EFFECT OF COOL ROOFS AND GREEN ROOFS ON TEMPERATURE IN THE TROPICAL URBAN ENVIRONMENT

Chun Liang Tan[1], Nyuk Hien Wong[2], Steve Kardinal Jusuf[2], Pei Yu Chia[2]

1 National University of Singapore
School of Design and Environment
Centre for Sustainable Asian Cities
4 Architecture Drive, Singapore
tcl@nus.edu.sg

2 National University of Singapore
School of Design and Environment
Department of Building
4 Architecture Drive, Singapore

ABSTRACT

The treatment of roof space with cool paint or vegetation is a widely employed urban heat mitigation strategy. As the allocation of roof space for social activity becomes more prevalent in the urban environment, there is a need to understand how cool roofs and green roofs can affect the outdoor thermal comfort of its users.

The study seeks to quantify the cooling effect of cool roofs and green roofs. Six plots, each measuring 3.0 m by 3.0 m, are set up at a rooftop. The setup consists of four plots of vegetation, one plot painted with cool paint and one with exposed concrete. The type of vegetation used for the green roofs are categorized according to regulatory guidelines. Analysis of air, surface and mean radiant temperature is conducted for the six plots.

Results show the effectiveness of cool roofs and green roofs in reducing surface temperature under direct sunlight. Significant reduction in mean radiant temperature is observed for plots with vegetation. The Leaf Area Index and physical dimension of plants do not show good correlation with the reduction mean radiant temperature. This study confirms the need for cool roofs and green roofs to be strategically sited to achieve optimal cooling effect.

KEYWORDS

Cool roof; green roof; mean radiant temperature; outdoor thermal comfort

1 INTRODUCTION

Cities around the world are expanding at a rapid pace. With rapid urbanization, rural hinterland is converted to concrete urban sprawls, resulting in numerous environmental issues such as pollution and the Urban Heat Island (UHI) effect. The rise in temperature, especially in the city, has a severe impact to our physiological well-being. Numerous thermal comfort and heat stress indices have been developed to indicate our willingness to accommodate to various thermal conditions (Epstein and Moran, 2006). Many strategies have been developed to improve thermal comfort. The introduction of cool roofs and green roofs are common methods employed to mitigate this change in climate. Cool roofs are characterised by their high solar reflectance and high thermal emittance. Heat transfer to the environment is reduced by reflecting incident solar irradiance in the day and by emitting heat stored in the roof surface at night. Green roofs reduce the thermal load by blocking incident solar irradiance using plant foliage and soil substrate, as well as by cooling the ambient temperature by means of evapotranspiration. The result is either a direct improvement in occupancy thermal comfort or a lessening of overall building cooling load through heat gain reduction (Akbari et. al, 2001; Santamouris, 2012).

Many studies on the effects of cool roofs and green roofs have focused on the surface temperature of roofs as well as the quantification of cooling energy savings for the building (Arthur et. al, 1998; Synnefa et. al, 2007). Research on green roofs often focus on the quantification of roof surface temperature. There are also studies into various aspects of rooftop greenery such as the types of plants used, growth substrates, acoustic performance, air quality and maintainability (Akbari, 2002; Parizotto and Lamberts, 2011; Baik et. al, 2012; Saadatian et. al, 2013). Various feasibility studies have also been conducted to determine the structural and logistical considerations for green roof implementation (Castleton et. al, 2010).

The reviewed literature suggests that most studies conducted for cool roofs and green roofs tend to focus on their impact to the indoor environment. There is little information on how cool roofs and green roofs will affect the outdoor environment. This is much more pertinent to green roofs, as green roofs are often designed as roof gardens and can be used as outdoor social spaces. The evaluation of thermal environments by most comfort or stress indices often requires the measurement of the air temperature, mean radiant temperature, air velocity and relative humidity. The mean radiant temperature (t_{mrt}) can be considered as one of the main factors contributing to both indoor and outdoor thermal comfort, as indicated in various studies which have showed that thermal comfort is highly dependent on the shortwave and long wave radiation fluxes from the surroundings (Mayer and Höppe, 1987; Mayer, 1993). In this study, in addition to surface and air temperature, t_{mrt} is quantified to determine the impact due to exposure to different types of green roofs and a cool roof.

2 METHODOLOGY

2.1 Measurement

The experiment is conducted at the National University of Singapore, School of Design and Environment (SDE 1) rooftop. Six plots are measured. Each plot has a dimension of 3.0 m by 3.0 m. The first four plots are plots with vegetation. The fifth plot is covered with an acrylic sheet painted with cool paint. The sixth plot is bare concrete roof, used as a control for the measurement. The characteristics of each plot are shown in Table 1.

Table 1. Plot characteristics

Plot	**Characteristic**	**Specification**
1	Shrub	Phyllanthus cochinchinensis
2	Shrub	Heliconia American Dwarf
3	Shrub	Sphagneticola trilobata
4	Turf	Cow grass
5	Cool Paint	*JOTUN* Jotashield extreme
6	Concrete	Control

Each plot is placed at regular intervals of 3.0 m to minimize interference from neighbouring plots. Sensors are deployed to measure the air temperature (t_a) and globe temperature (t_{globe}) of the different plots (Figure 1). Measurements are made at one minute intervals. A total of 36 sensors are deployed. Each globe temperature sensor is attached to a survey pole and measure t_{globe} at 1.3 m above the plots. Six sensors are placed underneath each plot to measure the roof surface temperature.

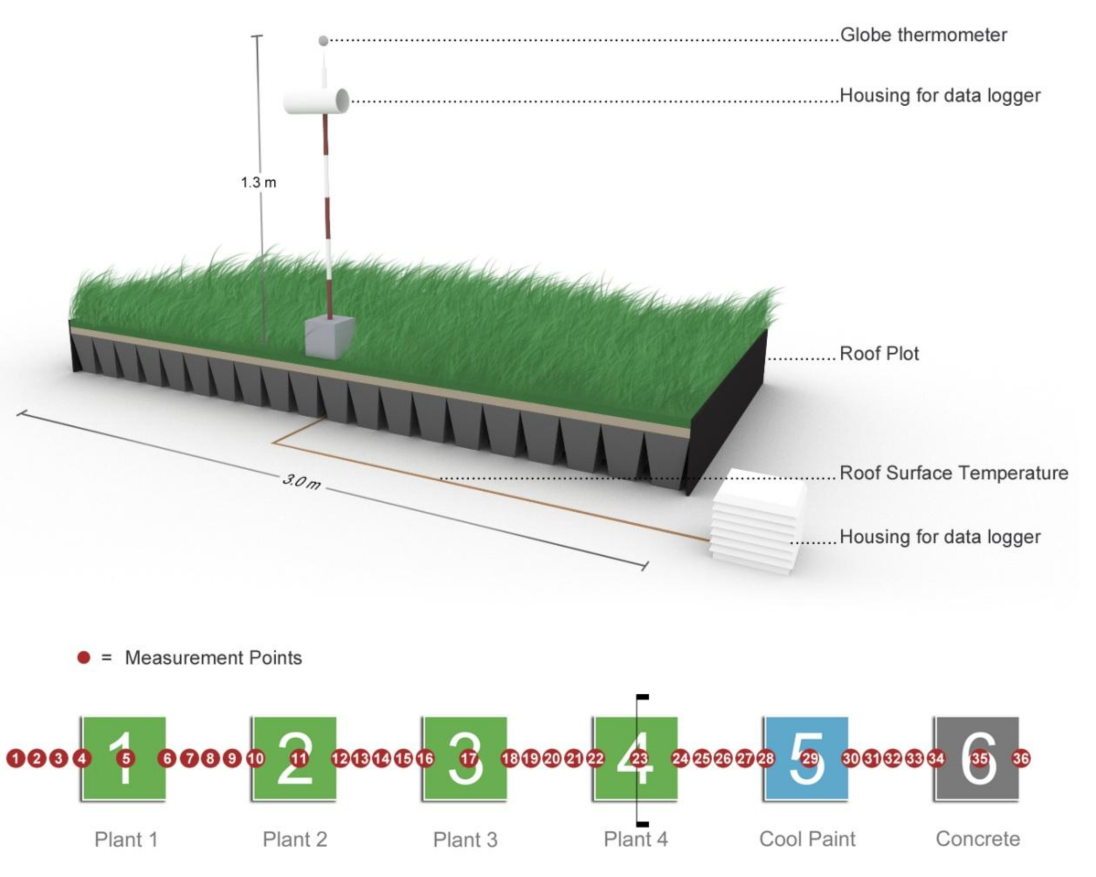

Figure 1. Measurement points and sectional perspective of setup

Thermocouples are used for surface temperature measurement. The LAI of plants used in Plots 1 to 4 is measured using both direct and indirect methods. The LAI-2000 is utilized for indirect measurement. The leaves are subsequently scanned using a flatbed scanner and the total leave area calculated using image editing software. A reflectivity test is performed for materials from the six plots. A total of six samples, each measuring 0.05 m by 0.05 m, are used for the reflectivity test. For the Plots 1 to 4, the selected leaves are glued onto a sample board and cover the surface entirely. Measurements from 23 days with clear sky conditions are averaged and used for analysis.

2.2 Customized globe thermometers

Estimation of t_{mrt} is done using the globe thermometer. Initially developed for indoor usage, the globe thermometer has since been adapted for outdoor use. For outdoor measurement, the 38 mm globe thermometer is a common option as the globe used is a table tennis ball, which can be readily purchased and conveniently replaced. The accuracy of the 38 mm globe thermometer can be adjusted to cater to outdoor conditions by recalibrating the mean convection coefficient. In this study, t_{mrt} is estimated using a formula specifically recalibrated for tropical outdoor use (Tan et al., 2013).

$$Tmrt = \quad Tg + 273.15 \ ^{4} + \frac{3.42 \times 10^{9} Va^{0.119}}{\varepsilon D^{0.4}} \times \ Tg - Ta \quad ^{0.25} - 273.15 \tag{1}$$

where,

t_g = Globe temperature (°C)
V_a = Air velocity (ms^{-1})
t_a = Air temperature (°C)
D = Globe diameter (mm)
ε = Globe emissivity

3 RESULTS AND DISCUSSION

The average diurnal air temperature profile is shown in Figure 2. The maximum and minimum air temperature recorded is 33.0 °C and 26.9 °C respectively. In general, plots with vegetation exhibit lower t_a during the day (With the exception of Plot 2). Plot 5 reached a peak temperature of 33.0 °C while Plot 1 registered the lowest peak temperature of 31.9 °C. Plot 2, which consists of Heliconia American Dwarf, is observed to be slightly higher than Plot 5. Both Plots 2 and 5 show higher air temperature readings than Plot 6, the control plot. At night, the air temperature for Plot 1 remains the lowest, while Plots 2 and 6 exhibit the highest air temperature. A lag of 1 hour is observed between the peak of the averaged solar irradiance and the peak of all the 6 plots.

The maximum and minimum values of t_{mrt} recorded are 63.0 °C and 24.9 °C respectively (Figure 3). The maximum difference during the hottest time (14:00 hrs) is approximately 6.0 °C. It is observed that Plots 4, 5 and 6 exhibit similar t_{mrt} profiles, peaking at approximately 63.0 °C. Of the six plots, Plot 1 (Phyllanthus cochinchinensis), has the coolest diurnal t_{mrt} profile, followed by Plot 2 (Heliconia American Dwarf) and Plot 3 (Sphagneticola trilobata). In the absence of sunlight (01:00 hrs – 07:00 hrs and 19:00 hrs to 00:00 hrs), the t_{mrt} profile for all six plots remain stable without much fluctuation.

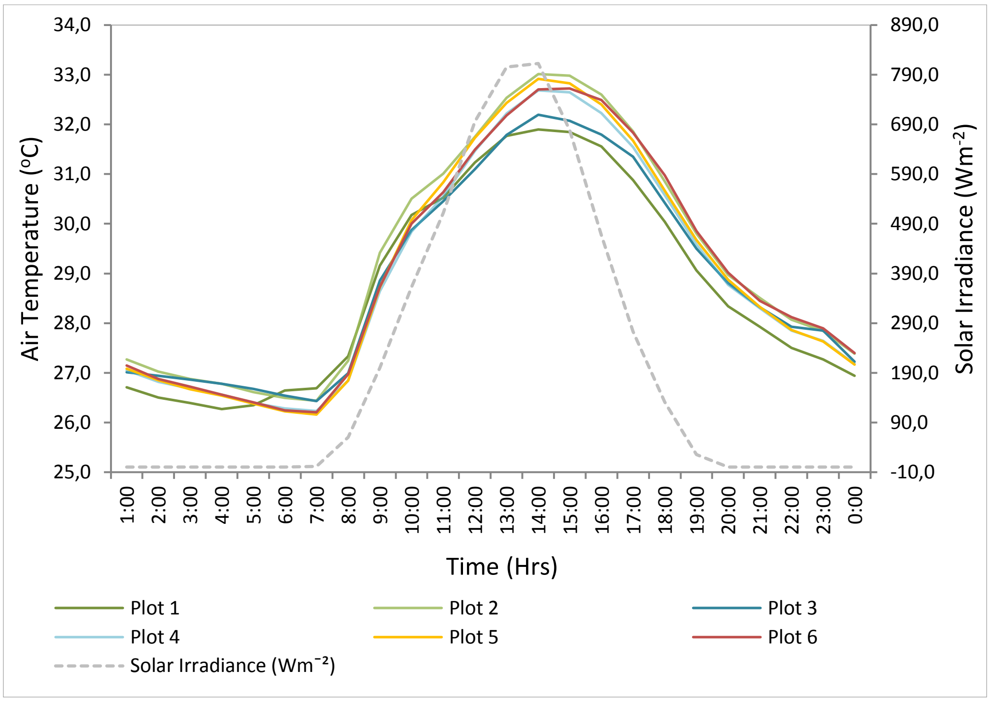

Figure 2. Diurnal t_a profile for clear sky conditions

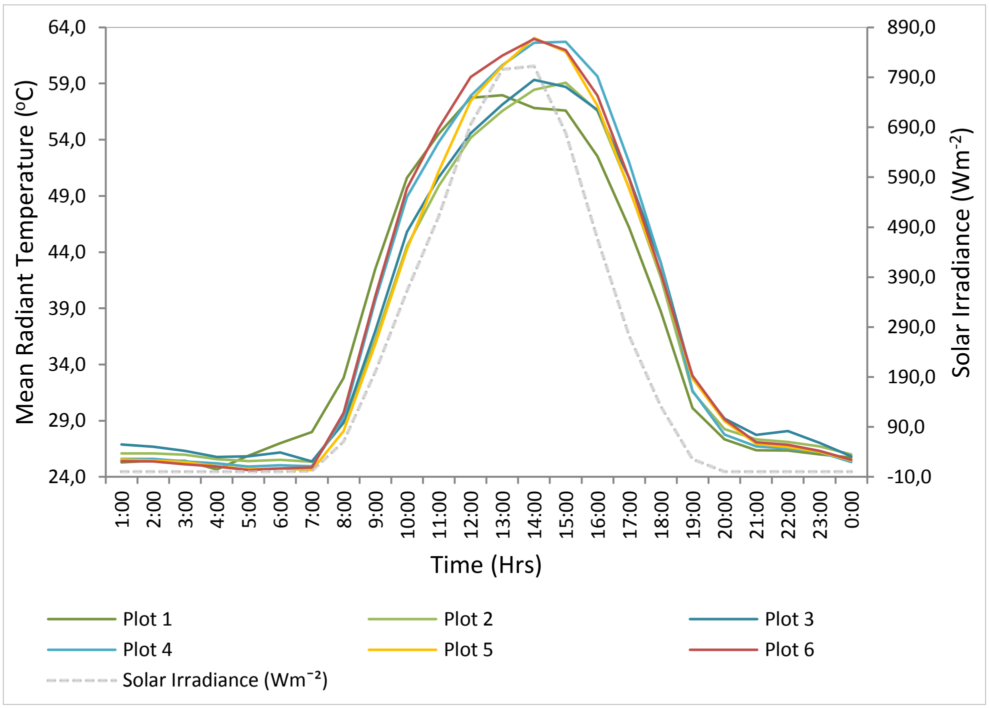

Figure 3. Diurnal t_{mrt} profile for clear sky conditions

3.1 Comparison of t_{mrt} and t_a between plots

The average t_a and t_{mrt} profiles of all 36 measurement points are shown in Figure 4. Only hourly profiles from 11:00 hrs to 15:00 hrs are displayed. This period is considered to be the hottest part of the day, with average solar irradiance ranging from 680.0 Wm^{-2} to 810.0 Wm^{-2}. In general, t_a is lower for Plots 1 to 3. Measurement Points 4 and 16 exhibits the lowest t_a profile at the hottest period (14:00 hrs), with temperatures of 32.1 °C and 31.9 °C respectively. In general, higher fluctuations in t_{mrt} can be observed in Plots 3, 4 5. The t_{mrt} profiles for Plots 1 and 2 have significantly less fluctuation.

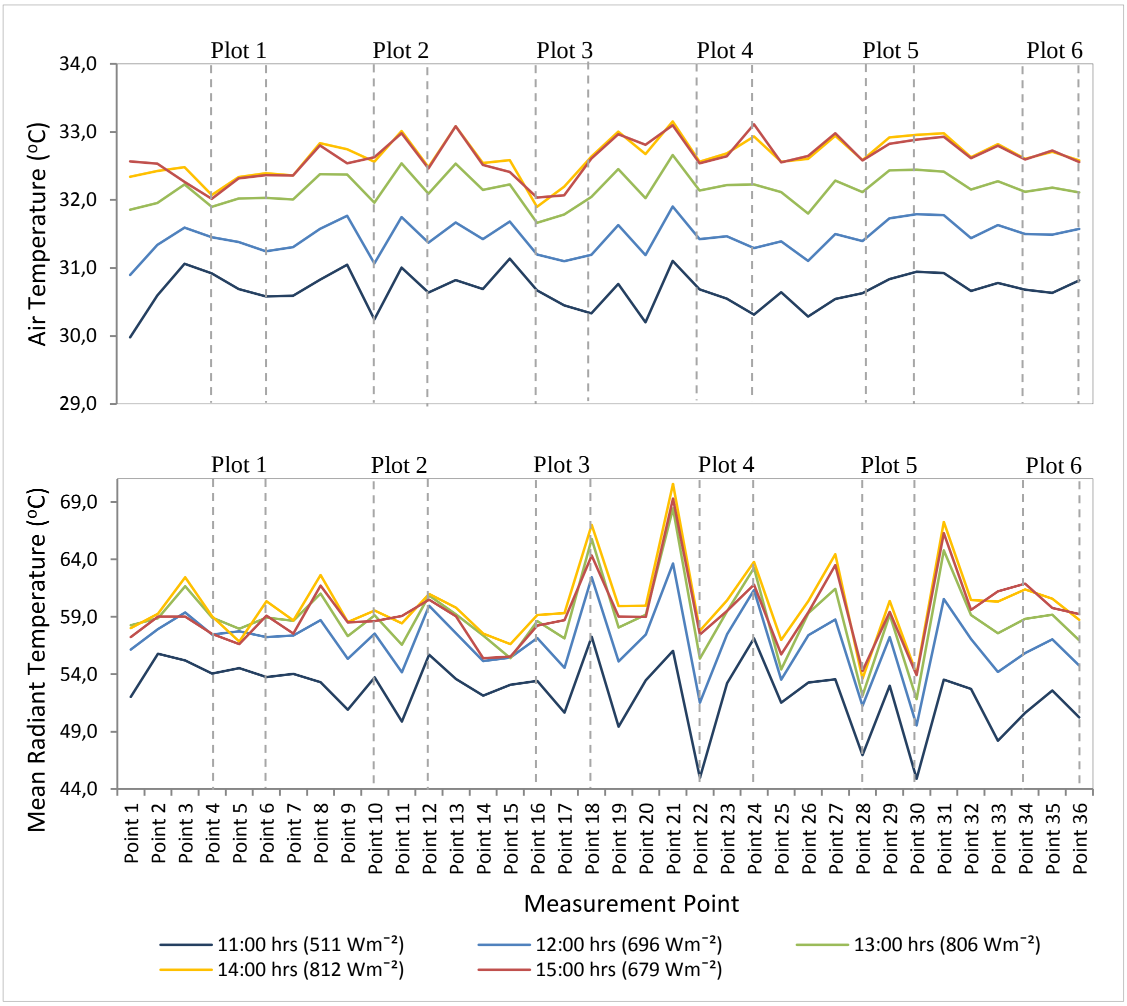

Figure 4. Profiles of t_a and t_{mrt} across 36 measurement points

3.2 Measurement of Leaf Area Index (LAI)

The LAI of all plants used in this study is shown in Table 2. The corresponding LAI for each plant provided by the Singapore National Parks Board (NParks) are also listed as reference (Tan and Sia, 2009). Using the indirect measurement method, Plots 1 and 3 show higher LAI values of 4.34 and 4.60 respectively. When the direct measurement method is utilized, the results are reversed. Plots 2 and 4 show much higher LAI values of 7.21 and 4.45, whereas Plots 1 and 3 show lower LAI values. The difference in both methods may be due to the excess direct shading captured by the LAI-2000 plant canopy analyzer to obtain measurement using the indirect measurement method.

Table 2. LAI values for Plots 1 to 4

Plot	Plant Species	LAI Indirect measurement (Averaged)	LAI Direct measurement	LAI Recommended by Nparks
1	Phyllanthus cochinchinensis	4.34	2.78	Shrub (Dicot) 4.50
2	Heliconia American Dwarf	3.47	7.21	Shrub (Monocot) 3.50
3	Sphagneticola trilobata	4.60	3.59	Ground cover 4.50
4	Cow grass	2.28	4.45	Turf 2.00

3.3 Reflectivity test

Material reflectivity is tested using a spectrophotometer and the results are shown in Figure 5. Under the visible light spectrum, which spans from approximately 380 nm to 700 nm, cool paint exhibits the highest reflectivity of above 80.0 %. This is followed by concrete with a peak of 40.4 %. Vegetation under visible light displays relatively lower reflectivity, peaking at 25.2 % (Plot 4), 21.6 % (Plot 3), 14.5 % (Plot 1) and 13.8 % (Plot 2) at around 550 nm.

For wavelengths in the near-infrared range (700 nm to 2500 nm), the reflectivity of cool paint reduces gradually, while the reflectivity of concrete increases at a similar pace. The reflectivity of the plants increases significantly from 700 nm to 1400 nm and undergoes a series of fluctuations, rising again from 1600 nm to 1800 nm and 2200 nm. It can be seen that the reflectivity of plants from the range of 701 nm to 1300 nm can equal that of cool paint.

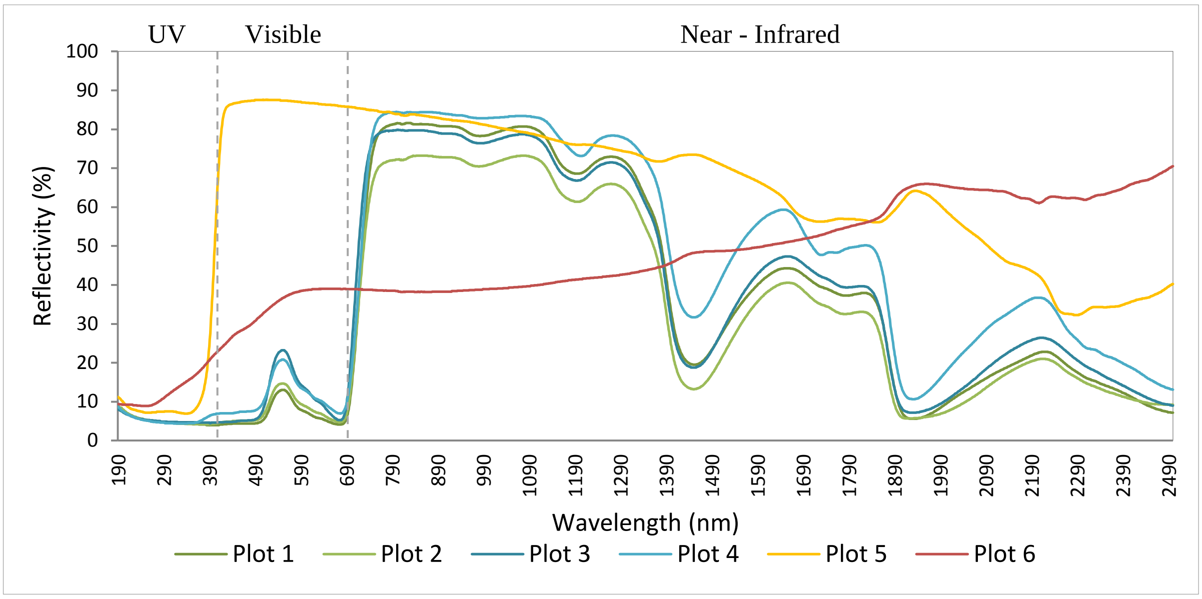

Figure 5. Spectrometer test results

3.4 Roof surface temperature

The average diurnal roof surface temperature profile is shown in Figure 6. The solar irradiance peaked at 1004.4 Wm^{-2} at 14:00 hrs. The surface temperature under Plots 1 to 4 is significantly lower than Plots 5 and 6 during daytime. The maximum difference between Plot 6 and Plot 3 is approximately 14.4 °C. The surface temperature of Plots 1 to 4 is maintained at between 26.0 °C to 29.0 °C throughout the day. In contrast, the surface temperature of Plots 5 and 6 increases greatly during the day. A peak of 45.9 °C is observed at 13:25 hrs for Plot 6, while the corresponding temperature of Plots 1 to 4 is only in the range of 27.0 °C to 27.5 °C. It can be observed that the diurnal surface temperature profile for Plots 5 and 6 are similar for large parts of the day, except for periods of high solar irradiance (11:00 hrs to 14:00 hrs), where temperature readings for Plot 5 are slightly lower than that of Plot 6. From 03:00 hrs to 07:00 hrs, it can be observed that Plots 5 and 6 (Cool paint and concrete roof) have a slightly lower temperature compared to the other plots.

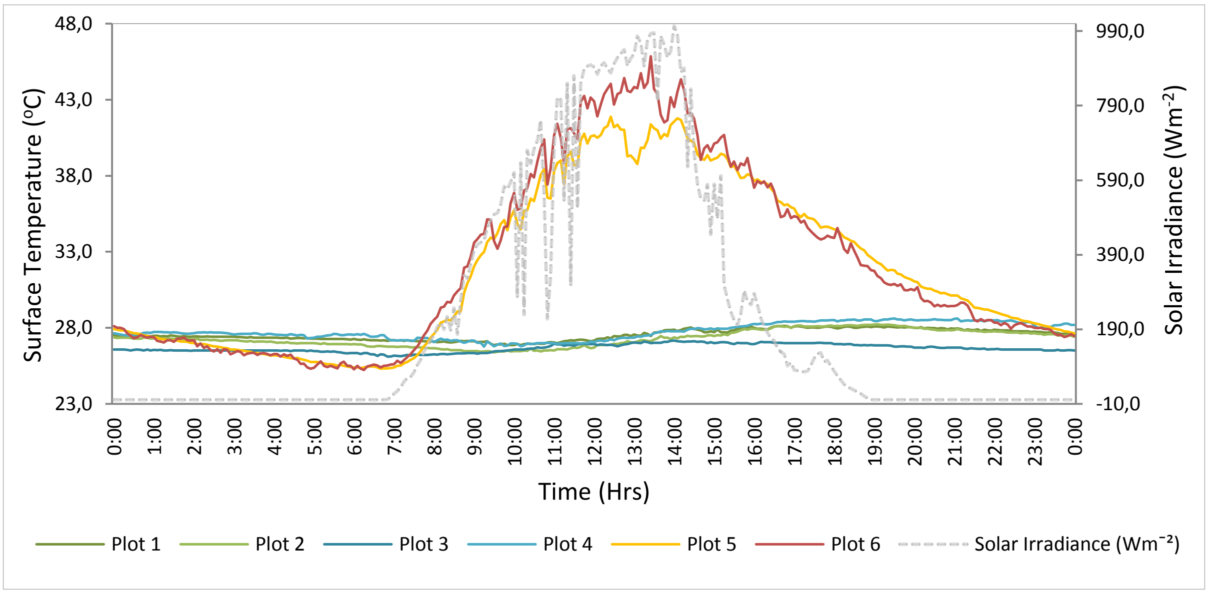

Figure 6. Roof surface temperature - 9th October 2012

3.5 Cooling effect of cool roofs and green roofs

Results from the various measurements show that when cool roofs and green roofs are exposed to direct solar irradiance, the surface temperature is significantly lower compared to the exposed concrete roof (Figure 6). However, only green roofs provide a substantial reduction in air and mean radiant temperature. At peak temperature, air temperature 1.3 m above the cool roof can reach up to 32.9 °C, which is 1.0 °C higher than Plot 1.

A possible reason for the lower air and mean radiant temperature experienced by Plots 1 to 4 may be due to the evapotranspiration of plants. The presence of moisture in the soil and emancipation of water from the plant stomata increases the latent heat of vaporization and cools the surrounding air. As shown in Figure 4, the cooling effect of Plot 1 is not just limited to Measurement Point 5, but for up to 3.0 m away.

Besides lowering the t_a and t_{mrt}, the introduction of green roofs can also help to minimize temperature fluctuations. Figure 4 shows that the t_{mrt} around Plots 1 to 4 fluctuate less than around Plots 5 and 6, and Figure 6 shows that the surface temperature for Plots 1 to 4 exhibit a diurnal temperature differential of about 3.0 °C, while Plots 5 and 6 show a diurnal temperature differential of about 20.0 °C. Fluctuations in radiant temperature will drastically change the solar radiation absorbed by an individual and the energy budget of the person, affecting the overall thermal comfort (Brown and Gillespie, 1995).

Results from the reflectivity test shows that for the visible light range (380 nm to 700 nm), the cool roof can have a reflectivity of more than 80 %. In comparison, the reflectivity of plants is in the range of 20 %, which is rather low. However, at the near-infrared range, especially from the range of 700 nm to 1400 nm, the reflectivity of plants can almost equal that of cool paint (Figure 5). Since up to 50 % of the solar irradiance distribution is in the near-infrared zone, this attribute may be crucial for reflecting heat back to the atmosphere. The high reflectivity of plants, in addition to the inherent cooling effect through evapotranspiration, may be the main factors leading to significantly lower t_s, t_a and t_{mrt} values.

4 CONCLUSIONS

Results from this study show that for clear sky conditions, the plots with vegetation can reduce the surrounding t_a and t_{mrt} by about 1.0 °C and 6.0 °C respectively. Reduced fluctuation in diurnal t_{mrt} is also observed for the plots with vegetation. The effect in temperature reduction is evident up for to 3.0 m away from the midpoint of the green plots.

Results from the reflectivity test show that cool paint has high reflectivity in the visible light range, and plants have comparable reflectivity in the near-infrared range (Figure 5). It is important to note that only a flat piece of leaf is used for testing with the spectrometer. Therefore, test results may not indicate the reflectivity of the entire shrub. Also, due to varying leave orientation, incident solar radiation may not be reflected directly back to the atmosphere. While cool roofs exhibit a high solar reflectance, the performance may decline over time due to aging, dirt and weathering (Bretz and Akbari, 1997; Synnefa et al., 2007). Studies have shown that due to dirt accumulation, the reflectivity of white-coated roofs may drop approximately 15 % in the first year, followed by a decline of 2 % annually (Bretz et al., 1998).

The installation of green roofs is much more complex and costlier than cool roofs. Most green roofs require a support tray or waterproofing membrane, soil substrate and plants. For cool roofs, the roofs only need to be painted with cool paint. Green roofs are also prone to maintainability issues. There will be inevitable drawbacks, such as the penetration of plant roots into the roof waterproofing membrane, damaging the roof insulation (Chew, 2010). Recognizing the challenges of installation and maintenance, countries such as Singapore have introduced incentive schemes to promote the incorporation of green roofs into building design (National Parks Board, 2013).

Cool roofs and green roofs are common staples in the design palette of architects and designers. In quantifying the cooling effect of different plants and cool material, objective criteria can be used to assess the performance of the outdoor roof space in terms of thermal comfort.

5 REFERENCES

Akbari, H. (2002). Shade trees reduce building energy use and CO_2 emissions from power plants. *Environmental Pollution*, 116, 119-126.

Akbari, H., Pomerantz, M., Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy,* 70(3), 295-310.

Arthur, H.R., Akbari, H., Romm, J.J., Pomerantz, M. (1998). Cool communities: strategies for heat island mitigation and smog reduction. *Energy and Buildings*, 28, 51-62.

Baik, J.J., Kwak, K.H., Park, S.B., Ryu, Y.H. (2012). Effects of building roof greening on air quality in street canyons. *Atmospheric Environment*, 61, 48-55.

Bretz, S. E., Akbari, H. (1997). Long-term performance of high-albedo roof coatings. *Energy and Buildings*, 25(2), 159-167.

Bretz, S.E., Akbari, H., Rosenfeld, A. (1998). Practical issues for using solar-reflective materials to mitigate urban heat islands. *Atmospheric environment,* 32(1), 95-101.

Brown, R. D., Gillespie, T. J. (1995). *Microclimatic landscape design: creating thermal comfort and energy efficiency*, John Wiley & Sons.

Castleton, H.F., Stovin, V., Beck, S.B.M., Davison, J.B. (2010). Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings*, 42, 1582-1591.

Chew, M. (2010). *Maintainability of facilities: for building professionals*, World Scientific.

Epstein, Y., Moran, D.S. (2006). Thermal comfort and heat stress indices. *Indust Health*, 44, 388-398.

Mayer, H. (1993). *Urban bioclimatology*. Experientia, 49, 957-63.

Mayer, H., Höppe, P. (1987). Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, 38, 43-9.

National Parks Board. (2013). Skyrise Greenery Incentive Scheme 2013. <http://www.skyrisegreenery.com/index.php/home/incentive_scheme/about/>

Parizotto, S., Lamberts, R. (2011). Investigation of green roof thermal performance in temperate climate: A case study of an experimental building in Florianópolis city, Southern Brazil. *Energy and Buildings*, 43, 1712-1722.

Saadatian, O., Sopian, K., Salleh, E., Lim, C.H., Riffat, S., Saadatian, E., Toudeshki, A., Sulaiman, M.Y. (2013). A review of energy aspects of green roofs. *Renewable and Sustainable Energy Reviews*, 23, 155-168.

Santamouris, M. (2012) Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, http://dx.doi.org/10.1016/j.solener.2012.07.003

Synnefa, A., Santamouris, M., Akbari, H. (2007). Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy and Buildings*, 39, 1167-1174.

Tan, P. Y., Sia, A. (2009). *Leaf Area Index of tropical plants: A guidebook on its use in the calculation of green plot ratio*. National Parks Board.

Tan, C. L., Wong, N. H., Jusuf, S. K. (2013). Outdoor mean radiant temperature estimation in the tropical urban environment. *Building and Environment*, 64, 118-129.