS for hypothetical urban spaces planted with six ground-cover species, compared with dry ground surfaces. Blue lines represent succulent species.

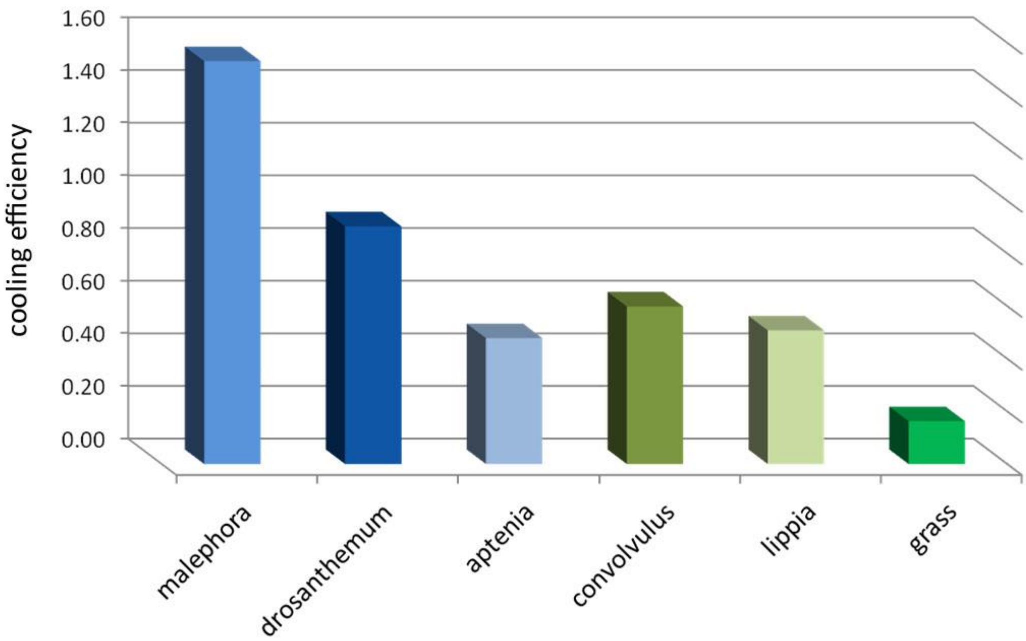

Figure 10. Cooling efficiency for the six species. It may be seen that the three succulents (left, in blue) have a higher average efficiency than the non-succulents, with the grass clearly having the lowest cooling efficiency.

4.3 Thermal stress in a coastal urban park

Finally, a case study of a Mediterranean coastal urban park (Saaroni et al. 2015) examined the ways in which thermal discomfort is perceived by local residents, and results indicated that the expressed thermal preferences of the park's users align robustly with predictions based on ITS.

As in the case described above (Pearlmutter et al. 2014), the linear relation between ITS (based on measured data) and the reported thermal sensation of park visitors (based on a summertime comfort survey) showed that the neutral sensation ("comfort") coincides with biophysical equilibrium (ITS=0) and that the increment between successive thermal sensation categories corresponds to an ITS interval of nearly 320 watts (Fig. 12). This independent finding lends further evidence pointing to the general applicability of the ITS as an indicator for thermal stress in outdoor urban environments.

Figure 11. A coastal urban park in the city of Tel Aviv-Jaffa, recently reclaimed from a former waste disposal site and extensively covered with exposed grass lawns and concrete paving. The perception of thermal discomfort by the park's users was closely predicted by the ITS model (Saaroni et al. 2015).

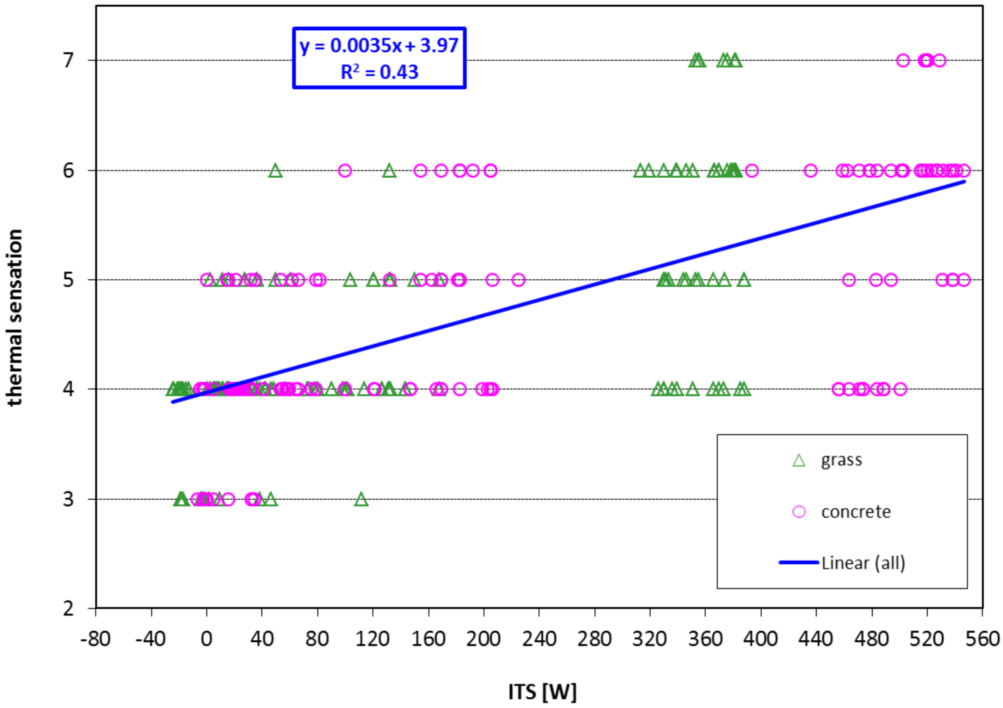

Figure 12. The relation between ITS and thermal sensation of park visitors, when located in areas covered with grass and concrete paving, respectively.

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