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Green and cool roofs' urban heat island mitigation potential in tropical climate

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ABSTRACT

Urban heat island (UHI) can significantly affect building's thermal-energy performance. Urban materials absorb solar and infrared radiation and the accumulated heat is dissipated in the atmosphere increasing further the air temperature. Roofs are envelope components which with advanced solutions such as cool roofs or green roofs can provide significant energy savings in air-conditioned buildings and improved indoor thermal conditions. By means of dynamic simulations in EnergyPlus software a numerical comparative analysis between these two solutions was done in a tropical climate like Singapore's, taking into account climatological, thermal, optical and hydrological variables.

Simulations of a typical summer day in Singapore were assessed to determine (i) UHI reductions for different green/cool roof scenarios; (ii) the diurnal heat fluxes dynamics and (iii) the buildings' thermal energy reduction for the investigated cases.

The results show that during peak periods (9 am to 5 pm) cool roofs reduce heat gain by about 0.14 KWh/m^2 (8%) and green roofs mitigate considerably less to about 0.008 KWh/m^2 (0.4%). And for the whole of a summer design day, cool and green roof reduces heat gain by 15.53 (37%) and 13.14 (31%) KWh/m^2 respectively.

The numerical simulation results confirm that an appropriate selection of roof materials contribute to the reduction of the negative effects of UHI but experimental data for air-conditioned buildings are yet to be carried out.

1. Introduction

The temperature difference between urban and rural areas, a phenomenon known as urban heat islands (UHI), has been the subject of extensive research over the past decades (Oke, 1982; Santamouris et al., 2014; Santamouris, 2015). The decrease in vegetation, increasing urbanization, and steep rise of population over the last century has led to an elevation in urban temperatures that exacerbate the phenomenon, in addition to its adverse association with thermal discomfort and endangerment of human health (Cartalis et al., 2001)) and it has caused more than 150,000 lives annually according to the World Health organization (WHO, 2005).

Especially the energy consumption for cooling buildings has increased tremendously in recent years (Asimakopoulos et al., 2012; Oikonomou et al., 2012). According to the International Energy Agency, on a global-scale, buildings account for 30–40% of worldwide energy consumption. In Singapore, about 50% of total electricity produced goes into buildings and for cooling alone buildings use about 30% of the country's total electricity production (Tan et al., 2010). The increase of urban temperatures that increases overheating risk and indoor thermal discomfort is greatly influenced by the sensible heat flux and energy storage of the construction materials (Pyrgou et al., 2017; Salata et al., 2015; Santamouris et al., 2014; Santamouris, 2014a). Roofs of buildings constitutes about 20–25% of urban surfaces. Studies found that the solar radiation impinging on the roofs can easily raise their outer surface temperature up to 50–60 °C (Andrade et al., 2007). To negate the above conditions the most common urban heat mitigation technologies associated with roofs are: (a) the cool (or reflective) roofs, and (b) green roofs (Yang, 2017).

The surface energy fluxes contribute to the Earth's mean energy

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budget and can assist in the explanation of the mitigation mechanisms. The net radiation (Q*) may be defined as:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \tag{1}$$

where Q_H, Q_E and ΔQ_S are the sensible, latent and conduction/storage heat fluxes respectively. Anthropogenic heat (Q_F) is fairly difficult to calculate and depends on energy consumption within buildings and transportation. The net heat flux by horizontal advection (ΔQ_A) has values close to zero and therefore is not considered. Cool roofs mitigation effect focuses on the decrease of the net radiation Q* by the increase of albedo of the urban surface (Li et al., 2014; Roman et al., 2016) and the decrease of the sensible heat flux and heat storage. Assuming a steady net radiation Q*, green roofs increase the latent heat flux compared to the sensible heat flux and the heat storage into the buildings and therefore leading to lower energy demands for cooling for the building. Latent heat loss is accomplished via either the transpiration of the plants or the evaporation of moisture from the soil, resulting to lower surrounding air temperature and a net cooling effect (Tian et al., 2017). Both these mitigation strategies aim to lower the roof surface temperatures thereby decreasing the sensible heat flux released to the atmosphere.

Cool roofs traditionally use natural white materials or second generation materials like artificial white paint to reflect the most of the incoming solar radiation and thereby decrease the net radiation within the building. They have performed better at reducing cooling loads within buildings when compared to conventional roofs (Doulos et al., 2004; Kolokotsa et al., 2012a, 2012b; Synnefa and Santamouris, 2012) leading to decreased air conditioning needs and improved indoor thermal comfort. Recent advancements in the field of cool coatings has paved way to thermo chromic paints, PCM doped coatings and advanced colored materials that use infrared reflective pigments. These present higher reflectivity compared to conventional materials and contribute to better performing buildings (Akbari and Levinson, 2008; Karlessi et al., 2011, 2009; Kolokotsa et al., 2012a, 2012b; Synnefa et al., 2011, 2007). Cool coatings can be applied both on existing and new roofs and they are environmentally-friendly as they don't add any additional waste.

Green roof typically is a vegetative layer with a growing medium, like soil, over a waterproofing membrane. There are two distinctive types in green roofs; extensive and intensive. Extensive roofs are cost-effective and easy to maintain, having a thin layer of low-growing vegetation and a shallow soil layer. Intensive green roofs require very high maintenance and heavy construction for support as it includes a deep growing medium and high-growing medium such as trees and shrubs. Green roofs are used globally for the insulation of buildings (Oberndorfer et al., 2007), as they enhance heat transfer through roofs and provide steadier outside roof temperatures in cold winters and hot summers (Jaffal et al., 2012; Tian et al., 2017). Additional cooling effect in green roofs can be obtained by increasing soil moisture through irrigation (Li et al., 2014). Creating green roofs on buildings requires a deep investigation of the most appropriate soil composition and height to ensure adequate drainage with respect to the existing weather conditions and whether the building can withhold the extra load. The many advantages of green roofs include decreased energy consumption within the buildings by reducing absorption of solar radiation (has higher reflectivity compared to normal roofs) and evapotranspiration of plants and insulation of buildings, reduction in UHI, improved microclimate, better air quality, reduced air pollution and greenhouse gas emissions as the plants remove the air pollutants through carbon sequestration, increase water-permeable city surface, enhanced stormwater management and increased durability of roof materials.

The studies conducted in the United States and Europe quantified the heat gain reduction, heat fluxes reduction and the thermal effect in these climate zones (Akbari and Konopacki, 2004; Kolokotroni et al., 2013; Kontoleon and Eumorfopoulou, 2008). A few studies have also been carried out in tropical climate (Zingre et al., 2015) to evaluate the use of cool roof and green roof at the location with abundant annual-averaged solar irradiation. Various boundary conditions (heat fluxes or heat transfer coefficients based on thicknesses and materials) affect the heat and moisture exchange between surface and atmosphere. The utilization of various scenarios of green/cool roofs in different locations in the world with variating boundary conditions result in differences in the surface energy balance (Sharma et al., 2016) and indoor air temperatures. In conventional roofs, incoming energy is mostly translated into sensible heat flux increasing the surface's surrounding air temperature. Kolokotsa et al. (2012a, 2012b) made a comparative analysis of cool roofs and green roofs in Crete, Rome and London with respect to a conventional roof, revealing higher mitigation potential of UHI for albedo higher than 0.6 for cool roofs and leaf area index higher than 1 for green roofs (Kolokotsa et al., 2012a, 2012b). Meteorological conditions and sunshine duration of tropical regions differ than climates in Europe (Mediterranean, subtropical or polar) and the US (subtropical, monsoon, arctic, Mediterranean) resulting to different boundaries and indoor air temperature behaviour. Particularly, high temperatures and high air moisture, apparent in tropical areas, affect the green roof performance because when the green roof is at a higher level of moisture than its field capacity, water will drain even if the roof is not irrigated. However, the overall energy performance of the two techniques has not been examined with different parametric and constructional characteristics under tropics and further investigation is needed.

From the literature review part above, the comparison of cool roof and green roof in detail is not studied for tropical climate. The purpose of this paper is to observe the heat fluxes and the thermal effect of cool and green roof for future design purposes and current design modifications for tropical climate through computer simulations only. Specifically, the scenarios studied evaluate the diurnal heat fluxes using recent meteorological data and variating properties for cool and green roofs in tropical climate.

2. Area of study

According to Singapore meteorological data from 1980 to 2010, Singapore is a tropical island country with mean outdoor temperature of 28 deg C (minimum 24 to maximum 32 deg C) and 84% outdoor relative humidity. Singapore shows a steady climatic condition throughout the year. Simulations have been carried out majorly for a summer design day as temperature vary very little from month to month and day to day as the proximity of the sea has a moderating influence on its climate. In the last 50 years, there has been a rapid development in Singapore with farms and forest areas diminishing and built-up area increasing from 28 to 50% from 1955 to 1998 (Chow and Roth, 2006). Due to this, roof area exposed to solar radiation has increased and the Government has set targets to cover their roofs with cool or green roofs by 2030 to bring about a positive change in their climate.

3. Variables affecting behaviour of cool and green roofs

Santamouris (2012) and Kolokotsa et al. (2013), identified four broader variables that influenced the behaviour and performance of the cool and green roofs (Kolokotsa et al., 2013; Santamouris, 2014b).

3.1. Climatological variables includes

- Intensity of solar radiation that determines heat storage, surface temperature and thermal balance of roofs.
- Ambient temperature that determines the sensible heat released by roofs.
- Ambient Humidity and precipitation that determines the moisture balance in green roofs.
- Wind speed and atmospheric turbulence that determines heat transfer coefficient between the surface and atmosphere.

3.2. Optical variables includes

- Roof albedo and emissivity define the performance in reflective roofs.
- Absorptivity of vegetation define the shielding effects in green roofs.

3.3. Thermal variables includes thermal capacity of roofs and their U-values

3.4. Hydrological variables include irrigation rate and moisture content of soil that defines the latent heat phenomena in green roofs

4. Methodology

Cool roofs and green roofs are examined as mitigation technologies to lower the roof surface temperatures and respectively decrease the heat flux released to the atmosphere. This study calculates, analyses and compares the mitigation potential of both these technologies.

- A case study institutional building model was developed using Open Studio and Energy Plus. The latter is popular for transient building simulation with conventional roof characteristics (Costanzo et al., 2016; Kolokotroni et al., 2016) but also for the evaluation of cool roof and green roof models (Kolokotsa et al., 2012a, 2012b; Sailor et al., 2012). There is no experimental data validation for this study. However, the model was calibrated and validated by the study carried by Yang et al. (2016) to estimate the performance of cool and green roofs (Yang et al., 2016).
- Then a parametric study was performed to evaluate the sensible heat flux released to the atmosphere for roofs under different building construction characteristics in tropical climate. The parametric study included the following:

For the cool roofs, the impact of the albedo, the U-value of the roof and its thermal capacitance has been determined for tropical climate. In particular, the following sensitivity analysis have been performed:

- Analysis of the sensible heat flux released for different solar reflectance versus the building's thermal mass.
- Analysis of the sensible heat flux released for different solar reflectance versus the building's insulation.

For green roofs, the impact of plant characteristics and irrigation rate has been calculated for the same climatic conditions as above. In particular, the following comparisons have been performed:

- Analysis of the sensible heat flux released versus the characteristics of the plants.
- Analysis of the sensible heat flux released versus irrigation rate.

The different scenarios used for simulation and their thermal properties are described in detail in their respective sections.

5. The building model

The case study building for the first phase is named SDE1 and is a research office building situated inside the campus of the University of Singapore and houses a part of the built environment school. This particular building has been chosen for this study since it is easily accessible for detailed modelling and all data about construction materials are readily available and this ensures simulation accuracy. This 3-storey institutional building, hosting mainly offices, computer rooms, amphitheatres and open plan architecture studios, is designed under standard design conditions and construction methods. Energy Plus v8.5 and Open Studio 2.3 offered the capability to develop the building model and helped to simulate the sensible heat flux for both cool and green roofs across a wide range of thermal properties under the tropical climatic conditions of Singapore. The building was simulated under standard HVAC system loops.

Table 1
parameters for sensitivity analysis.

	Variable	Value
ɵ1	Thickness (m)	0.15
ɵ2	Conductivity (W/m-K)	0.38
ɵ3	Density (kg/m^3)	1200
ɵ4	J/kg-K	1000
ɵ5	Solar absorptance	0.7
ɵ6	Visible absorptance	0.7

6. Sensitivity analysis

Morris Method (Morris, 1991), as is tested in different studies on the building material and energy sensitivity studies (Campolongo et al., 2007; Eisenhower et al., 2012; Menberg et al., 2016), is adopted to test the roof material sensitivity on the building roof heat gain rate.

Six variables, listed in Table 1, are changed to ± 20% of each original value randomly. Elementary effect of the six variables are investigated based on the assumption that the elementary effect can be summarised accurately by the measures of absolute mean (Campolongo et al., 2007) and standard deviation (Morris, 1991).

The results of the sensitivity analysis are reported in Fig. 1. The results are quite consistent across different zones. The Solar Absorptance of the roof material shows the highest $\mu*$, (Absolute mean value of elementary effects), indicating a significant influence on the model's output. The solar absorbance also exhibited the highest σ value, (Standard deviation value), indicating its important role in interactions with other factors, followed by thickness and conductivities. Based on these results, the parametric study on different conditions and materials investigated under cool roof will include effect of sensible heat flux especially during peak periods. Surface inside and surface outside temperatures will be compared to get a holistic effect of cool roof performance on a tropical institutional building.

7. The mitigation potential of cool roofs

The purpose of this study is to understand the effects of heat fluxes and thermal variations of cool and green roofs for future design purposes and current design modifications. The 3-storey institutional building designed and constructed under typical tropical conditions. The various scenarios developed to evaluate the diurnal heat fluxes uses recent meteorological data and variating properties for cool roofs.

The first step is to study the combined effects of sensible heat flux on the surrounding environment for the whole summer period. Fig. 2 shows the comparison of UHI mitigation potential for a typical construction between different cool roof albedos 0.9, 0.8, 0.7, 0.6 and conventional roof albedo of 0.3 under tropical conditions of Singapore. It is observed as a trend that roofs with higher solar reflectance (0.6, 0.7, 0.8 and 0.9) present a negative median sensible heat flux. As the solar reflectivity of the roof increases from 0.6 to 0.9, the median sensible heat flux drops from $-1.42\,W/m^2$ to $-16.8\,W/m^2$. On the contrary, the conventional roof presents a median of $5.94\,W/m^2$. Moreover, the maximum values for cool roofs with SR = 0.6–0.9 range from 67.6 to 16.1 W/m^2 correspondingly whereas the conventional roof on the other hand presents a number as high as 171 W/m^2. This analysis clearly shows that cool roofs minimize the heat stress on the surrounding atmosphere and are highly heat reflecting when compared to conventional roofs.

Similar results can be gathered from Fig. 3 that represents the sensible heat flux for different cool roof albedos on a typical summer design day. Around 13:00, all roof scenarios exhibit the daily maximum heat flux when the outdoor temperature also is at its maximum (around 33 °C). It is noted that a conventional roof with SR = 0.3 presents a maximum heat flux of 268 W/m^2 whereas a cool roof with SR = 0.9 presents a daily maximum at just 1 W/m^2. From Table 2, it is observed

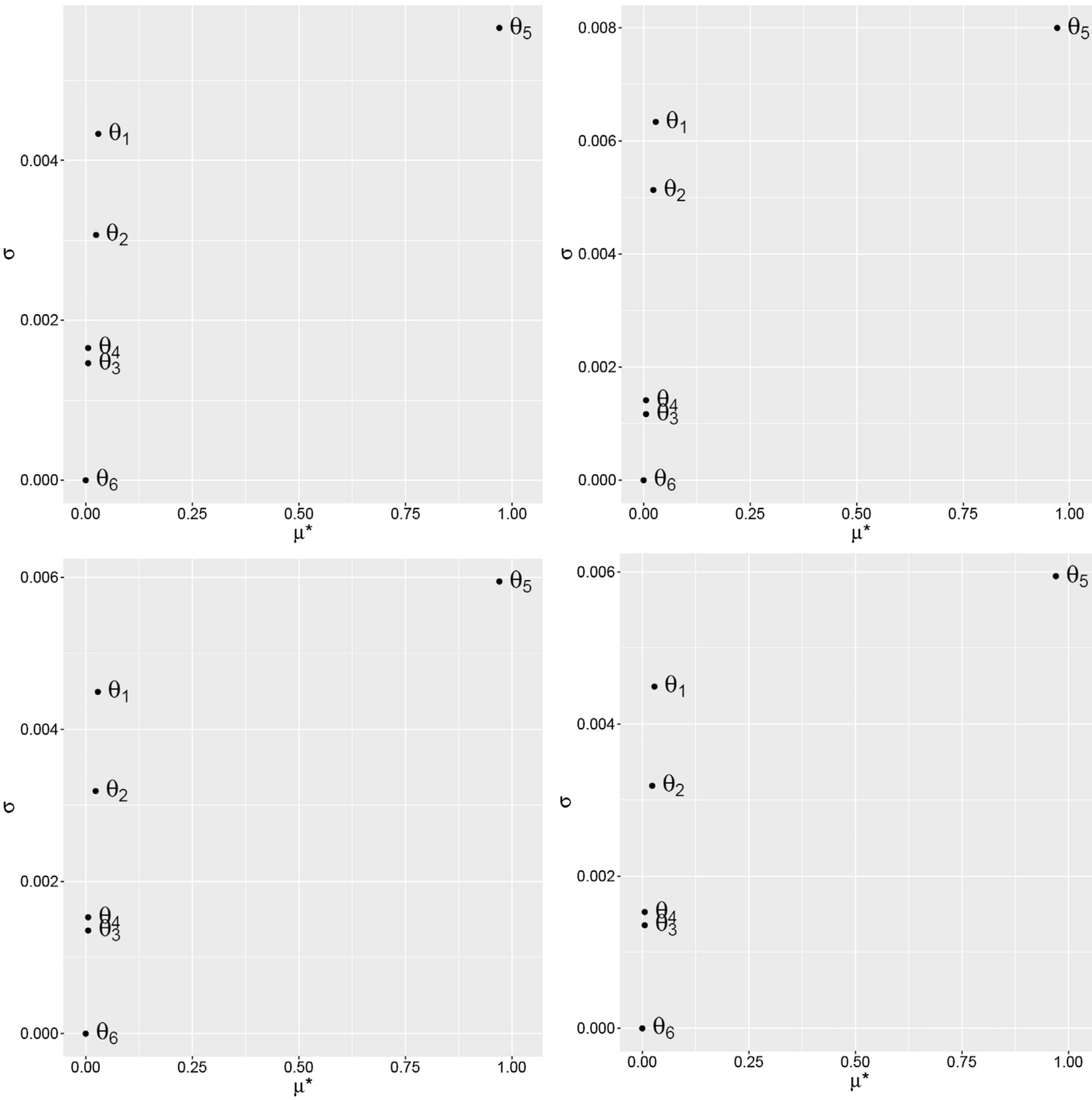

Fig. 1. Scatter plots of the Morris sensitivity measures for various parameters of different zones.

that on a summer design day, a conventional roof gives out a total of 1524 W/m^2 whereas a highly reflective cool roof presents a negative value of -587 W/m^2. Therefore, it can be concluded that on a typical summer design day, a conventional roof emits 2112 W/m^2 additional sensible heat to the surrounding atmosphere than a highly reflective cool roof with SR = 0.9.

7.1. Cool roof vs. thermal mass characteristics

In this section, a conventional roof and a highly reflective cool roof (SR = 0.9) with different thermal mass characteristics, namely, heavy weight concrete (HWC), medium weight concrete (MWC), light weight concrete (LWC), ultra-light weight concrete (ULWC) and wood has been examined using the building model developed in Energy Plus 8.5. The different scenarios and their respective characteristics are outlines in Table 3.

These thermal mass characteristics along with the corresponding roof albedos present a large variation in the sensible heat flux produced. Figs. 4 and 5 gives the sensible heat flux for a conventional roof and a highly reflective roof across various thermal mass characteristics.

The graphs present the following observations -

1. Sensible heat flux is largely negative for a cool roof with SR = 0.9 across different roof materials especially for heavy weight and medium weight concrete.
2. Night time UHI for a conventional roof is very wide ranging from -30 W/m^2 to 20 W/m^2 with an average difference in the order of 10, 25, 14, 2 W/m^2 for different thermal masses from HWC to ULWC whereas for a cool roof with SR = 0.9, the extreme limits are relatively narrower between -40 W/m^2 to -20 W/m^2 but follows a similar trend for difference as in conventional roof in the order of 3, 7, 4, 3 W/m^2. It can be concluded from this observation that during the night, the diurnal range for HWC and MWC is much greater than LWC, ULWC and wood for both conventional and cool roof, but cool roof presents a much lower range than conventional roof.
3. Peak hour variation between 9:00 and 17:00 is extremely important to understand the impact of thermal mass. Comparatively, heavy weight roofs with greater solar reflectivity presents a higher mitigation potential than lightweight roofs. The extreme peak difference between HWC and ULWC for a conventional roof is observed to be

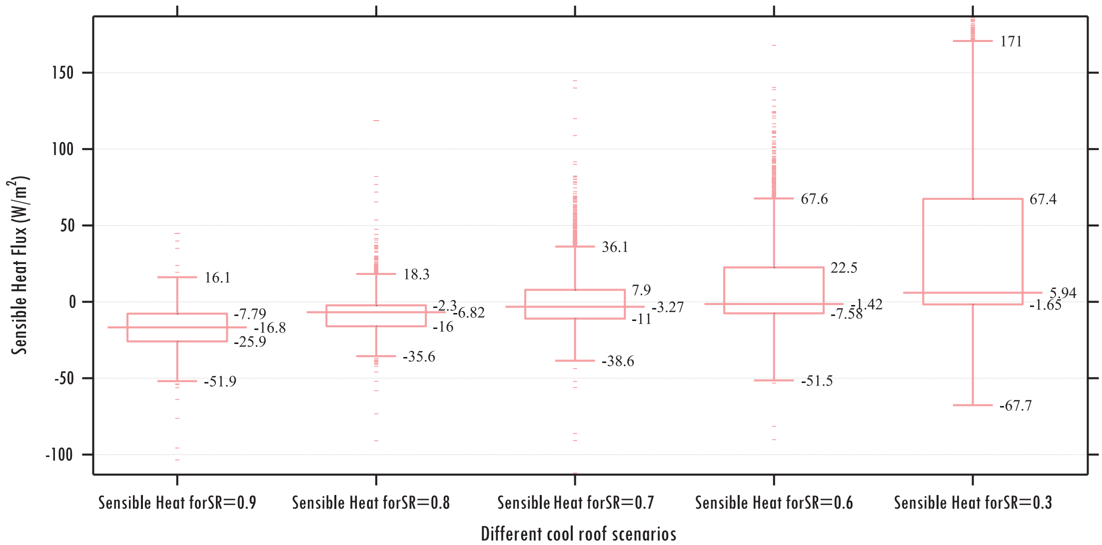

Fig. 2. Comparison of UHI mitigation potential for a typical construction between different cool roof albedos and conventional roof.

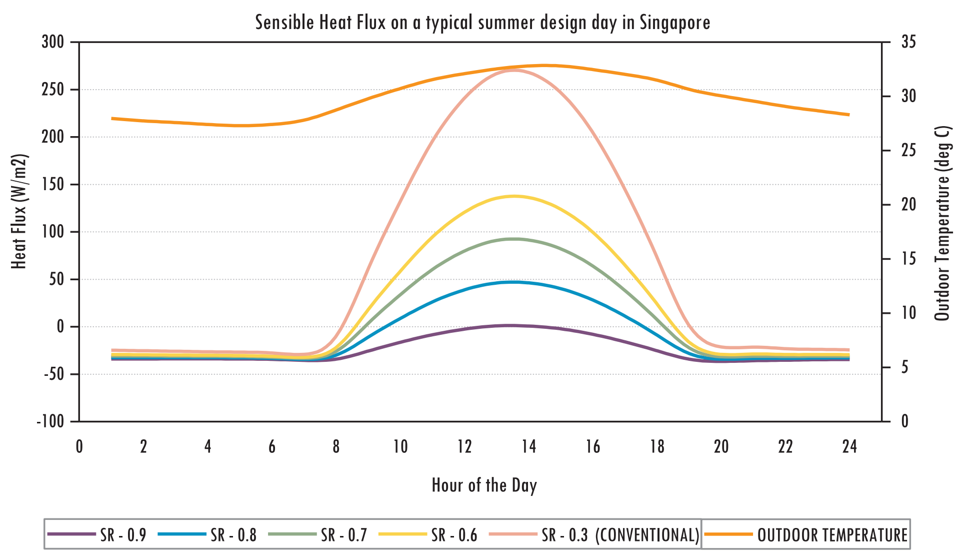

Fig. 3. Sensible Heat flux for a typical construction on a typical summer design day in Singapore with various solar reflectance scenarios.

Table 2
Comparison of sum of sensible heat on a typical summer design day for various roofs' albedo.

SR	0.9	0.8	0.7	0.6	0.3
Integrated sensible heat (W/m^2)	−587.4	−230.1	125.5	478.9	1523.7

125 W/m^2 whereas for a cool roof with SR = 0.9, the difference is much lesser at 33 W/m2. Hence the daytime benefits of a heavy weight construction for a roof with high reflectance is higher compared to a conventional roof.

4. The day and night fluctuation of sensible heat flux is much higher and positive for a conventional roof compared to a highly reflective cool roof which is comparatively negative for all thermal mass configurations.5. From Fig. 6, When we compare sensible heat flux for different thermal mass configurations between conventional and cool roofs, It is observed that maximum peak differences occur at around 14:00–15:00 and for an ultra-light weight concrete construction it is 316 W/m^2 which is way higher compared to that of a heavy weight construction which is 231 W/m^2. It is the opposite for minimum peak difference which occurs at around 7:00–8:00 where a lightweight construction is the least in the order of 3 W/m^2 when compared to heavy weight which is 24 W/m^2.

Table 3
Thermal characteristics of cool roof scenarios.

Name of material	HWC	MWC	LWC	ULWC	WOOD
Roughness	Medium rough	Medium rough	Medium rough	Medium rough	medium smooth
Thickness (m)	0.15	0.15	0.15	0.15	0.15
Conductivity (W/m-K)	2	1.13	0.38	0.14	0.117
Density (kg/m^3)	2400	2000	1200	800	430
Specific Heat (J/kg-K)	850	1000	1000	870	1630
Thermal absorptance	0.9	0.9	0.9	0.9	0.9
Solar absorptance	0.3–0.9	0.3–0.9	0.3–0.9	0.3–0.9	0.3–0.9

Fig. 7 compares the sensible heat flux for different roof albedos across various thermal mass configurations for the peak hours of a

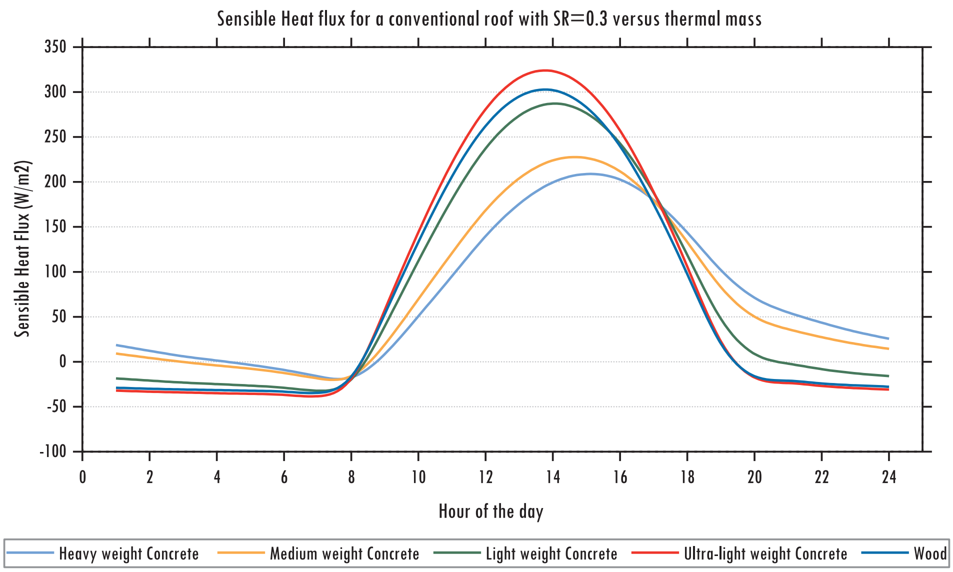

Fig. 4. Sensible Heat flux versus thermal mass for a cool roof with SR = 0.3 for Singapore.

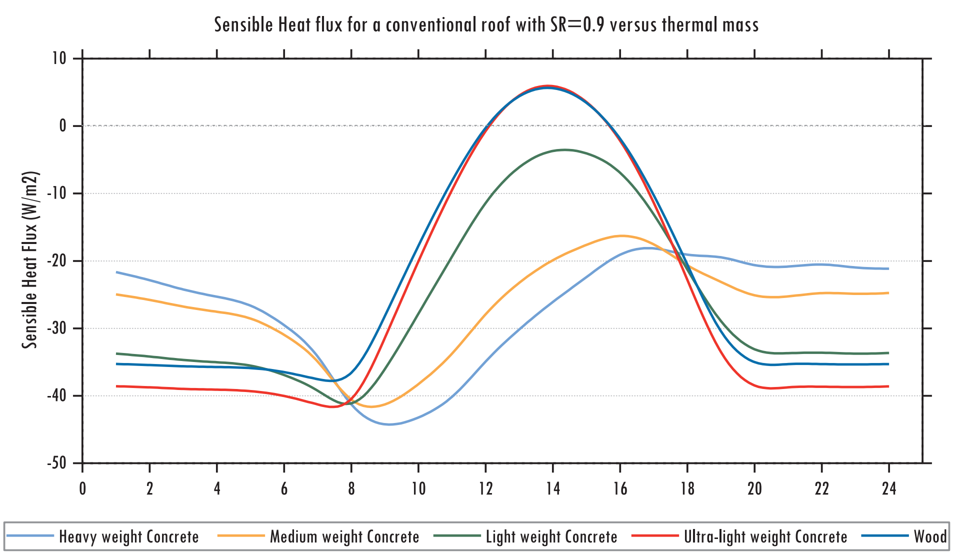

Fig. 5. Sensible Heat flux versus thermal mass for a cool roof with SR = 0.9 for Singapore.

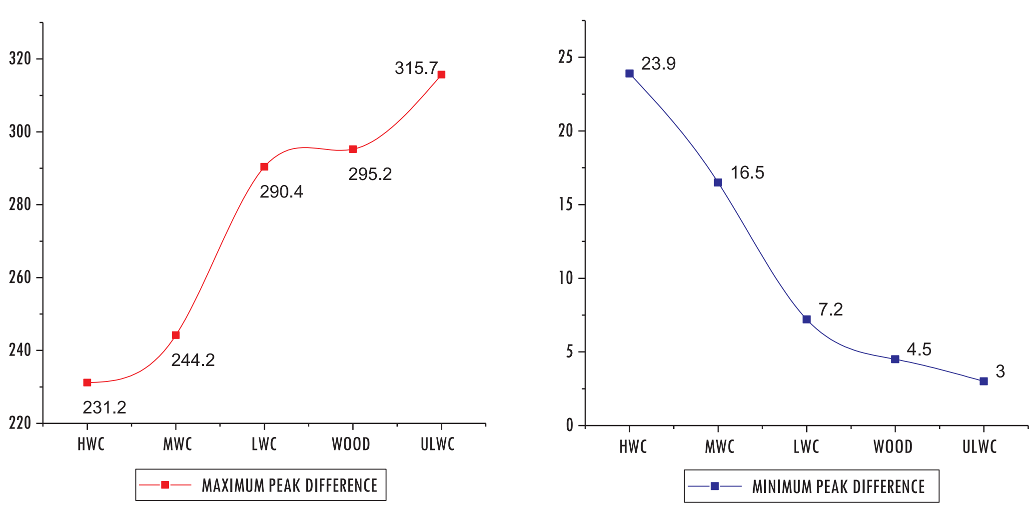

Fig. 6. Comparison between maximum and minimum peak differences for various thermal mass configurations.

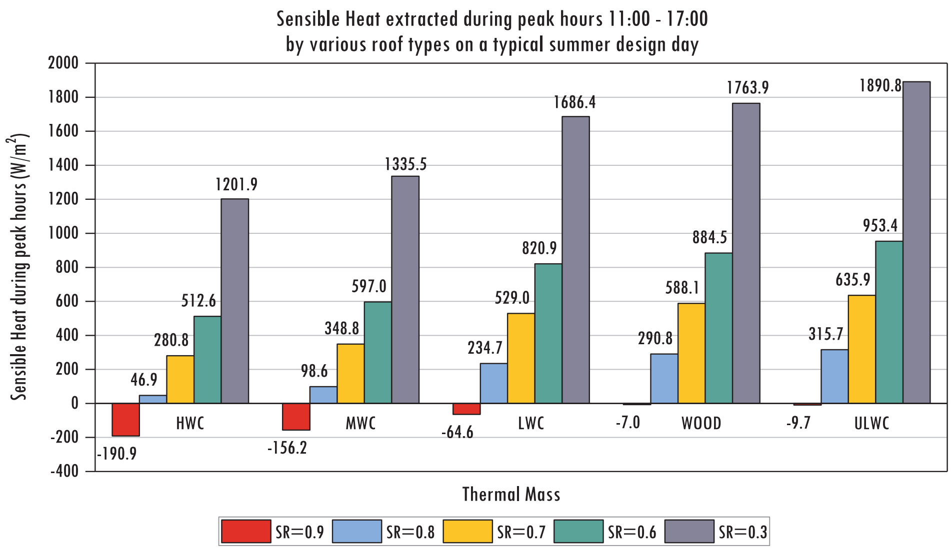

Fig. 7. Integrated sensible Heat for various thermal mass levels of the roof during a typical summer design day for Singapore.

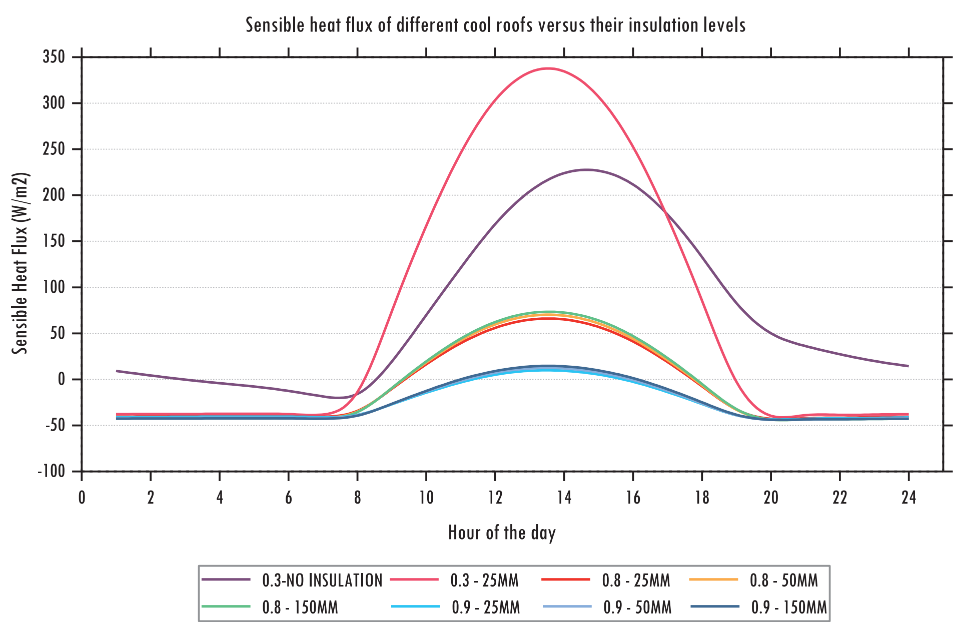

Fig. 8. Sensible Heat flux released from different cool roof scenarios with various insulation levels for a typical summer design day.

typical summer design day. It is observed that heavy weight roofs for highly reflective roof (SR = 0.9) produces a lower sensible heat flux when compared to ultra-light weight construction of the same roof reflectivity with a difference of about 181 W/m2. Similarly for other roof albedos of 0.8, 0.7, 0.6 and 0.3 the sensible heat reduction differences are 269 W/m^2, 355 W/m^2, 440 W/m^2 and 689 W/m^2 respectively. From these observations, it can be concluded that higher the roof reflectance and heavier the construction, more stable and lesser is the sensible heat flux which in turn results in higher and beneficial mitigation potential.

7.2. Cool roof vs. thermal insulation

In this section, various roof scenarios with different roof albedos across multiple insulation thickness have been examined for the building model developed in EnergyPlus 8.5. The insulation type used is polystyrene with the following physical properties -

Thickness used for various simulations – 25 mm, 50 mm, 150 mm
Conductivity – 0.035 W/mk
Density – 20 kg/m^3
Specific heat – 1500 J/kg-k

Fig. 8 depicts the sensible heat flux for different roof scenarios with various insulation levels. It is observed that insulation thickness does not have a big influence on the heat flux released by the roof. With no insulation, a typical construction at the highest peak presents a sensible heat flux of 216 W/m^2 whereas with 25 mm insulation the heat flux is around 334 W/m^2. For a highly reflective cool roof (SR = 0.9) heat flux at the peak is 14 W/m^2, 12 W/m^2 and 9.4 W/m^2 for 150 mm, 50 mm and 25 mm insulation respectively with the difference of the order 2–2.5 W/m^2. Similarly, for a SR = 0.8 cool roof, heat flux difference at peak ranges from 3 to 4 W/m^2. Hence it is characteristic for roofs with higher roof albedos that increase in insulation thickness for a particular roof albedo results in increase in sensible heat flux.

It is observed that the sensible heat flux is greater during peak temperatures for roofs with higher insulation when compared to a roof without insulation or lower insulation across all roof albedos. This

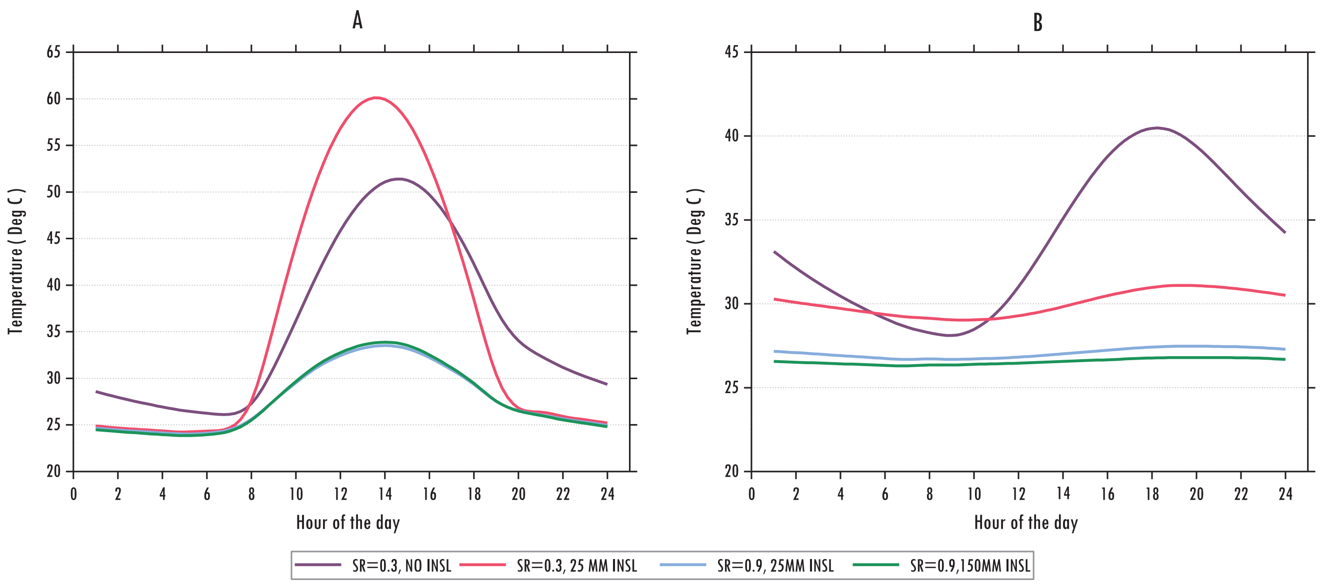

Fig. 9. (A). Surface outside temperature for different roofs with various insulation levels for a typical summer design day. (B). Surface inside temperature for different roofs with various insulation levels for a typical summer design day.

Table 4
Properties of green roof used in simulation.

Characteristics	Unit	Values
Height of plants	m	0.2
Leaf area index	Dimensionless	0.5–3
Leaf reflectivity	Dimensionless	0.22
Leaf emissivity		0.95
Minimum stomatal Resistance	s/m	180
Roughness		Medium Rough
Thickness	m	0.1
Conductivity of dry soil	W/m-K	0.35
Density of dry soil	Kg/m^3	1100
Specific heat of dry soil	J/kg-K	1200
Thermal absorptance		0.9
Solar absorptance		0.7
Visible absorptance		0.75
Saturation volumetric moisture content of soil layer		0.3
Residual volumetric moisture content of soil layer		0.01
Initial volumetric moisture content of soil layer		0.1

phenomenon can be attributed to the fact that roofs with insulation have longer heat storing capability and slower heat dissipation rate to the inside of the building thereby maintaining lower indoor temperatures. The cool roofs also present a similar trend but insulation thickness plays a very negligible role in sensible heat flux values. From Fig. 9 it is observed that surface outside temperature can reach up to 60 deg C for a conventional roof with 25 mm insulation whereas the surface inside temperature for the same roof is only 31 °C. The temperature difference comes to around 30 °C. Similarly for a highly reflective cool roof the temperature difference from outside to inside is 7.3 deg C for 150 mm insulation whereas for 25 mm insulation it is around 6.5 deg C. It is also observed that irrespective of roof albedo, the surface outside temperature is higher for roofs with higher insulation. Hence, higher insulation levels restrict the flow of heat transfer to the interior of the building and thus contribute to increase in sensible heat flux and higher surface outside temperatures but ensures lower indoor temperatures. For a conventional roof, the summer indoor maximum temperature for 25 mm insulation drops around 9 °C lower than a roof without insulation. For a highly reflective cool roof, the temperature drop is negligible of about 1 °C. Another observation that Fig. 9 presents is that, the exterior surface temperature is lower than the corresponding indoor temperature during the nights. This can be explained from the fact that heat transfer happens from indoor to outdoor during nights and night cooling happens faster for building with low insulation thickness resulting in lower indoor temperatures till early afternoon. On the other hand highly reflective cool roofs present a steady indoor temperature throughout the day irrespective of their insulation thickness.

8. The mitigation potential of green roofs

This section analyses the diurnal variation of the net radiative heat flux and its components; sensible and latent heat fluxesfor the green roof scenarios. The green roof models were developed under several assumptions including:

- The green roof was horizontal and the problem was one-dimensional.
- The temperature of the foliage and canopy air was considered uniform.
- The heat transfer by conduction in the plants was negligible.

The different properties of green roof used in simulation are outlined in Table 4 below.

Green roofs are comprised by the vegetation, the soil, the filter layer, the drainage layer and the waterproof membrane over the conventional roof. The soil needed to be lightweight to conform with the roof's loading weight restrictions, drain properly and also retain a certain amount of rain water. The leaf area index (LAI) of vegetation varied from 0.5 to 3 in this analysis.

The tropical climate of Singapore has no significant seasonal variation in meteorological parameters but the low speed wind and the frequent rainfall offers adequate irrigation for green roofs playing an important role in the LAI and soil characteristics.

The proposed green roof scenarios were analysed in terms of sensible and latent heat fluxes based on the choice of soil and vegetation. The diurnal variation of sensible, latent and heat storage heat fluxes explains the effect on the surrounding air temperature and consequently their UHI mitigation potential. Surface heat fluxes are determined by the incoming solar and long wave radiation. Sensible heat flux is directly proportional to the difference in air and surface temperatures; whereas latent heat flux is directly proportional to the

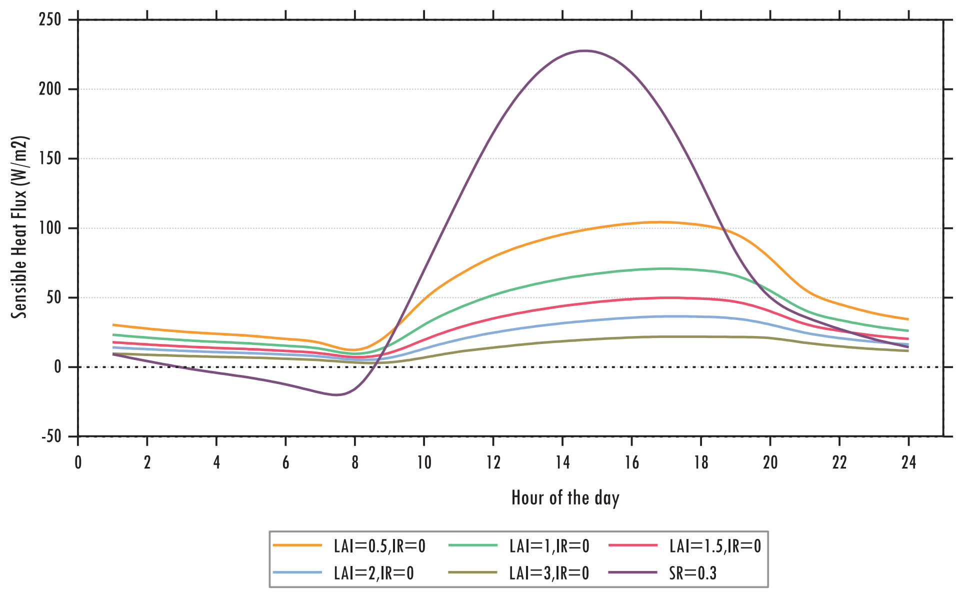

Fig. 10. Sensible heat flux released from green roofs with no irrigation rate for a typical summer design day.

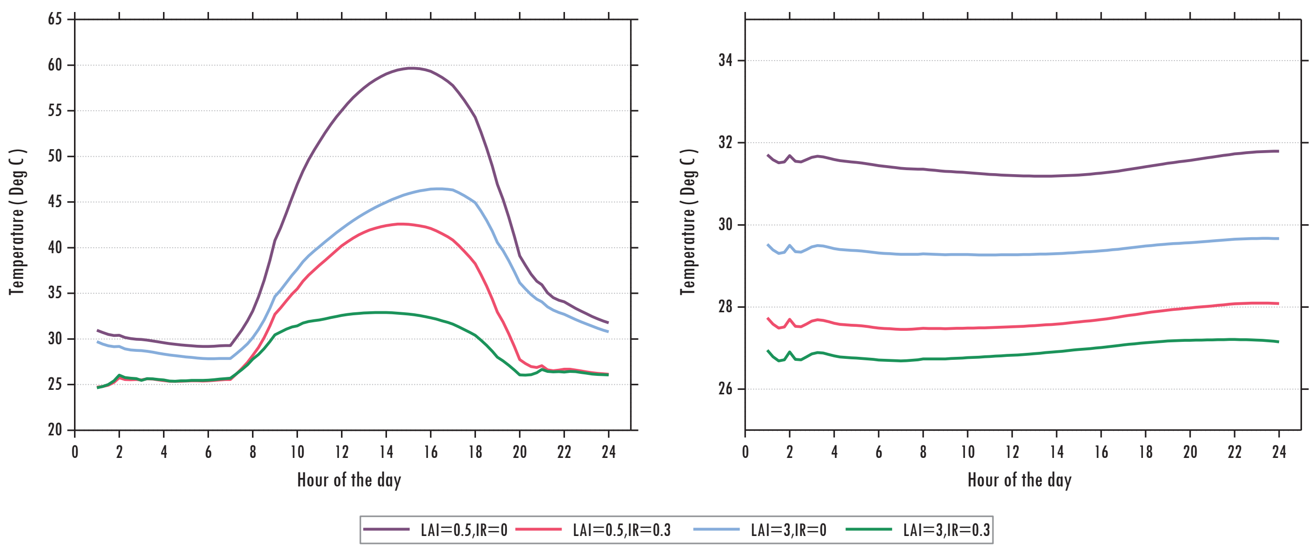

Fig. 11. Comparison of Inside temperature differences between conventional roof and non irrigated green roofs for various LAI.

Table 5
Maximum and integrated daily sensible heat flux for a typical summer design day for various LAI and IR rates.

LAI	IR = 0		IR = 0.1		IR = 0.3	
	Maximum	Integrated	Maximum	Integrated	Maximum	Integrated
0.5	104	1341	46	49	46	48
1	71	929	37	63	37	61
1.5	50	664	30	13	30	9
2	36	494	24	-19	24	-21
3	22	310	-2	-546	-2	-547

difference in vapour pressure of air and the saturated vapour pressure of the surface.

The heat fluxes' variation and the consequent mitigation potential were calculated using the hourly measurements of the green roof scenarios implemented in Energy Plus software. Net radiation was decreased compared to the conventional roof with smaller decrease for shallow soils and low LAI index and larger decrease for thicker soil layer and higher LAI value.

To obtain lower energy demand for the building and lower surrounding temperatures the net radiation should be close to zero throughout the entire day. The utilization of various soil thicknesses and different LAIs affects the diurnal cycle and peak times of sensible and latent heat fluxes leading to different temperature mitigation profiles. Reasoning is that higher thickness of soil leads to higher insulation and thermal mass of the roof and that higher LAI covers the soil resulting to a stable lead temperature and a decrease in soil evaporation. For smaller LAIs (short vegetation) green roofs are aerodynamically smoother and dissipate heat less effectively reaching higher net radiation values and lower UHI mitigation compared to larger LAIs.

8.1. Sensible heat of green roofs vs LAIand irrigation rate

Leaf Area Index(LAI) is typically 1 for a green roof. The different LAI considered for the simulation are 0.5, 1, 1.5, 2 and 3 across irrigation rates(IR) of 0.1, 0.3 and no irrigation.

From Fig. 10, it can be observed that the peak sensible heat released for a conventional roof is 227 W/m^2 whereas for non irrigated green roofs across different LAI from 0.5 to 3 ranges from 104 W/m^2 to 22 W/

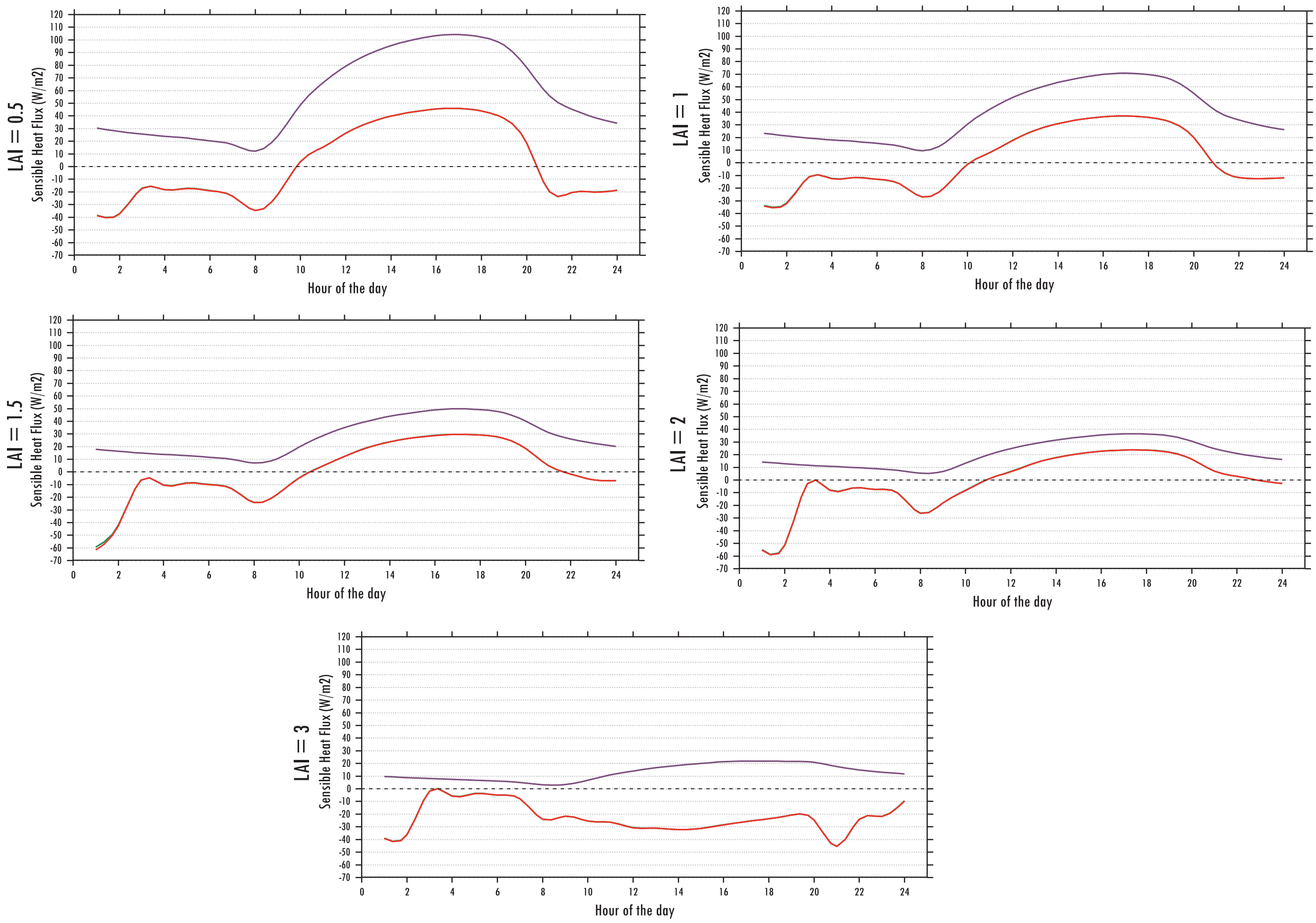

Fig. 12. Comparison of Sensible Heat flux differences between green roofs for various LAI and IR Blue line – Non irrigated green roof (IR-0) Red Line – Irrigated green roof (IR-0.1/0.3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

m^2.

Comparing different LAI and IR factors it is characteristic of green roofs that higher LAI means denser vegetation and greater reduction of sensible heat flux released to the atmosphere. From Fig. 11 it is observed that the indoor surface temperature is consistent during the whole day and night across all LAI and IR values, but irrigated roofs present a 2–3 deg C lower temperature than non-irrigated green roofs and irrigated-high LAI green roof presents the lowest temperature at around 27 deg C. The peak outdoor surface temperature difference between a lower LAI non irrigated green roof and an irrigated higher LAI green roof is approximately around 27 deg C. Clearly it can be concluded that irrigated green roofs with higher LAI perform better compared to non-irrigated green roofs with lower LAI.

From Table 5 it can be noticed that for non-irrigated green roofs with different LAI ranging from 0.5 to 3, maximum sensible heat reduction is from 54 to 90% when compared to a conventional roof. Whereas for IR = 0.1 and 0.3, the maximum sensible heat reduction doesn't vary much for increase in irrigation rate and is of the order 80–100%. Similarly form Table 5 it can be observed that for IR = 0 across different LAI, there is a 23–82% significant reduction in the integrated sensible heat released. Whereas for IR = 0.1 and 0.3, the integrated sensible heat reduction doesn't vary much for increase in irrigation rate but is of the order 97–131%.

Fig. 12 illustrates the sensible heat flux released between green roofs of different LAI across various irrigation rates. From these graphs it is observed that – As LAI increases, the sensible heat flux released decreases. Irrigated green roofs present a higher heat flux reduction compared to non-irrigated green roofs. Sensible heat flux for green roofs with IR = 0.1 and 0.3 are similar throughout with very negligible difference. It is clearly evident that higher the LAI and higher the irrigation rate, greater is the mitigation potential of the green roofs. And an irrigated green roof with more than LAI = 2, the reduction in sensible heat flux is incredibly significant and sometimes negative compared to a conventional roof with SR = 0.3 and in certain cases a 100% reduction is observed during peak hours.

9. Comparison between cool roof scenarios and green roof scenarios

The peak sensible heat flux and Integrated sensible heat flux for various cool roof and green roof configurations in comparison with conventional roof scenarios for the tropical climate of Singapore on a typical summer design day is illustrated in Figs. 13 and 14.

The main parameters influencing sensible heat flux for cool roofs are-

- Roof albedo
- Thermal mass character
- Insulation thickness

The main parameters influencing sensible heat flux for green roofs are-

- Leaf area Index and vegetation intensity
- Irrigation rate
- Soil composition and thickness

Some important observations from Figs. 15 and 16 are as follows -

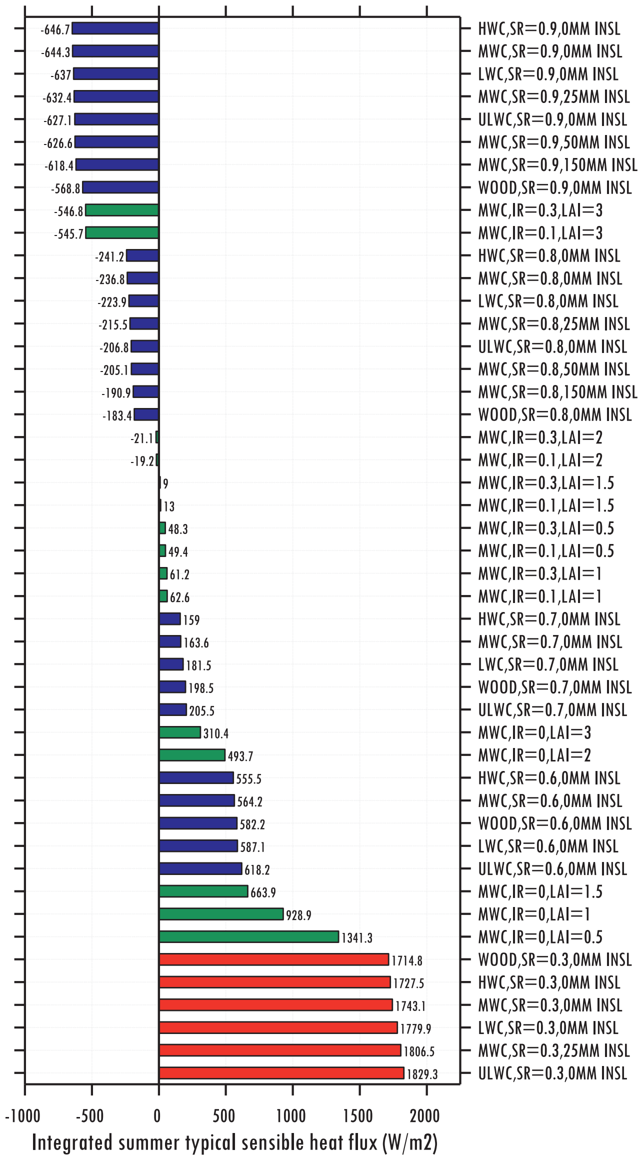

Fig. 13. Integrated sensible heat flux for a typical summer design day extracted for various cool and green roof configurations in Singapore.

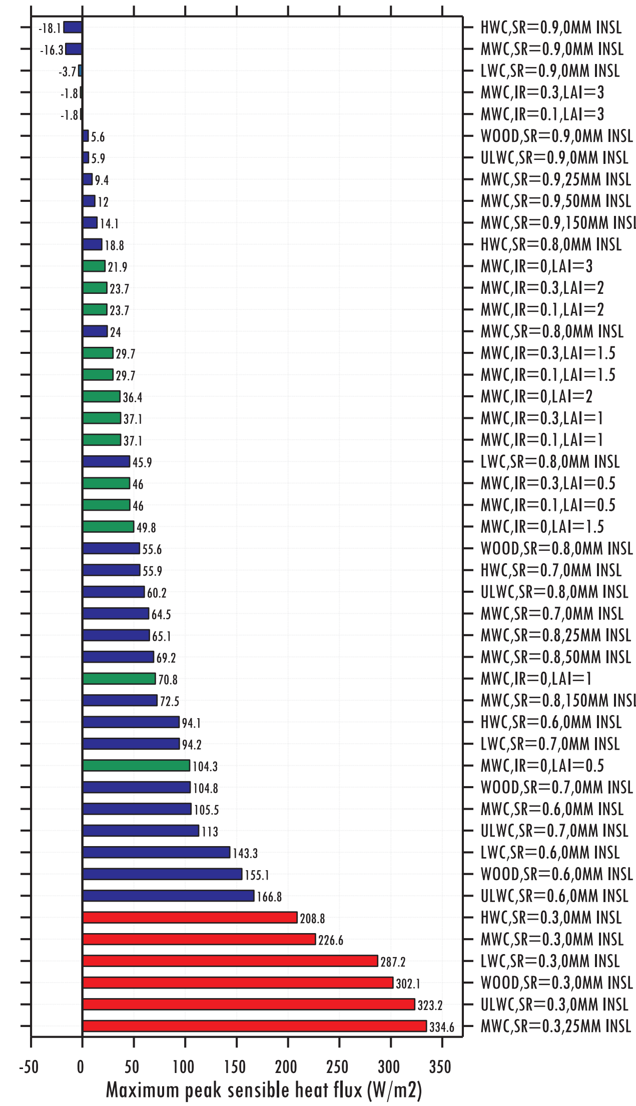

Fig. 14. Maximum sensible heat flux released for a typical summer design day for various cool and green roof configurations in Singapore.

1. For Singapore climatic conditions, it is observed from the comparisons that Heavy weight construction cool roofs with SR = 0.9 present the best mitigation potential for both peak periods as well as for whole summer design day. The cool roof configuration with SR = 0.9 and 0.8 is largely negative and gives the best performance to mitigate UHI when compared to other roof scenarios which are highly positive for the whole of summer design day. Similarly irrigated green roofs with higher LAI of the order 3 also presents a highly negative value of −546 W/m2 and irrigation rate increase from 0.1 to 0.3 plays very negligible effect on heat reduction.
2. For the whole summer design day, it is observed that cool roofs with SR = 0.8 and 0.9 presents a better mitigation potential than irrigated green roofs with LAI < 2. The cool roofs with SR = 0.7 release a sensible heat flux of up to 200 W/m2 whereas cool roofs with SR = 0.6 release up to 600 W/m2. In parallel, irrigated green roofs with LAI = 0.5–2 release a sensible heat flux of about 63 to −21 W/m^2 respectively when compared to non irrigated green roofs of same range of LAI which release up to 500–1350 W/m2. However, conventional roofs with SR = 0.3 present the highest sensible heat flux averaging from 1700 to 1800 W/m2.
3. For the peak sensible heat flux released during the summer design day, it is observed again that highly reflective cool roofs with SR = 0.9 present negative values (about −18 W/m^2) contributing highly to mitigate UHI. Similarly irrigated green roofs with LAI = 3 also present negative value of −2 W/m^2. This is almost same as the mitigation potential offered by a LWC cool roof with SR = 0.9 with no insulation (−3.7 W/m2). It is observed that irrigated green roofs generally present a lower positive sensible heat flux released and roofs with LAI > 2, sensible heat flux is less than 24 W/m^2 for all types of irrigation rates. However, conventional roofs with SR = 0.3 present the highest sensible heat flux released (> 200 W/m2) during the peak periods.

Fig. 15 shows a comparison of possible sensible heat flux reduction of different cool and green roofs when compared to a conventional roof of SR = 0.3 with no insulation. The data includes cool roofs with different thermal mass configurations with various insulation thicknesses and green roofs with varying LAI and irrigation rates. On a typical summer design day, the integrated sensible heat flux released for a conventional roof with SR = 0.3 is around 1743 W/m^2 and the peak sensible heat flux released is around 227 W/m^2. It is observed that Cool roofs present an integrated sensible heat reduction close to 2390 W/m^2 when compared to a conventional roof whereas a green roof presents a

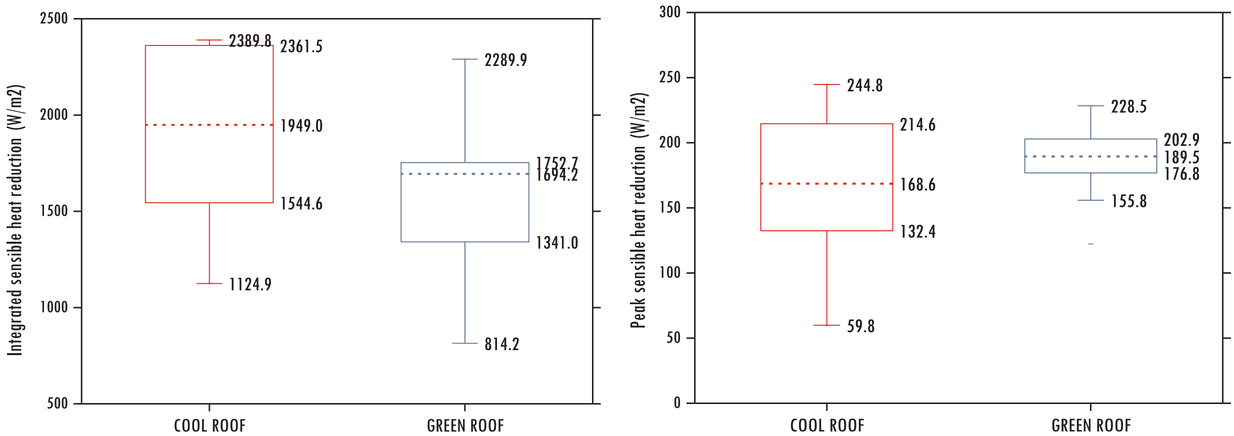

Fig. 15. Integrated and peak sensible heat reduction for a typical summer design day for various cool and green roof configurations in Singapore.

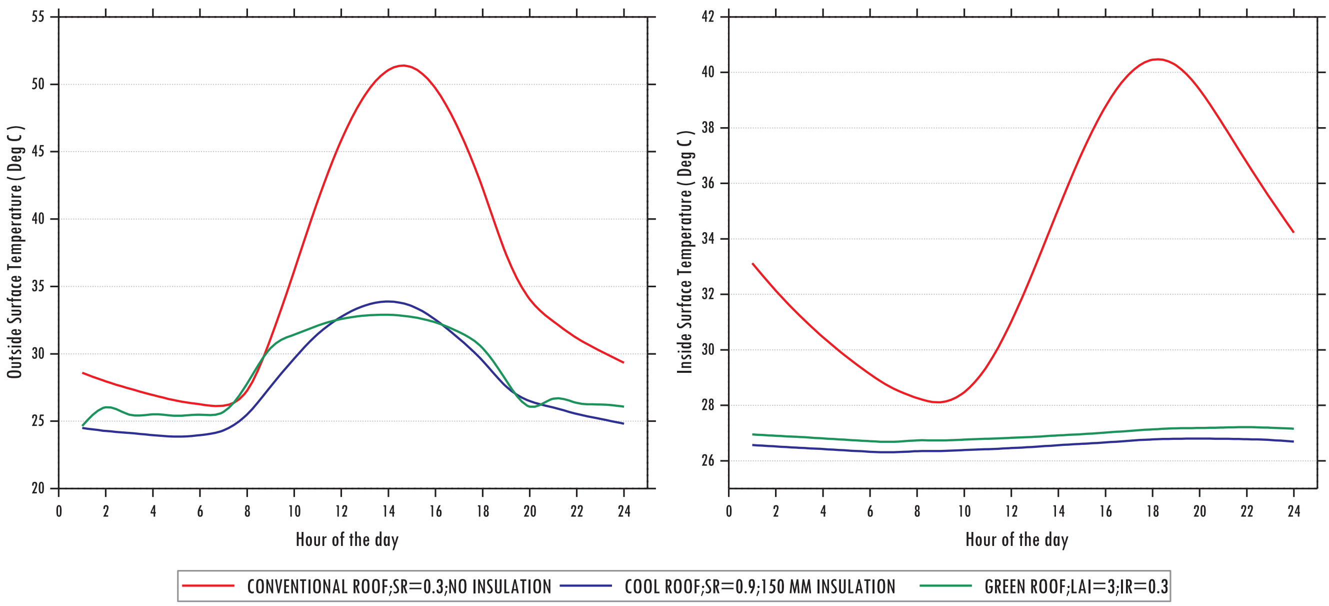

Fig. 16. Outside and Inside surface temperature comparisons for conventional roof, best cool roof and best green roof scenarios.

reduction of 2290 W/m^2. Therefore, for a summer design day in comparison to a conventional roof, cool roof reduces heat gain by 15.43 KWh/m^2 (37%) and green roof reduces by 13.14 KWh/m^2 (31%). Similarly for the peak period, a cool roof mitigates about 245 W/m^2 whereas a green roof mitigates 228 W/m^2. Therefore, for peak periods in comparison to a conventional roof, cool roof reduces heat gain by 0.144 KWh/m^2 (8%) and green roof reduces by 0.008 KWh/m^2 (0.4%). From this data analysis it can be concluded that cool roofs consistently present a higher mitigation potential than green roofs for both peak periods and for the integrated sensible heat flux reduction. This could be because of many reasons like excess latent heat released in green roofs in comparison to cool roofs due to the presence of moisture in soil and plants.

Fig. 16 presents a comparison of oustside and inside surface temperatures for a conventional roof, a best cool roof (SR = 0.9 and 150 mm insulation) and a best green roof (LAI = 3; IR = 0.3). It is clearly observed that though both green and cool roof reduce temperature significantly, it is cool roof that has consistently maintained the lowest temerature across the whole day.

10. Conclusion

Comparison of cool roof and green roof is first time compared in detail in tropical climate in this study. Highly dense tropical cities faces problems of ever increasing population, high ambient temperatures, deteriorated comfort conditions, amplified pollution and thereby increasing the energy demand. The evidence from the simulations of this study support the idea of cool and green roofs in the urban environment of Singapore as it has illustrated the possibilities of mitigating urban heat island under different varying factors and conditions. From the simulation results it is gathered that both cool roofs and green roofs present a reduction in energy demand by decreasing heat flux. It is observed that during peak periods (9 am to 5 pm) on a typical summer design day in Singapore, cool roofs reduce heat gain by about 0.14 KWh/m^2 (8%) and green roofs mitigate considerably less to about 0.008 KWh/m^2 (0.4%). And for the whole of a summer design day, cool and green roof reduces heat gain by 15.53 (37%) and 13.14 (31%) KWh/m^2 respectively. However it is also observed that cool roofs have a higher mitigation potential compared to green roofs for the climatic conditions of Singapore as vegetation can add to latent heat flux due to evapo transpiration and needs high maintenance. And furthermore, irrigated green roofs present a higher mitigation potential than non-irrigated green roofs since water can retain heat and delay the heat transmission to the inside.

Limitations of the study however include the fact that this paper largely depends on computer simulations and experimental data for air-conditioned buildings are yet to be carried out in Singapore for cool and green roofs. Future works could include the study for the whole year under various seasons and then a holistic mitigation potential of green and cool roofs may be derived. Major disadvantages that cool and green roofs can pose are they can be easily subjected to wear and tear and given the frequent rainfall they are susceptible to mold and algae growth. Also to maximize mitigation potential other factors like the lifetime of cool materials, the species and maintenance of plants should be taken into account for a long term improvement in microclimate.

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