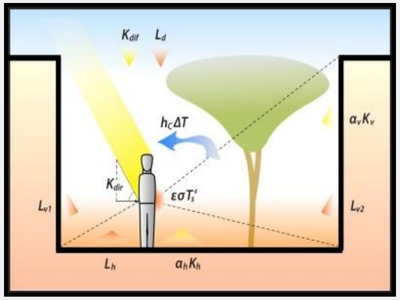


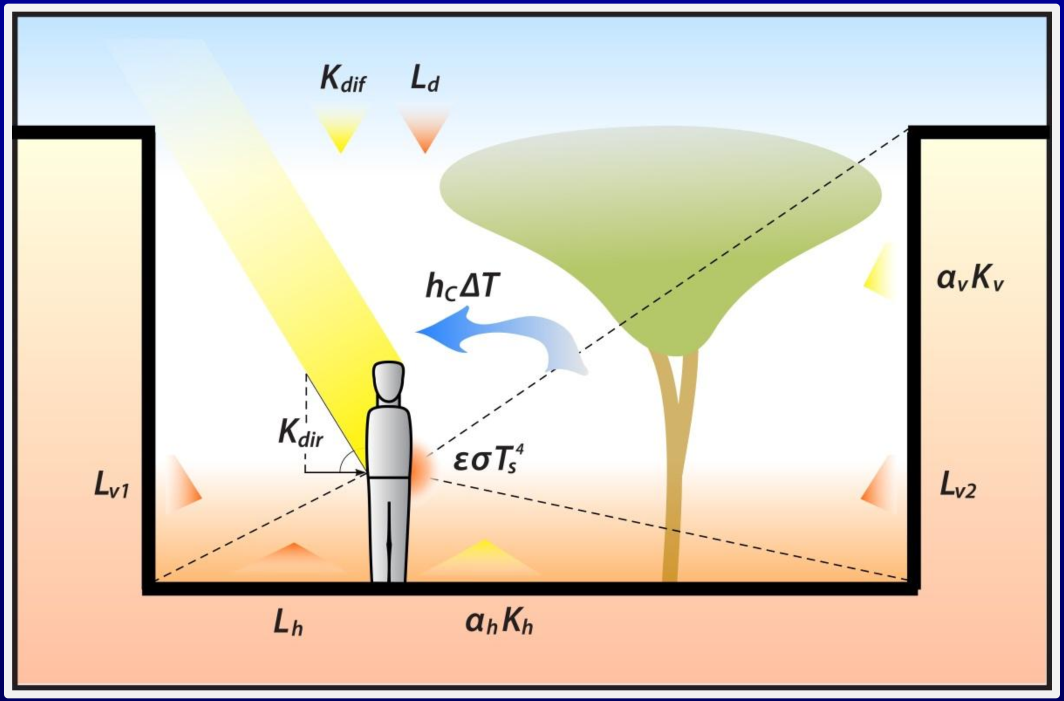
Watts in a comfort index:

Evaluating pedestrian energy exchange and thermal stress in urban environments

David Pearlmutter

Desert Architecture & Urban Planning
Bona Terra Department of Man in the Desert
Blaustein Institutes for Desert Research
Ben-Gurion University of the Negev, Israel

Characterizing the thermal environment of a pedestrian



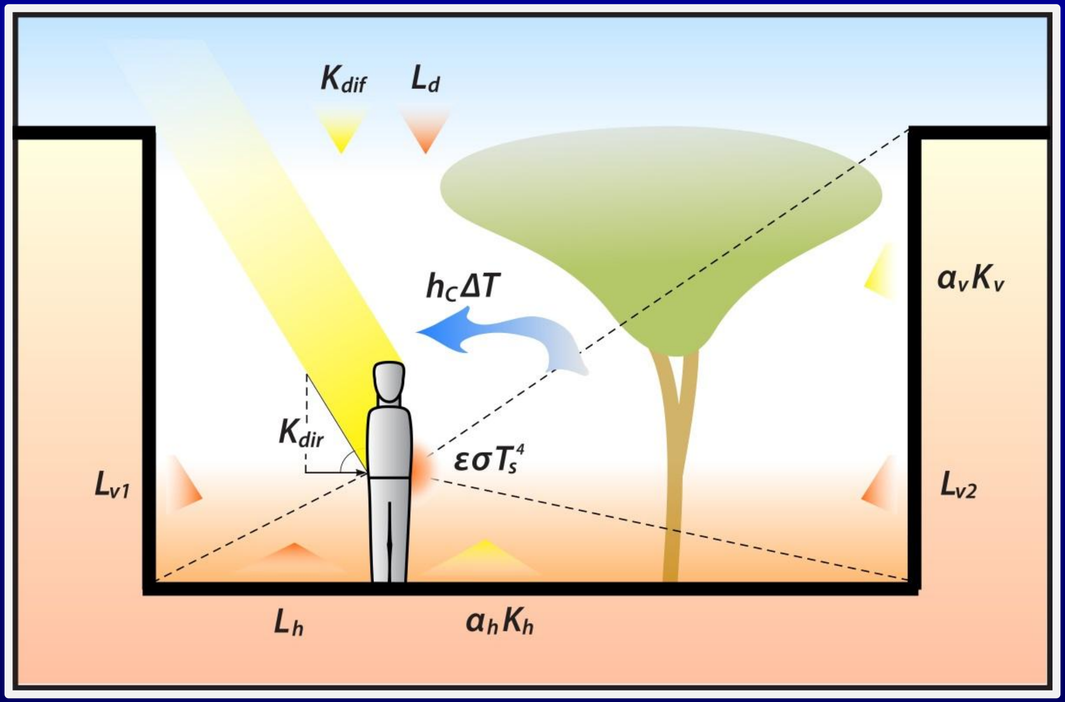
The thermal environment in cities is commonly described in terms of *temperature*:

- T_{air} (°C)
- T_{mrt} (°C)
- *PET* (°C)
- *UTCI* (°C)

❖ "Equivalent" temperatures are extremely sensitive to T_{mrt} – which is difficult to quantify in a dynamic outdoor environment

❖ The human body's thermal endings are not sensors of temperature – but rather of *heat flow*

Modeling pedestrian thermal stress



Index of Thermal Stress

$$ITS = (R_n + C + M) / f$$

[measured in watts]

R_n and C = radiant and convective energy exchanges between pedestrian body and urban environment

M = metabolic heat

f = sweat efficiency based on RH

(Givoni, 1963; Pearlmutter et al, 2007)

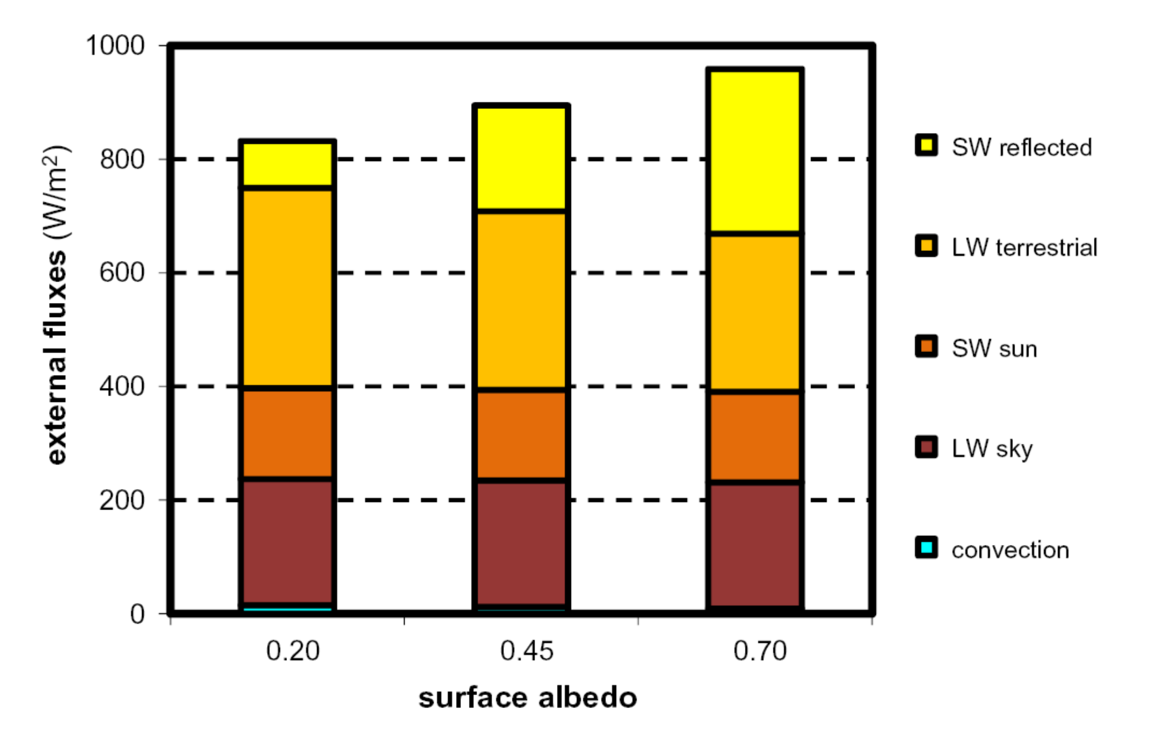
Net Radiation (W m^{-2} of body area):

$$R_n = (K_{dir} + K_{dif} + \alpha_h K_h + \alpha_v K_v)(1-\alpha_s) + L_d + L_h + L_v - \varepsilon\sigma T_s^4$$

Convection (W m^{-2} of body area):

$$C = h_C \Delta T$$

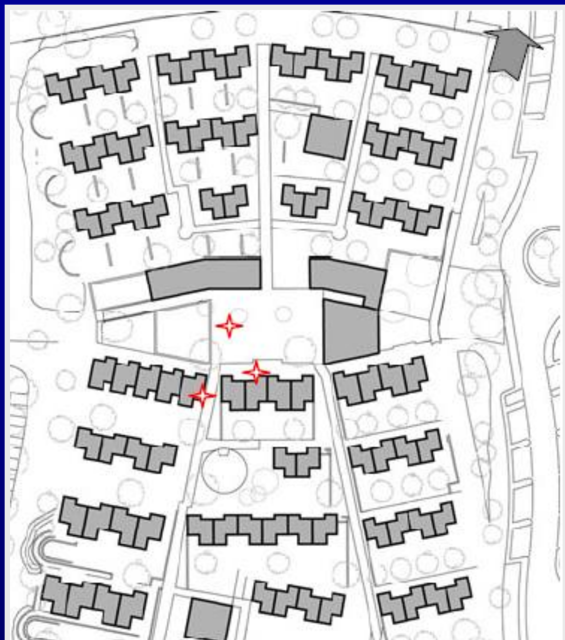
Modeling pedestrian thermal stress



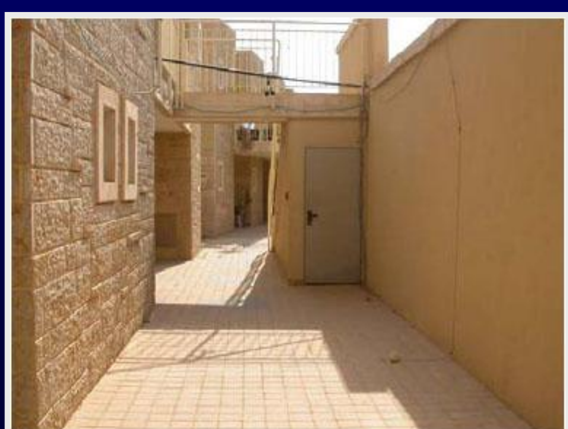
Daytime energy fluxes for a pedestrian in an open space, as affected by ground surface albedo
(Erell E., Pearlmutter D., Boneh D., Bar P., 2014)

- Individual energy fluxes can be compared to better understand the impacts of urban design features
- But how does the body’s energy balance correlate with perceived thermal comfort?

Corollating pedestrian thermal stress and thermal sensation



Dormitory complex, Sede-Boqer Campus



E-W pedestrian path

Open square

N-S pedestrian path

Measured environmental variables for ITS:

- Air temperature
- Surface temperatures (ground, walls)
- Surface albedo
- Global/diffuse insolation
- Wind speed
- Relative humidity

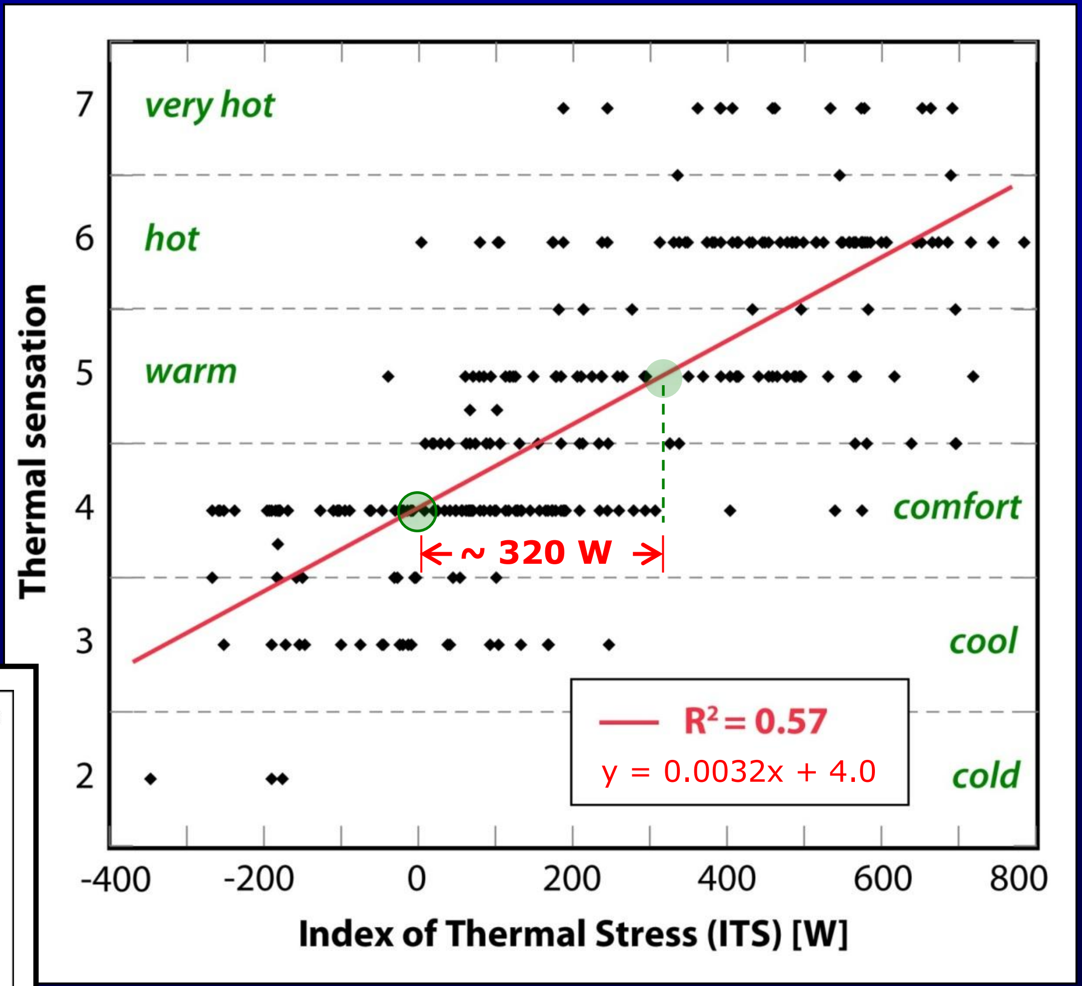
For PET: Globe temperature

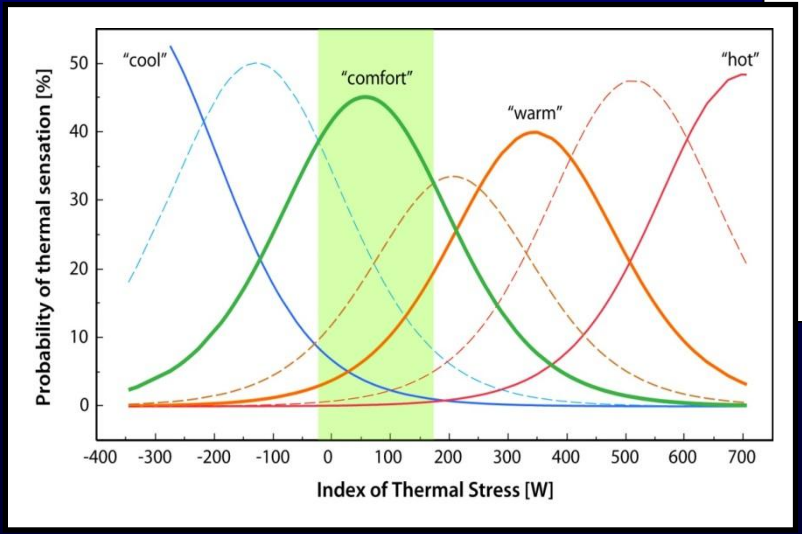
Surveyed personal variables*

- Thermal sensation (7-point scale)
- Explanatory behavioral variables

*** 220 responses, July 2009**

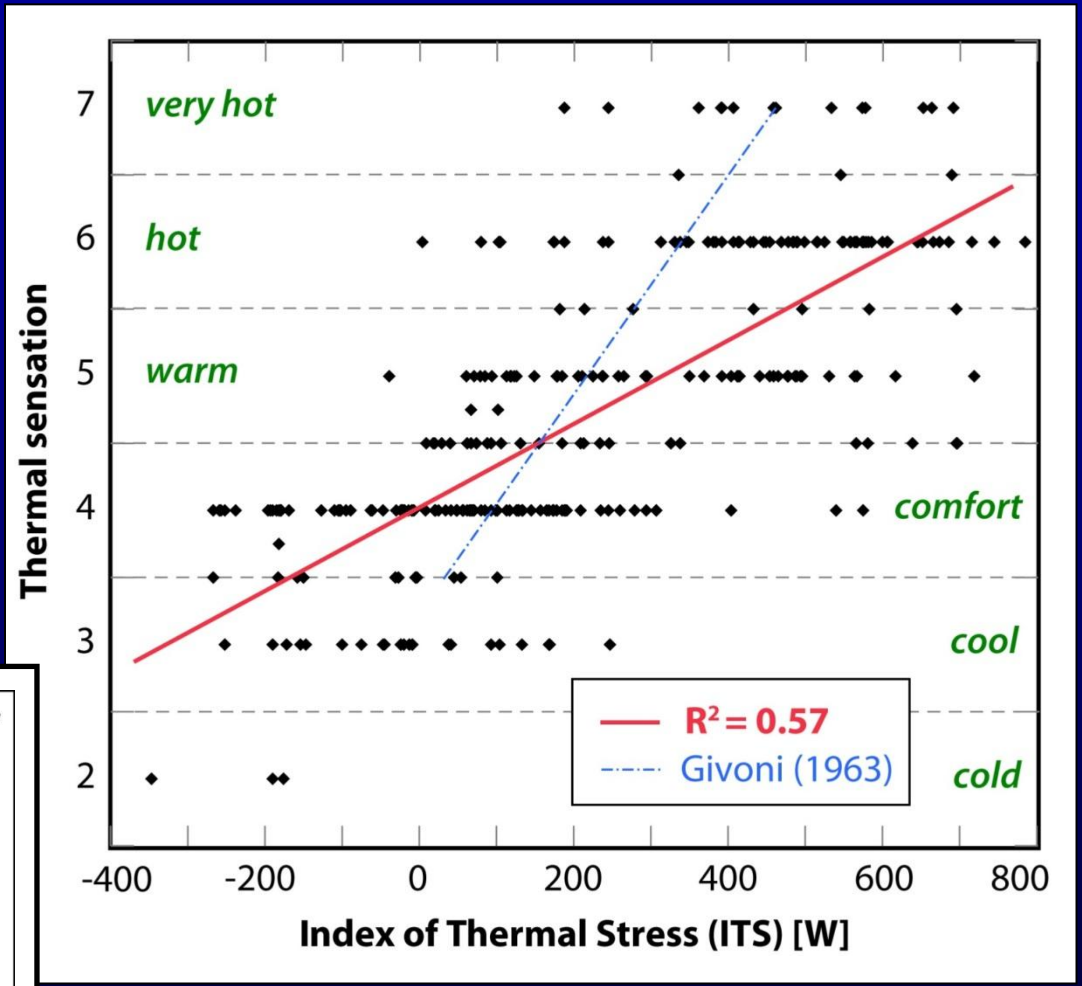
Pedestrian thermal stress and thermal sensation

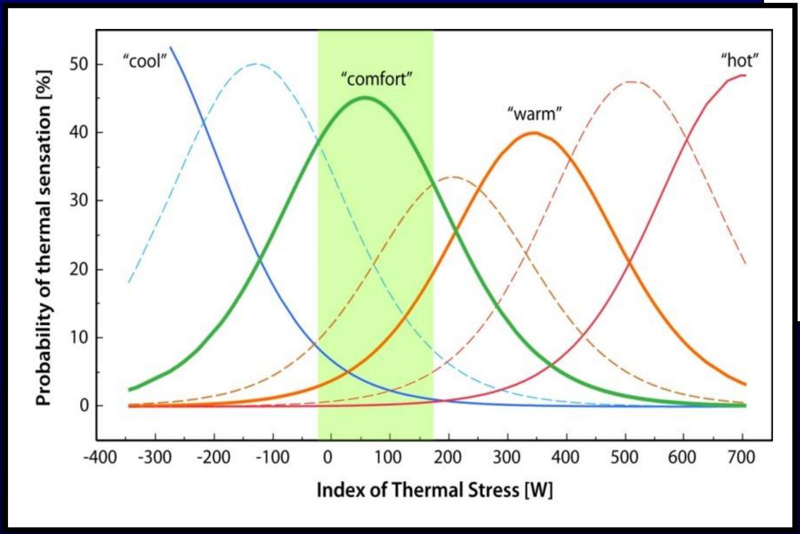




Pearlmutter D., Jiao D., Garb Y. (2014)

Pedestrian thermal stress and thermal sensation

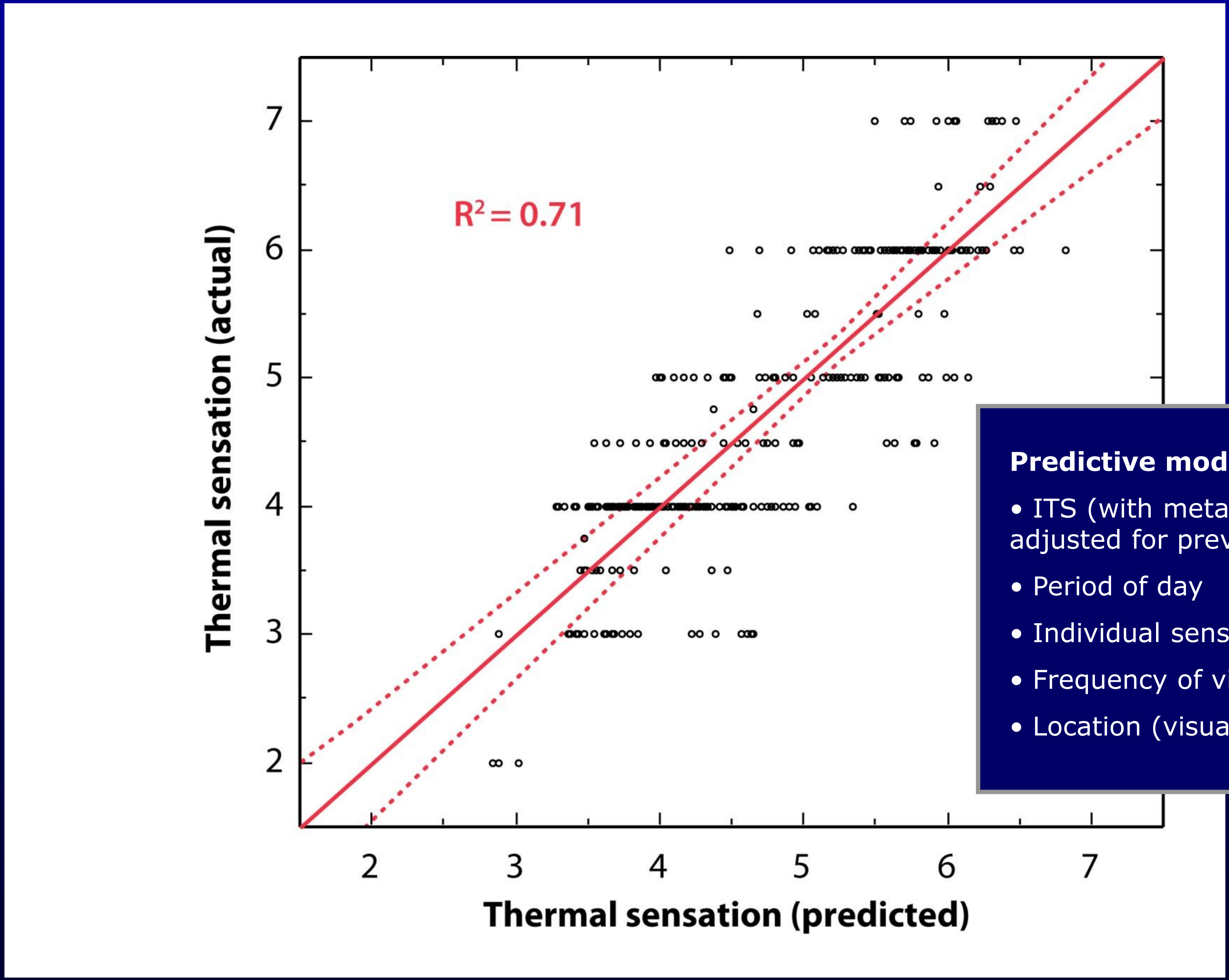




Pearlmutter D., Jiao D., Garb Y. (2014)

Actual vs. Predicted Thermal Sensation

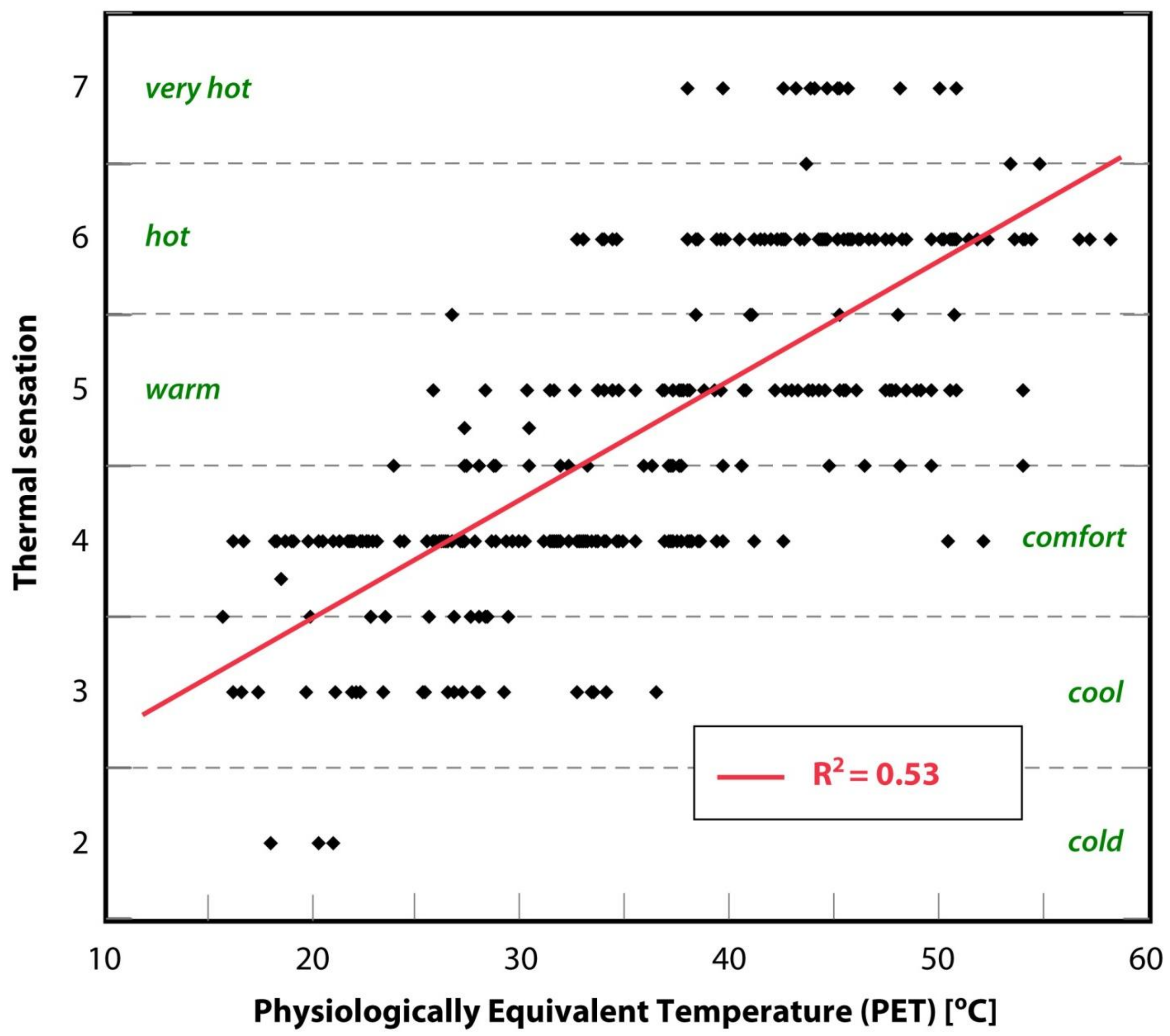
with multivariate regression model including ITS and significant survey variables



Predictive model includes:

- ITS (with metabolic heat adjusted for previous activity
- Period of day
- Individual sensitivity
- Frequency of visitation
- Location (visual comfort?)

PET vs. Thermal sensation



Physiologically Equivalent Temperature (PET)

Mean Radiant Temperature (T_{mrt})

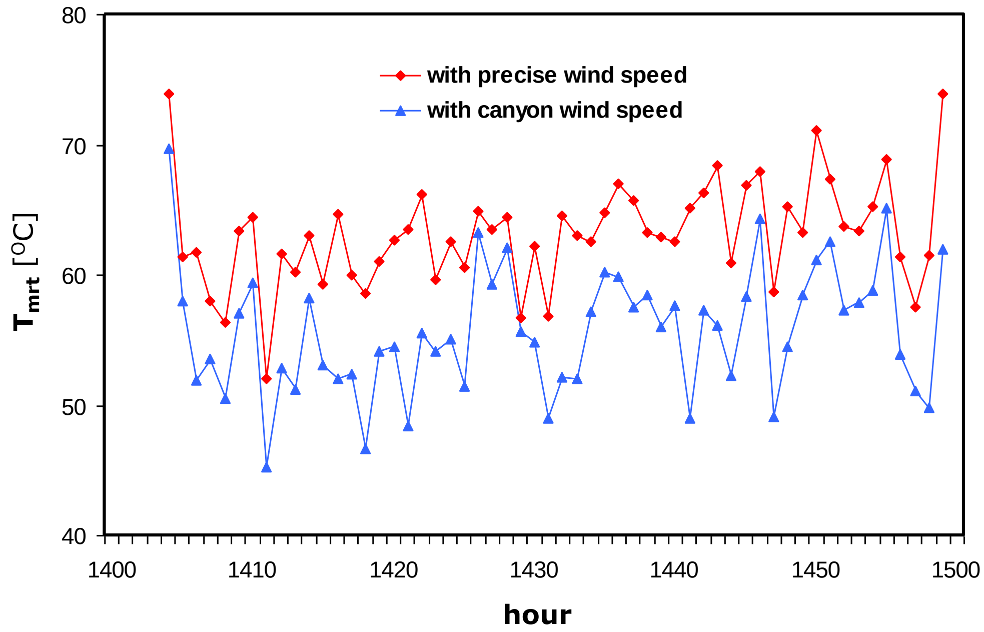
$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.1 \times 10^8 Va^{0.6}}{\varepsilon D^{0.4}} \times (T_g - T_a)\right]^{1/4} - 273.15$$

T_g = globe temperature (°C) **V_a = wind speed (ms^{-1})**

T_a = air temperature (°C)

ε = globe emissivity *D* = globe diameter (mm)

(Thorsson et al., 2007)



Calculation of PET:

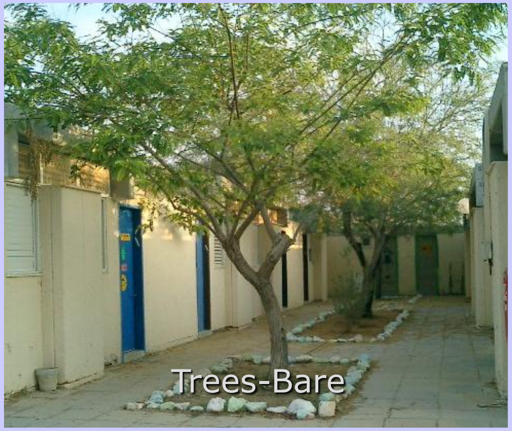
- RayMan (urbanclimate.net/rayman)
- Mean Radiant Temperature based on globe thermometer measurements; sensitive to accuracy of wind speed

Measurement of globe temperature (T_g) and air temperature for PET

Vegetation & microclimate: A controlled outdoor experiment

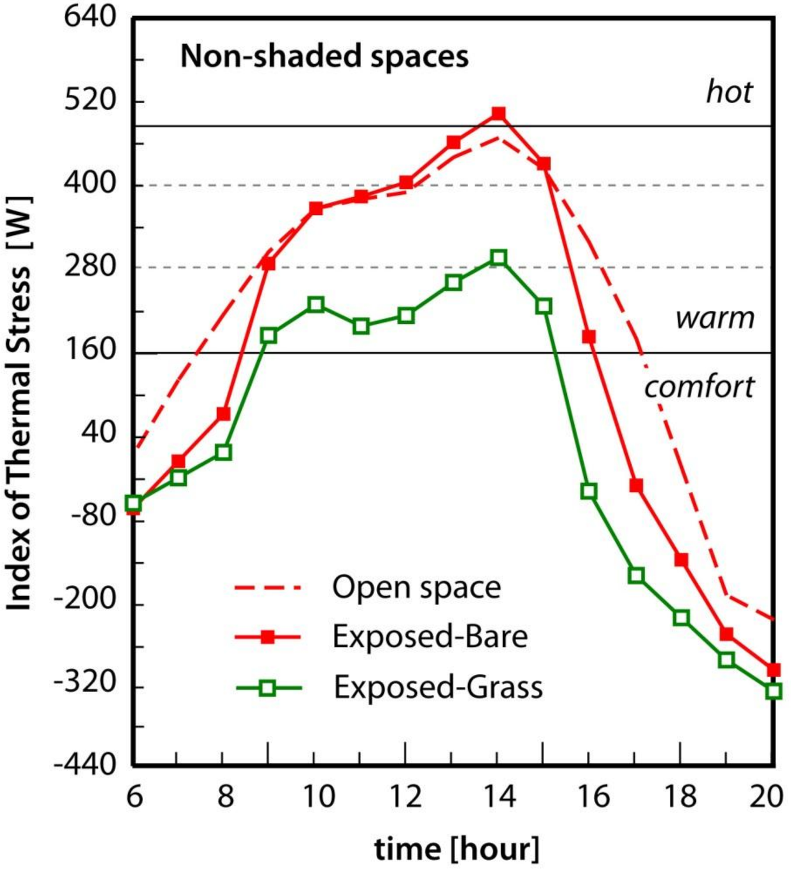
Overhead cover: Trees | Exposed | Mesh

Ground cover: Bare | Grass

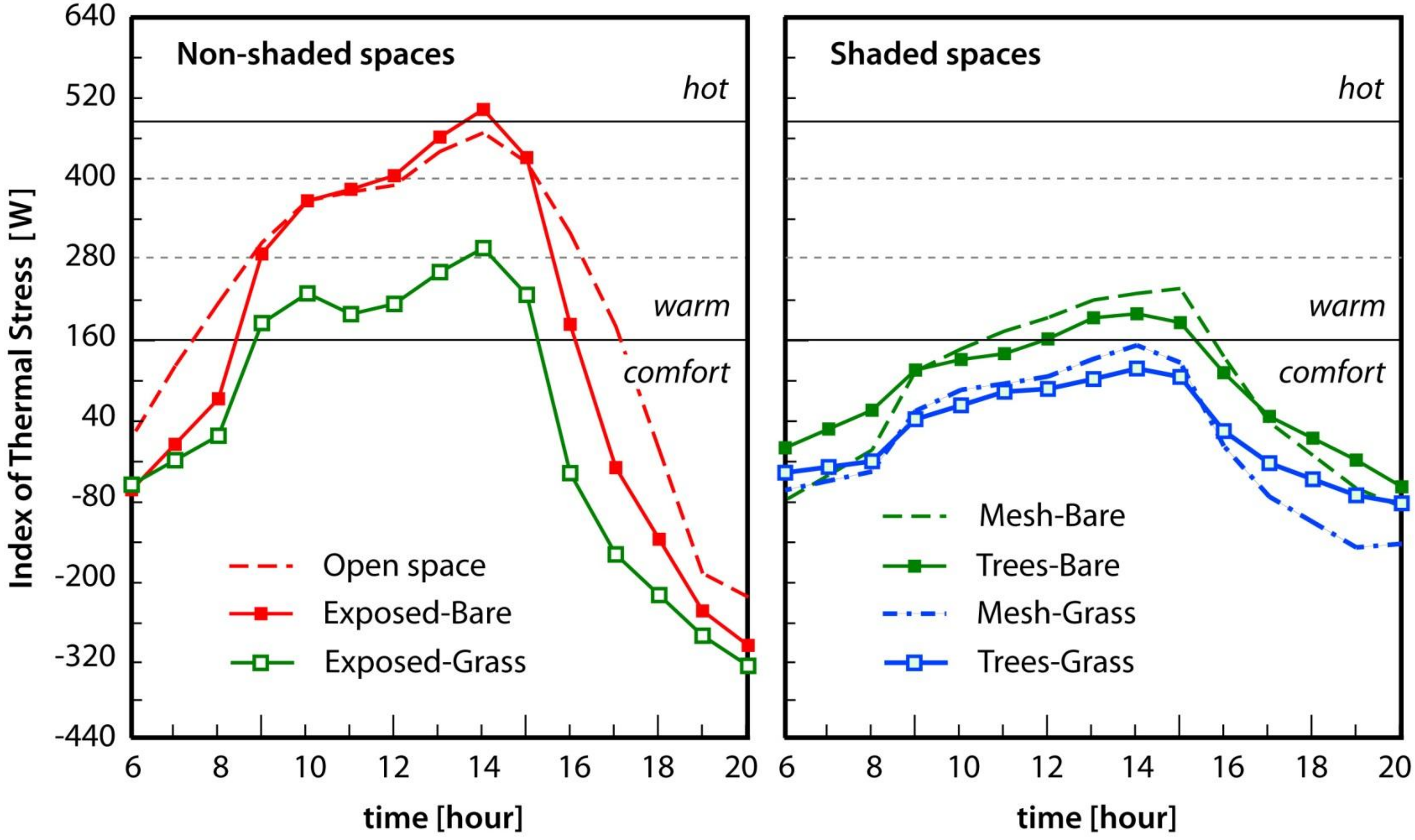


Courtyard spaces used for comparing thermal stress conditions (Shashua-Bar, Pearlmutter & Erell 2009; 2011)

Results: Thermal stress and thermal sensation

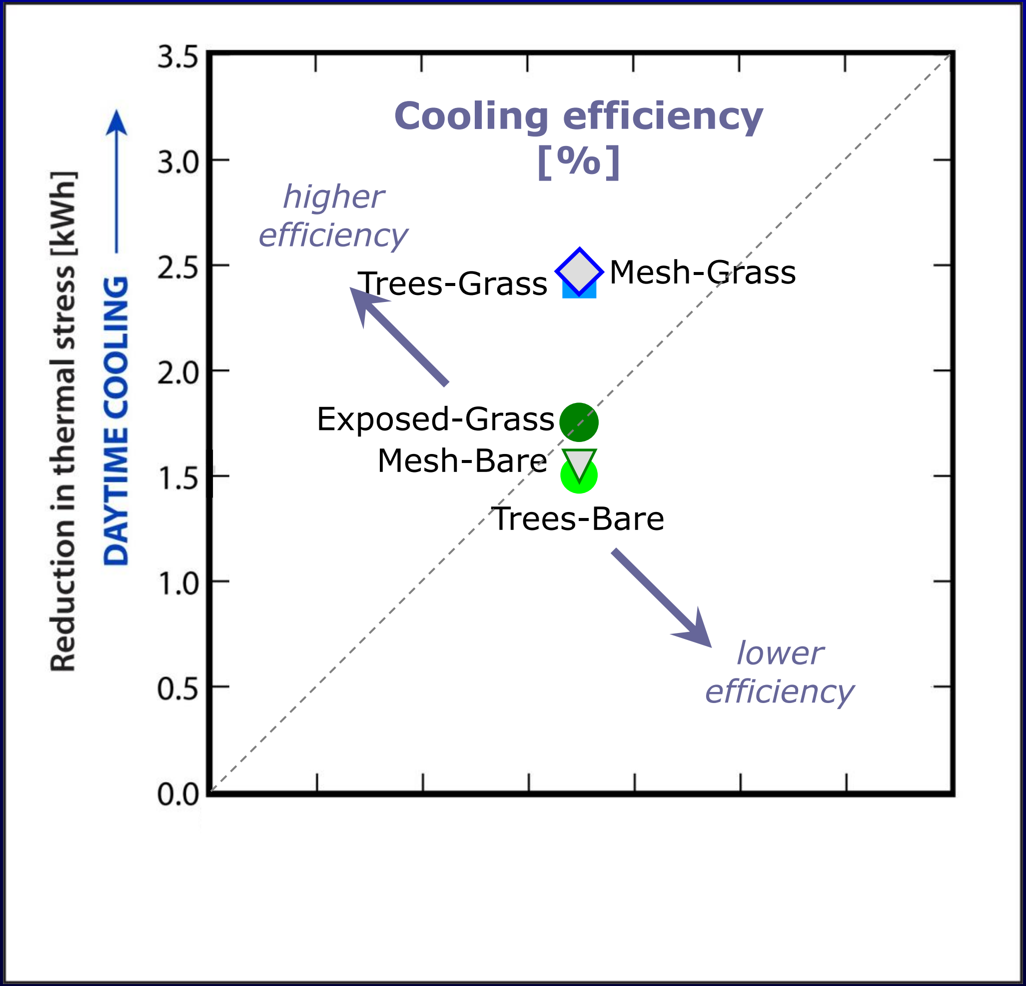


Results: Thermal stress and thermal sensation



*Each landscape treatment made a clear contribution to pedestrian comfort, with the **greatest reduction in mid-day thermal stress** provided by a **combination of shade trees and grass***

Results: Cooling and water use efficiency



Cooling Efficiency:

Ratio between daytime **cooling** (kWh) and daily **water** use (kWh)*, as a percentage (%).

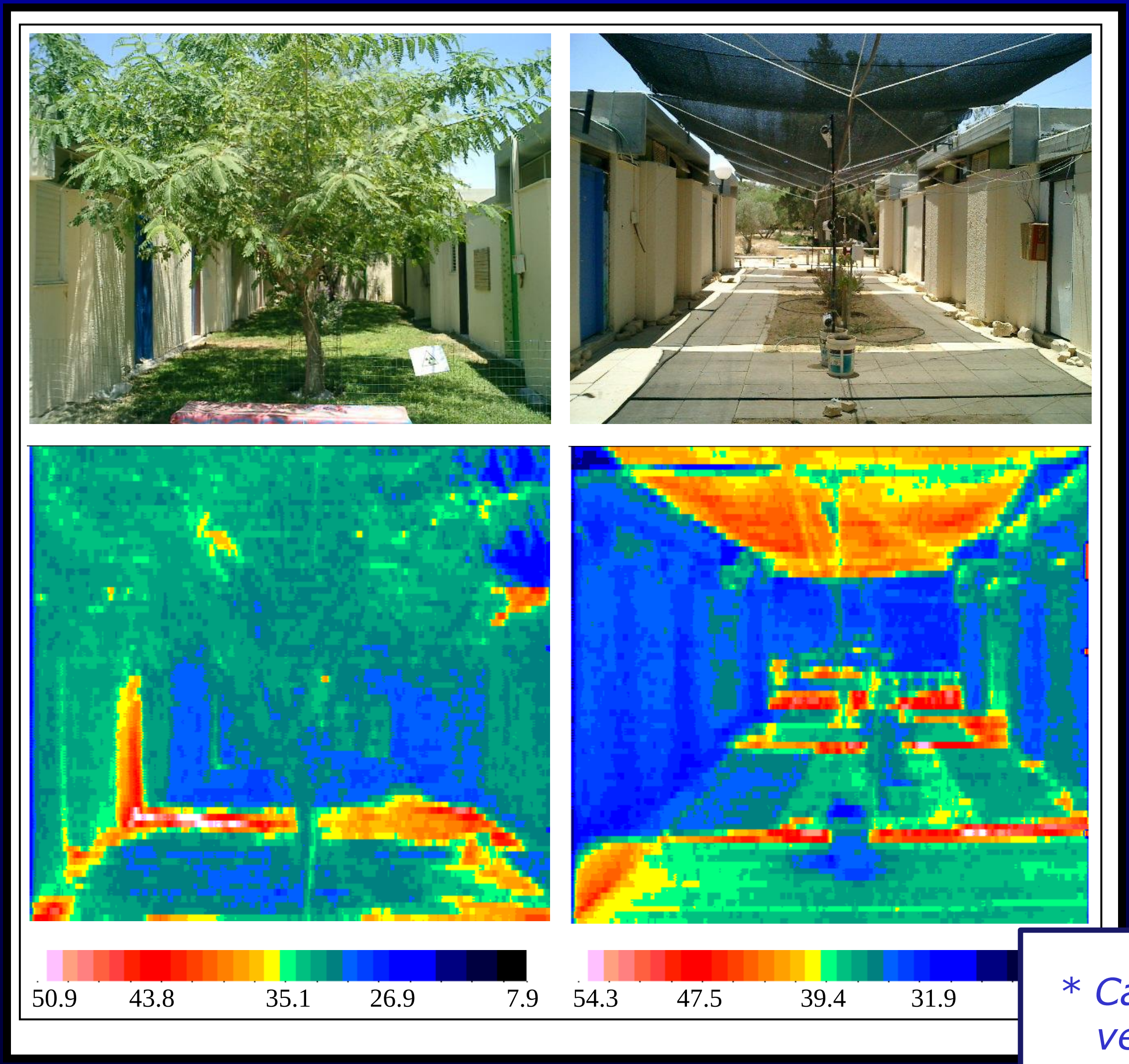
* Equivalent latent heat of evapotranspiration

Highest cooling efficiency:
***shade trees** alone*

*Exposed grass requires more water than grass and shade trees **combined***

*Vegetation reduces thermal stress despite **negligible effect** on air temp.*

Vegetation: surface temperature, albedo & cooling efficiency



Trees + Grass

Mesh + Bare

The cooling effect of trees was more pronounced than artificial mesh, due to its elevated **radiative surface temperature**

Likewise, grass reduces pedestrian exposure to long-wave radiation due to its **low surface temperature**

… and uniquely among urban materials, planted surfaces also minimize short-wave reflection due to their **low surface albedo**

However, grass requires **intensive irrigation**!

** Can alternative, **water-efficient** vegetation be utilized to create "cool" ground surfaces?*

Vegetation: surface temperature, albedo & cooling efficiency

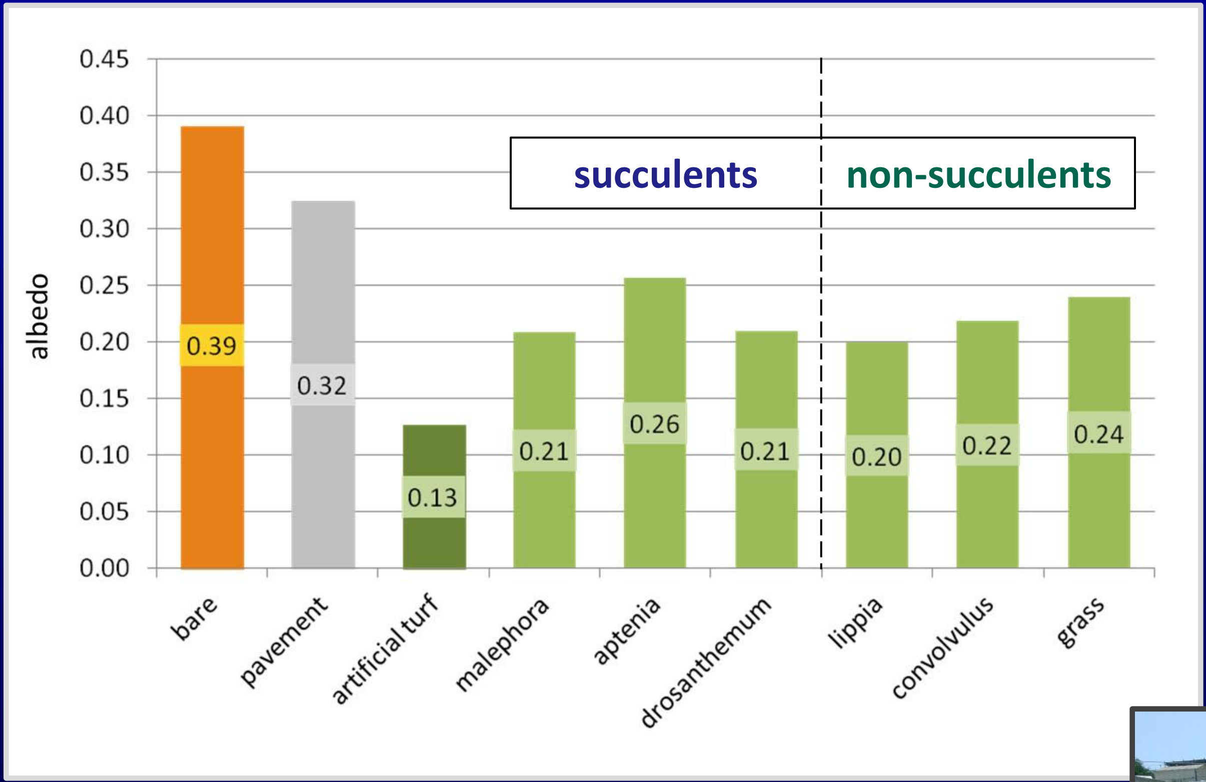
Test plots with three types of succulent plants and three non-succulents including grass

Dry surfaces:

- Artificial turf
- Concrete paving
- Bare loess soil

- The **potential of succulent plants** and other alternatives to grass in urban landscaping were examined in the Negev desert (Snir, Erell & Pearlmutter)
- Experimental were plots planted with six varieties of **ground-cover vegetation**, and compared with dry surfaces for measurement of **radiant surface temperature** and **albedo**
- Results were used as input to calculate pedestrian **thermal stress** in hypothetical urban spaces using each landscape treatment
- **Cooling efficiency** was calculated from water requirements based on measured evapotranspiration

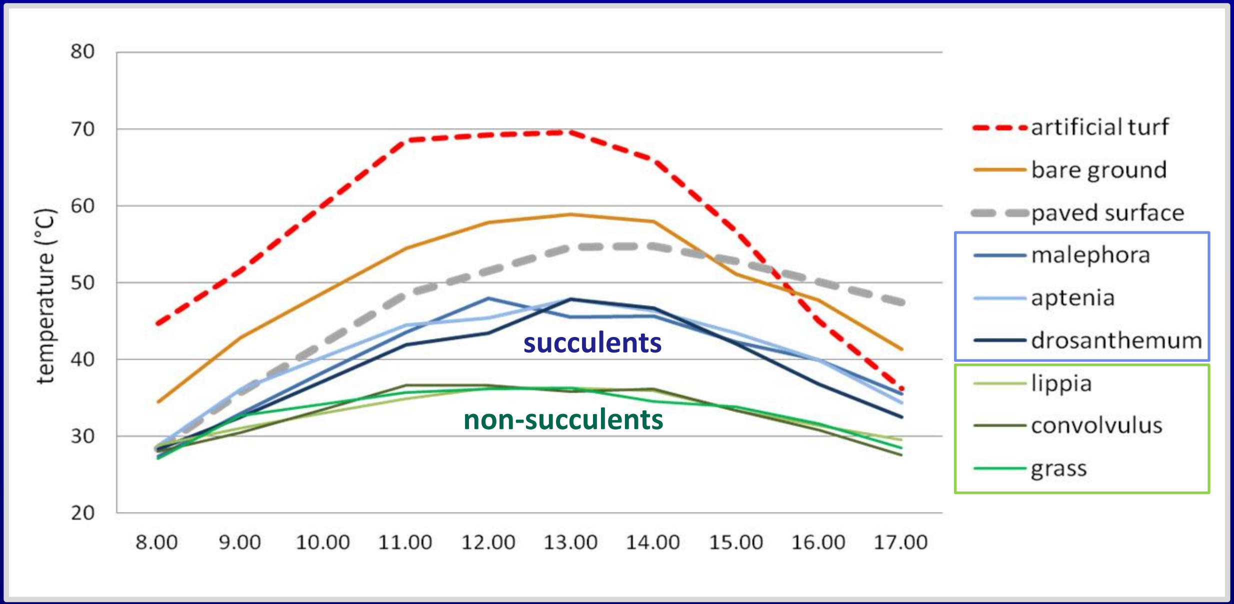
Vegetation: Surface albedo



Average mid-day albedo for planted and dry test surfaces, measured with paired upward and downward-facing pyranometers

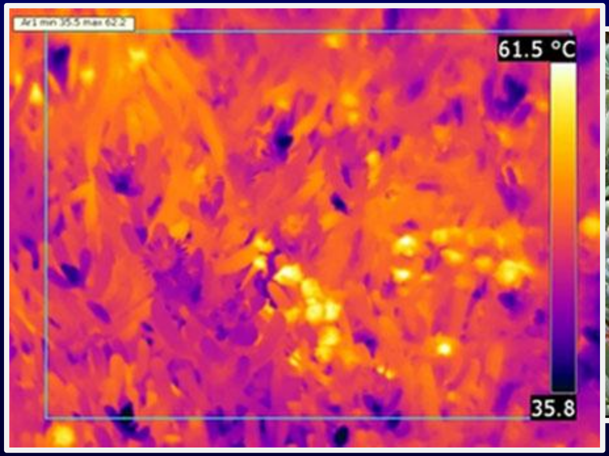
- Only **minor differences** in albedo were found between all plants, including grass
- Albedo values of all plants are significantly **lower** than concrete paving or bare soil, though higher than artificial turf

Vegetation: Surface temperature

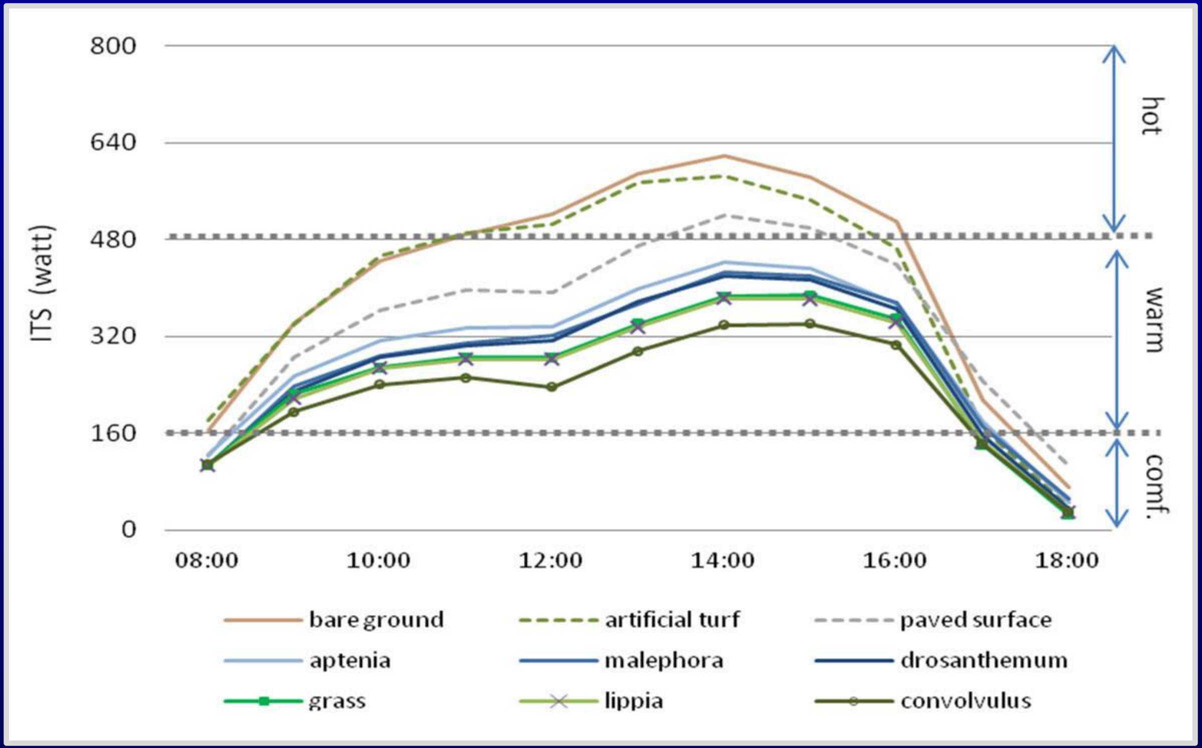


Hourly surface temperatures of planted and dry ground surfaces

- Succulent plant varieties maintain somewhat **higher** surface temperatures than grass and other non-succulents
- Compared to all plants, temperature of bare soil is elevated at all daytime hours - and artificial turf reaches **70ºC**!

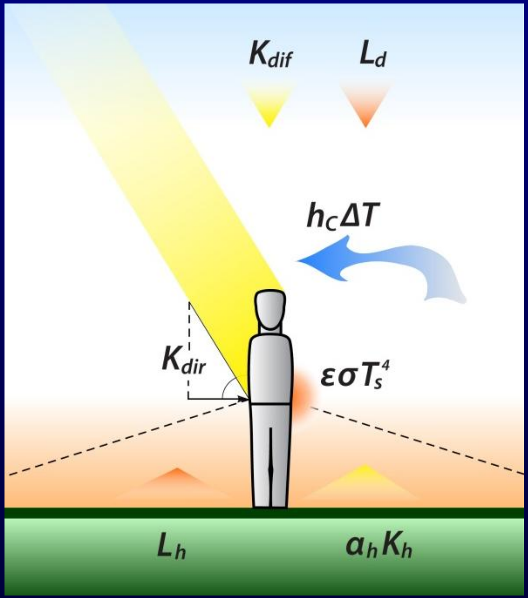


Vegetation: Reduction of pedestrian thermal stress



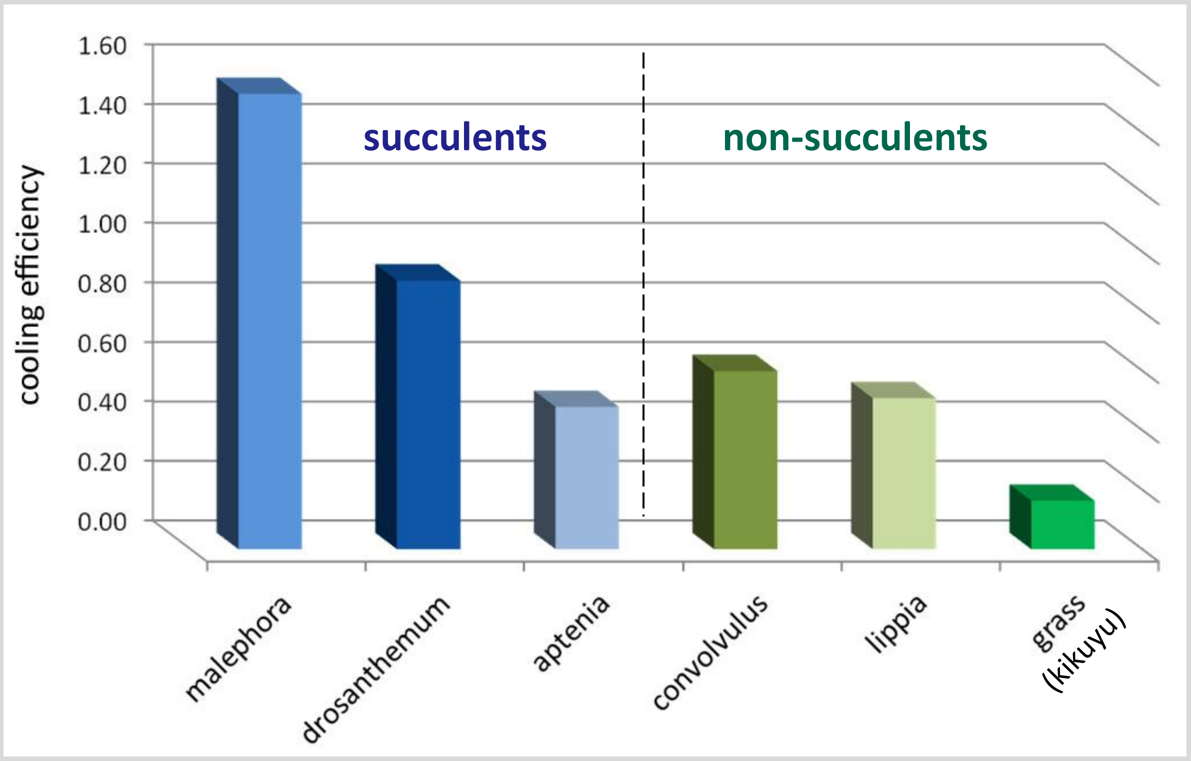
Hourly Index of Thermal Stress (ITS) calculated for pedestrians in urban spaces with planted and dry ground surfaces

- All planted surfaces provide significant cooling (reduced ITS relative to dry surface)
- Differences between grass and alternatives are modest



ITS calculation with L_h and $a_h K_h$ modified for temperature and albedo of each surface

Cooling and water use efficiency: Alternative ground-cover



Cooling efficiency of landscape treatments in urban spaces with different ground-cover vegetation (water requirements based on measured ET)

** Despite negligible differences in albedo, surface temperature or cooling effects, alternative ground cover plants are substantially more* ***water-efficient*** *than grass*

Before > After
10 days without irrigation

Conclusions of initial studies

The effective use of urban vegetation for reducing thermal stress in hot-arid cities requires a **holistic planning approach**, which considers:

- the **geometry of the built urban fabric**: compact open spaces
- the **combination of shade trees with vegetative ground cover**
- the integration of **drought-resistant plant species**

❖ **AVOID LARGE EXPANSES OF EXPOSED GRASS!**

Coastal urban parks & environmental challenges

- Coastal urban locations are attractive for parks – but pose severe environmental challenges in warm regions with limited fresh water
- The sea breeze provides cool air, but ground surfaces and people are vulnerable to solar exposure and overheating

Given local and global warming trends, this study (Saaroni, Pearlmutter & Hatuka, 2015) aimed to:

❖ quantify the level of thermal stress (ITS) in an urban coastal park with a prominent sea breeze and expanses of unshaded grass

❖ compare the levels of physical thermal stress with the subjective thermal perception of park users

Evaluating pedestrian thermal stress and thermal sensation

Physical measurements

Radiation:

- ❖ Global and diffuse radiation
- ❖ Ground surface temperature and albedo

Convection/evaporation:

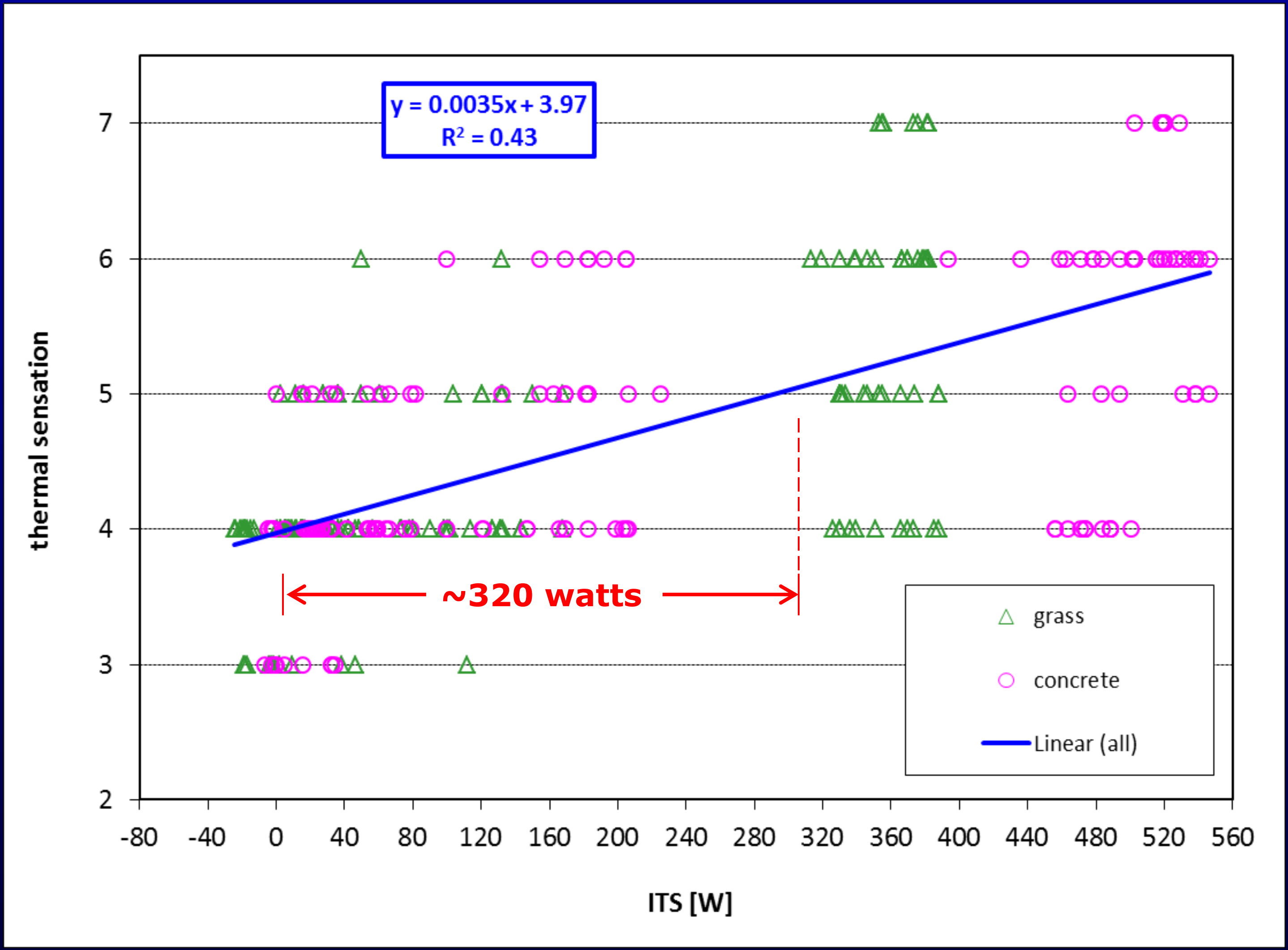
- ❖ Air temperature
- ❖ Wind speed (average and upper gust)
- ❖ Relative humidity

Survey of user satisfaction

300 questionnaires divided evenly in:

- ❖ two locations (grass and concrete plaza)
- ❖ three daily periods (13:00-15:00, 17:00-19:00 and 20:00-22:00)

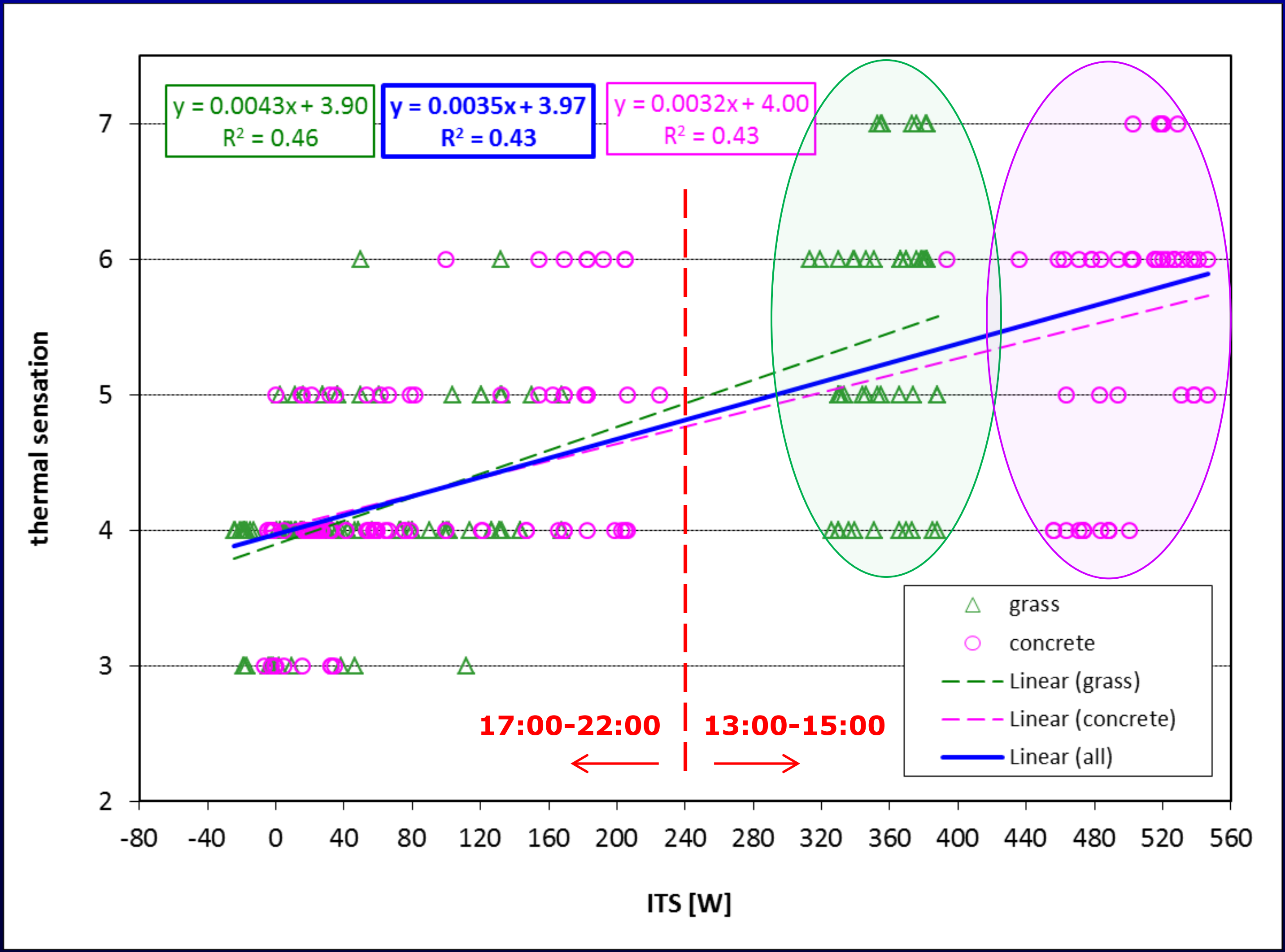
Results: Thermal Stress vs. Thermal sensation



Relation between Index of Thermal Stress (ITS) and comfort vote

(1 = very cold, 2 = cold, 3 = cool, 4 = comfortable, 5 = warm, 6 = hot, 7 = very hot)

Results: Thermal Stress vs. Thermal sensation



Relation between Index of Thermal Stress (ITS) and comfort vote

(1 = very cold, 2 = cold, 3 = cool, 4 = comfortable, 5 = warm, 6 = hot, 7 = very hot)

Jaffa Slope Park: Urban coastal park in Tel Aviv-Jaffa

As previously:

- the neutral comfort sensation coincides with biophysical equilibrium (ITS=0)
- the increment between successive thermal sensation categories corresponds to an ITS interval of almost 320 W.

This independent finding reinforces the applicability of ITS as an indicator for thermal stress in urban environments.

And some food for thought…

Regional warming and drying trends would indicate that open space design should focus on increasing comfort and minimizing use of fresh water. How sustainable is this approach to the design of urban parks?...

Thank you!

http://www.bgu.ac.il/mid

Erell E., Pearlmutter D., Boneh D., Bar (Kutiel) P., 2014: Effect of high-albedo materials on pedestrian heat stress in urban street canyons. *Urban Climate*, 10(2):367-386.

Givoni B., 1963: *Estimation of the effect of climate on man: Development of a new thermal index.* Technion-Israel Institute of Technology, Haifa.

Pearlmutter D., Bitan A., Berliner P., 1999: Microclimatic analysis of 'compact' urban canyons in an arid zone. *Atmospheric Environment*, 33(24-25), 4143-4150.

Pearlmutter D., Berliner P., Shaviv E., 2006: Physical modeling of pedestrian energy exchange within the urban canopy," *Building and Environment* **41**(6):783-785.

Pearlmutter D., Berliner P., Shaviv E., 2007: Integrated modeling of pedestrian energy exchange and thermal comfort in urban street canyons. *Building and Environment* 42(6):2396-2409.

Pearlmutter D., Jiao D., Garb Y., 2014: The relationship between bioclimatic thermal stress and subjective thermal sensation in pedestrian spaces. *International Journal of Biometeorology*, 58:2111–2127.

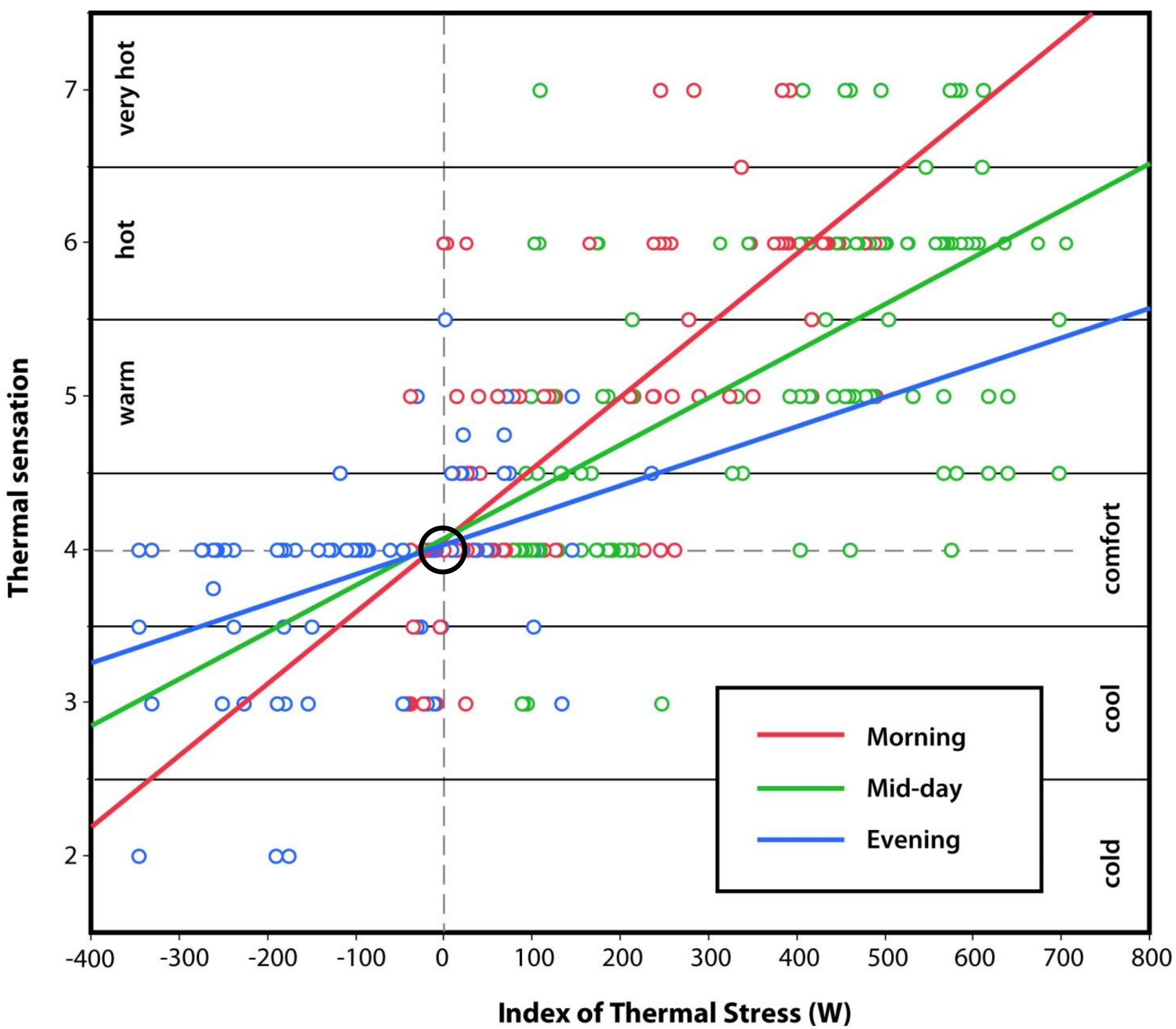
Saaroni, H., Pearlmutter D., Hatuka T., 2015: Human-biometeorological conditions and thermal perception in a Mediterranean coastal urban park. *Intl. Journal of Biometeorology* (DOI:10.1007/s00484-014-0944-z).

Shashua-Bar, L., Pearlmutter D., Erell E., 2011: The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *International Journal of Climatology* 31:1498-1506.

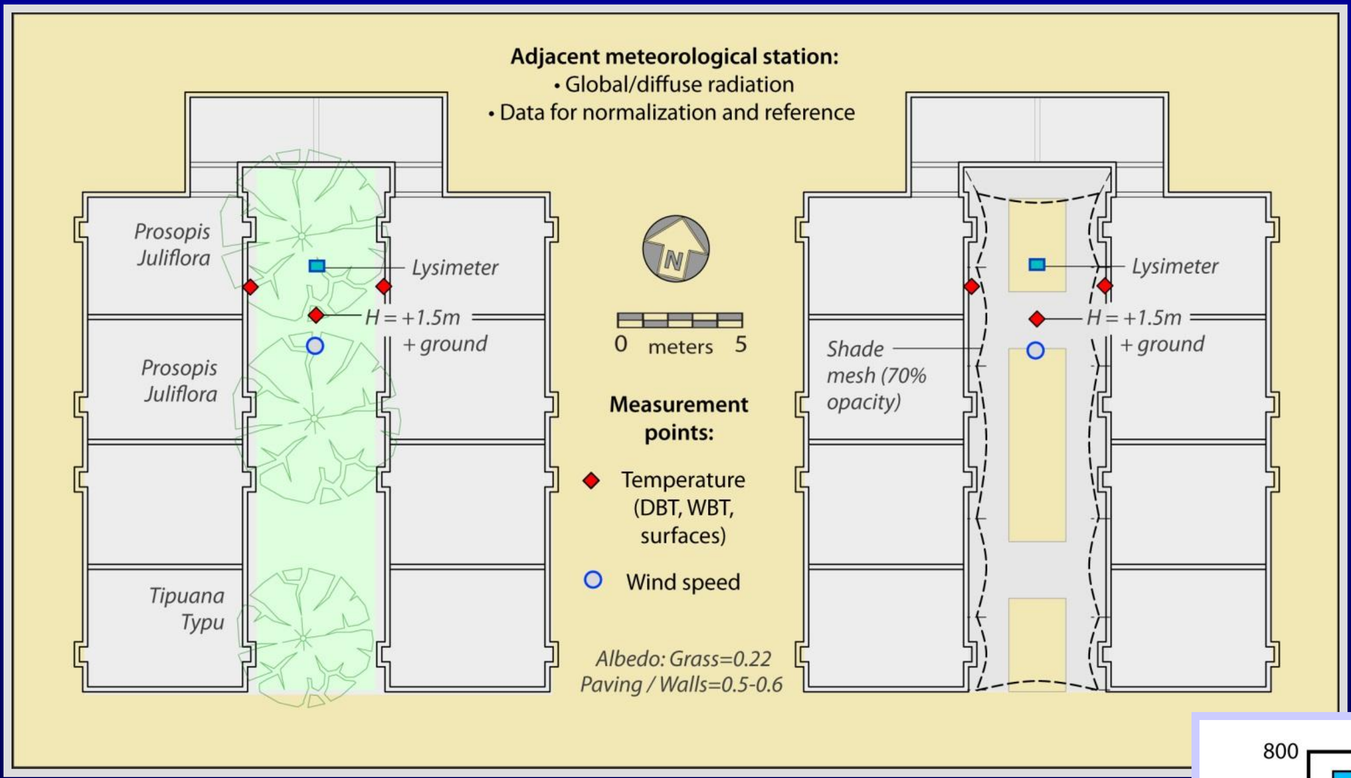
Snir K., Pearlmutter D., Erell E., 2013: The Moderating Effect of Desert Ground Cover Plants on Pedestrian Thermal Sensation. *Proceedings of PLEA2013: Sustainable Architecture for a Renewable Future*, Munich, September 2013.

Thorsson, S., Lindberg, F., Eliasson, I., and Holmer, B., 2007: Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International Journal of Climatology* 27(14):1983-1993.

ITS vs. Thermal sensation by time of day

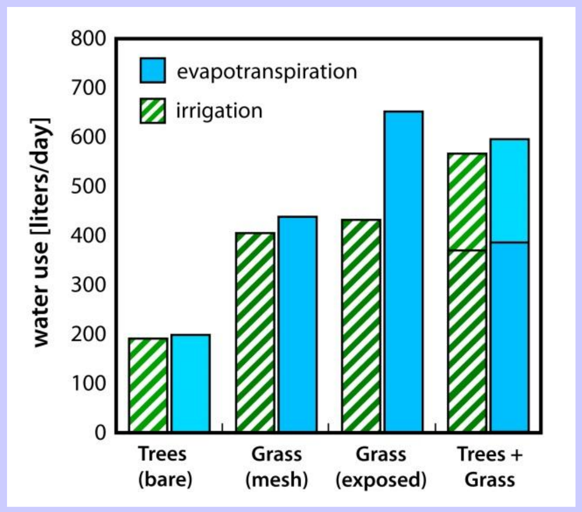


Experimental setup: Measurement tools & techniques



Both courtyads:

- Elongated N-S axis
- H/W = 0.5



DBT+WBT: Aspirated psychrometer

Grass ET: Mini-lysimeter

Tree transpiration: Sap-flow probes