Green roofs' urban heat island mitigation potential in tropical climates for institutional buildings under free floating conditions

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Abstract. The elevated urban temperatures and the increased energy demand urge the need for decreased energy needs by cost-effective measures and building design. Green roofs are used globally for the mitigation of higher temperatures in cities as well as for the insulation of buildings. They enhance the heat transfer through roofs and provide steadier outside roof temperatures in cold winters and hot summers. The aim of the present work was to study the mitigation potential of green roofs by performing a comparative analysis of heat fluxes for several green roof scenarios and conventional roof for an institutional building. The impact of the effect of green roofs' soil thickness and vegetation index were examined. The results revealed negligible variation of heat fluxes for different soil compositions, whereas larger soil thickness decreased greatly heat storage but had no effect on latent and sensible heat fluxes. Vegetation index had a negative correlation with sensible heat flux for all green roof simulations.

Keywords: Green Roof, Energy Plus, Tropical Climate

INTRODUCTION

The elevated urban temperatures and the increased energy demand urge the need for efficient HVAC systems and decreased energy needs by cost-effective measures and building design. Green roofs are used globally for the mitigation of higher temperatures in cities as well as for the insulation of buildings (Oberndorfer et al., 2007). They enhance the heat transfer through roofs and provide steadier outside roof temperatures in cold winters and hot summers (Jaffal et al., 2012). Specifically green roofs contribute to the mitigation of the urban heat island effect (Li et al., 2014; Oberndorfer et al., 2007) and become an urban sink for the elevated CO_2 levels.

A green roof is comprised of a structure, decking and a waterproof membrane topped with growing media/soil and plants. Green roofs are divided into extensive (soil thickness about 10cm), semi-intensive (soil thickness about 25cm) and intensive (soil thickness about 35cm) roofs according to the soil height and also the plants grown on them. The different range of soil height affects the available range of growing media but also the overall load applied to the building. The ground needs to be sufficiently irrigated and supply nutrients, whereas there should be adequate drainage (Oberndorfer et al., 2007). It is fairly difficult to decide on the appropriate media for a green roof as the different meteorological parameters and structure of the building to hold the extra load affect these decisions. The vegetation behaves as a shading mechanism but absorbs part of the thermal energy for photosynthesis.

Even though the analytical solutions of the green roofs heat fluxes are well understood (Quezada-Garcia et al., 2017) there are many aspects for the determination of the more appropriate green roofs for each establishment (Chan and Chow, 2013; Jaffal et al., 2012). This is because of the mechanism of evaporative cooling in the various growing media and plants. Latent heat loss is accomplished via either the transpiration of the plants or the evaporation of moisture from the soil, resulting to lower temperatures of the roof. Green roofs will become an even more important component for energy efficiency and urban sustainability in the future due to their favorable contribution to the reduction of the phenomenon of urban heat island (Li et al., 2014). Urban heat island is the phenomenon when cities are hotter than the rural surrounding areas. The urban constructions have taken over vegetation areas and resulted to a decrease of evapotranspiration and a greater heat storage capacity in buildings, exacerbating the extreme hot weather conditions in some areas. The latent heat loss from the plants and growing media reduces the surroundings' air temperature and generates a net cooling effect. Moreover the heat gain of buildings is reduced and therefore the need for indoor air-conditioning is also reduced. Considering the energy balance for the green roof it can be expressed as:

$$R_n = H + LE + G$$

Where Rn is the net radiation, H is the sensible heat flux, LE is the latent heat flux resulting from soil evaporation or plant evapotranspiration and G is the heat flux into the buildings or the heat storage. Assuming a steady Rn, 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.

In this study the effect of various green roof scenarios on the net heat balance equation and particularly sensible, latent heat fluxes and heat storage were investigated. To this aim, 16 green roof models with 2 different soil compositions and 4 different vegetation indexes were coupled with an existing building model in EnergyPlus software. EnergyPlus software offered the advantage of temporal investigation of all the analytical solutions behind heat exchange and photosynthesis with respect to the existing meteorological weather conditions. This study also investigated several green roof parameters, such as thermal conductivity, specific heat capacity and thickness of soil and leaf area index for plants.

2. Materials and methods

The study is carried in Singapore, where a tropical climate exists with an average of 28^{o}C outdoor temperature and 82% outdoor relative humidity throughout the year. According to data from 1980-2010 of the meteorological service of Singapore the diurnal variation of temperature from May-November varied from 25-32^{o}C and relative humidity from 94% in the morning to about 65% in the mid-afternoon on days when there was no rain.

The case study building for the first phase is a multi-functional building consisting of offices, computer studios, and a small library. It is situated inside the campus of the University of Singapore (Latitude: 1^{o}17'50.94"N, Longitude: 103^{o}46'14.92"E). The building was drawn initially in SketchUp studio and later simulated in EnergyPlus. Only electricity was used for the HVAC and equipment uses, from which 35-40% was used for space cooling and non for heating purposes.

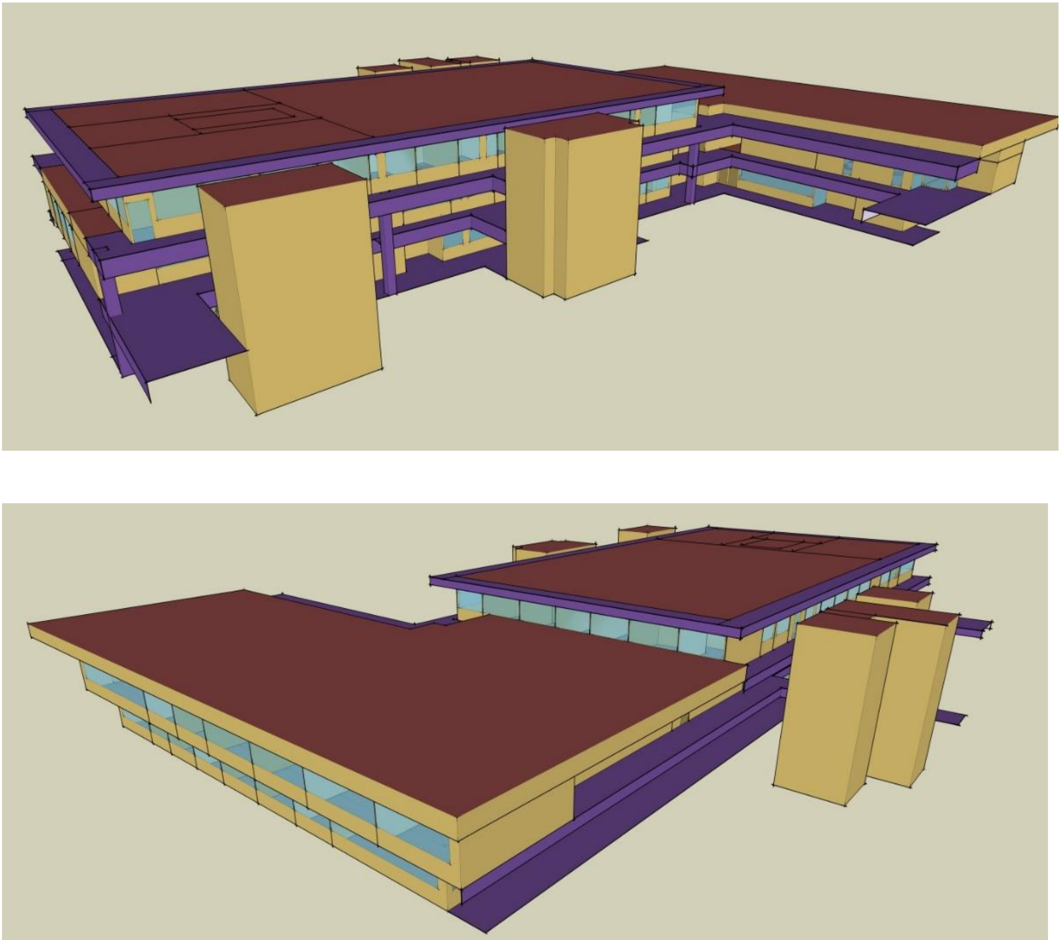

Figure 1: 3D views of the investigated institutional building

The purpose of the present paper was to (i) create different green roof scenarios for an institutional building in EnergyPlus, (ii) analyze the diurnal variation of the net radiative heat flux and its components; storage of the surfaces, sensible and latent heat fluxes of the soil and vegetation of green roofs and finally (iii) comparison of green roof scenarios with the conventional roof case. The methodology implemented in the present work consisted of the following main steps:

a. Green roof models

The green roof models were developed under several assumptions. These were:

- 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 layers of a green roof comprised on top of the conventional roof a waterproof layer, then drainage and filter layers and then the soil and the vegetation. The different characteristics of these layers are outlined in the following table (table 1).

Table 1: Stratigraphy and thermal properties of green roof models

ROOF LAYERS (outside→ inside)	**Thickness[m]**	**λ – thermal conductivity [W/mK]**	**ρ** [kg/m^3]	**Heat capacity Cp** [J/kgK]
Vegetation layer	Varies according to grown plants			
Soil layer	Varies according to composition of soil			
Filter layer	0.005	0.06	160	2500
Drainage layer	0.05	0.08	14 (dry)	920
Waterproof layer	0.004	0.2	1200	5200
Light weight concrete	0.1	0.53	1280	8400
Medium weight concrete	0.15	1.72	2243	8370

Green roof's soil needed to be lightweight to conform to the roof loading weight restrictions, drain properly and also retain a certain amount of rain water. Two different soil compositions were investigated with two different heights; 10cm for soil cases 1 and 2 (SC1 & SC2) and 25cm for soil cases 3 and 4 (SC3 & SC4) to account for extensive and semi-intensive green roofs respectively. The thermal absorbance of soil was 0.9 and the visible absorbance was 0.7. The saturation, residual and initial volumetric moisture contents were 0.5, 0.01 and 0.15 respectively.

All the investigated vegetation cases (VC1-VC8) had 0.22 leaf reflectivity, 0.95 emissivity and minimum stomatal resistance of 180. The height of the plants in the extensive green roofs scenarios (VC1-VC4) was 15cm, and for the semi-intensive green roofs scenarios (VC5-VC8) was 35cm. Moreover, the variating parameter was the leaf area index which took the following values: 0.5 for sparse vegetation, 1, 2 and 5 for dense vegetation. The 16 simulated green roof cases are outlined in the following table:

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Table 1: Thermo-physical properties of the vegetation and soil layers

Case	Composition of soil	Soil thickness[cm]	Plants' height [cm]	Leaf Area Index (LAI)
SC1VC1	50% pumice, 10% compost, 40% sand	10	15	0.5
SC1VC2	50% pumice, 10% compost, 40% sand	10	15	1
SC1VC3	50% pumice, 10% compost, 40% sand	10	15	2
SC1VC4	50% pumice, 10% compost, 40% sand	10	15	5
SC2VC1	75% pumice, 10% compost, 15% sand	10	15	0.5
SC2VC2	75% pumice, 10% compost, 15% sand	10	15	1
SC2VC3	75% pumice, 10% compost, 15% sand	10	15	2
SC2VC4	75% pumice, 10% compost, 15% sand	10	15	5
SC3VC5	50% pumice, 10% compost, 40% sand	25	35	0.5
SC3VC6	50% pumice, 10% compost, 40% sand	25	35	1
SC3VC7	50% pumice, 10% compost, 40% sand	25	35	2
SC3VC8	50% pumice, 10% compost, 40% sand	25	35	5
SC4VC5	75% pumice, 10% compost, 15% sand	25	35	0.5
SC4VC6	75% pumice, 10% compost, 15% sand	25	35	1
SC4VC7	75% pumice, 10% compost, 15% sand	25	35	2
SC4VC8	75% pumice, 10% compost, 15% sand	25	35	5

The proposed green roof scenarios were analyzed in terms of the heat fluxes variabilities of the soil and vegetation chosen. Therefore the outputs of their simulations were hourly measurements of the following parameters; i-v for green roofs and v-vi for conventional roof:

i. Soil sensible heat transfer rate per area [W/m2]

ii. Vegetation sensible heat transfer rate per area [W/m2]

iii. Vegetation latent heat transfer rate per area [W/m2]

iv. Soil latent heat transfer rate per area [W/m2]

v. Surface heat storage rate per area [W/m2]

vi. Surface outside face convection heat gain rate per area [W/m2]

According to the equation in the introduction section the net radiation Rn of the green roof surface is the sum of the outputs i-v, whereas for the conventional roof is the sum of outputs v-vi, as there was no latent heat. All the obtained measurements underwent a preliminary error analysis to disregard any outliers and missing values.

It was important to observe the diurnal variation of these three heat fluxes (sensible heat, latent heat, heat storage) individually, the net radiation Rn of their sum and explain how these variations may decrease the surrounding air temperature and consequently mitigate UHI.

The percentage increase compared to the conventional roof was found for the net radiation, the sensible heat and the heat storage and the difference using the hourly measurements was shown graphically. Later the diurnal variation graphs revealed the peak and minimum throughout the day and the effect of the LAI, soil composition and soil thickness were evaluated. The diurnal variation of the heat fluxes in the green roof scenarios was later compared with the conventional building's heat fluxes. (1)

RESULTS AND DISCUSSIONS

a. Heat fluxes mechanisms in green roofs

Singapore is a country with a tropical climate and no significant seasonal variation of the meteorological parameters. Surface heat fluxes are determined by the incoming solar and longwave radiation. Sensible heat flux is directly proportional to the difference in air and surface temperatures; whereas latent heat flux is directly proportional to the difference in vapour pressure of air and the saturated vapour pressure of the surface. In Singapore, low speed winds dominate and the frequent rainfall offers adequate irrigation for green roofs. Over the course of a typical day, the majority of the net radiation is dissipated as latent heat for well-watered green roofs, which is the case in Singapore. In drier soils evapotranspiration is lower, the canopy resistance increase and the majority of energy is dissipated as sensible heat or stored in the ground. Also, all the meteorological parameters affect stomatal resistance and consequently latent heat released back in the atmosphere.

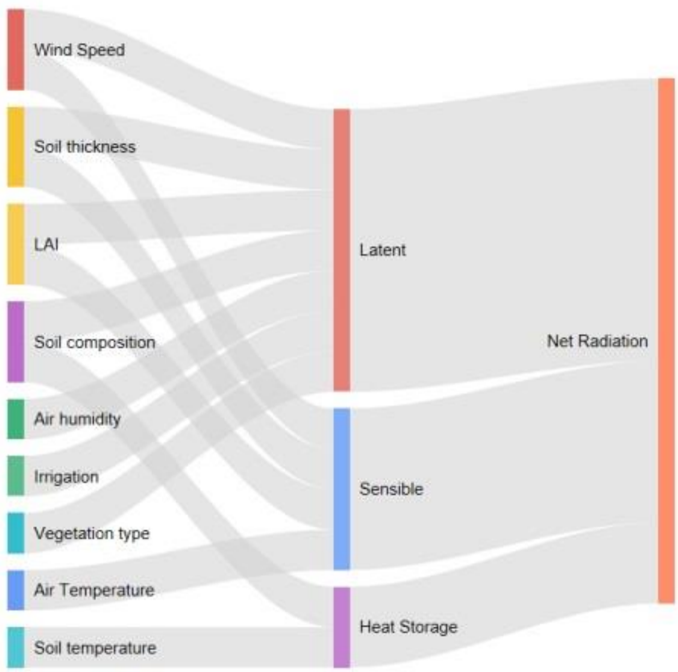

Figure 2: List of parameters affecting the investigated heat fluxes

The heat fluxes' variation in the energy balance equation was calculated using the hourly measurements of the green roof scenarios implemented in EnergyPlus software. The various implemented scenarios offered the possibility to evaluate the heat fluxes variability in different LAI and with various soils. The results, outlined in table 3, suggested that the net radiation was decreased in all scenarios, with a minimum percentage decrease of 2.2% in the SC1VC1 scenario and a maximum percentage decrease of 69.9% in the SC4VC8 scenario. Looking into the sensible heat and the heat storage difference of table 3 it was observed that for extensive roofs and low LAI the heat storage increased. LAI over 2 played a more significant role in the decrease of heat storage ability of the roof, reaching a maximum of 78.2%. SC4VC8 was considered as the most intense case of the studied green roofs and led to the highest percentage decrease of all heat fluxes. According to figure 3 it was observed that the range of the sensible heat and heat storage decreased and the range of latent heat increased as LAI increased at the vegetable cases VC4 and VC8.

Table 3: Percentage increase of the heat fluxes of the various green roof scenarios with conventional roof using hourly measurements

Green Roof Scenario	Net Radiation – Rn (%)	Sensible Heat – H (%)	Heat storage – G (%)
SC1VC1	-2.2	-120.7	12.5
SC1VC2	-7.8	-117.0	5.7
SC1VC3	-32.6	-125.2	-42.4
SC1VC4	-53.0	-180.3	-61.1
SC2VC1	-13.7	-118.8	0.2
SC2VC2	-18.0	-115.7	-5.3
SC2VC3	-54.1	-126.9	-47.6
SC2VC4	-56.8	-163.7	-64.8
SC3VC5	-14.0	-110.4	-4.8
SC3VC6	-19.6	-107.9	-10.4
SC3VC7	-30.3	-103.5	-20.4
SC3VC8	-44.7	-83.5	-53.0
SC4VC5	-22.1	-109.5	-14.9
SC4VC6	-26.9	-107.2	-19.6
SC4VC7	-34.1	-103.3	-25.5
SC4VC8	-69.9	-209.9	-78.2

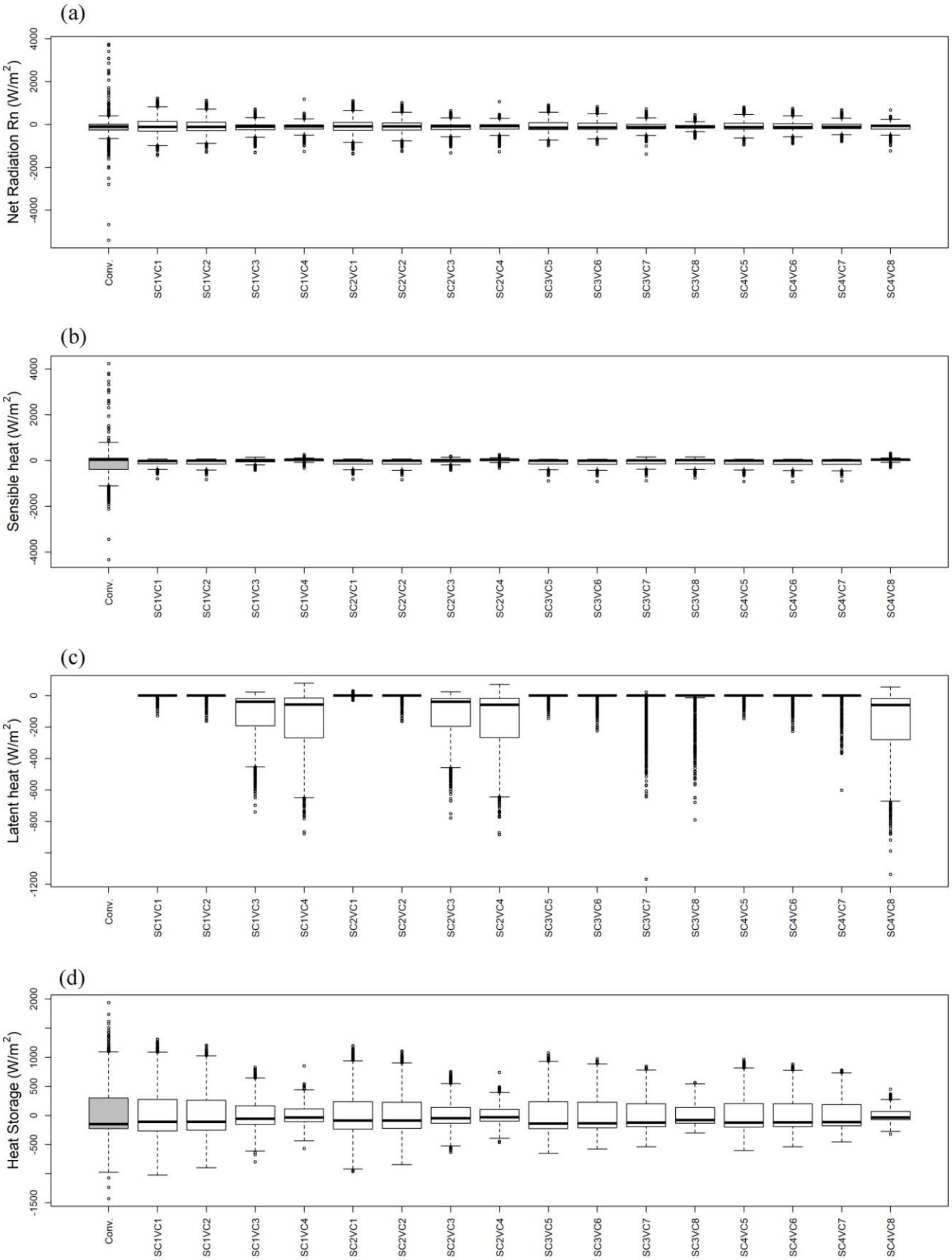

Figure 3: Boxplots of (a) Net radiation, (b) Sensible heat, (c) Latent heat and (d) Heat storage for the conventional roof (grey box) and the different green roof scenarios using hourly measurements

Figures 4 and 5 show the diurnal variation of the several heat fluxes for all the green case scenarios. The positive values indicated the heat flux absorbed by the roofs and the negative values indicated the energy release into the atmosphere. For lower energy demand inside the building and lower urban temperatures the total heat flux (Rn) should be close to zero throughout the entire day.

b. Impact of soil's composition and thickness

Variation of soil composition and thickness leads to higher insulation and thermal mass of the roof that would ideally lead to decrease energy consumption. In this section the net radiation, sensible heat, latent heat and heat storage were compared for the various soil compositions and thicknesses.

Comparing soil composition for similar LAI and soil thicknesses, that is case SC1VC1 with case SC2VC1 and case SC3VC5 with case SC4VC5 showed no particular effect in any heat flux, just a very small decrease of heat storage G for semi-intensive green roofs. However, when comparing similar composition but for different soil thicknesses, that is cases SC1VC1 with SC3VC5 and cases SC2VC1 with SC4VC5 it showed a greater decrease of the heat storage for higher thickness of soil but negligible effect on latent heat and sensible heat diurnal variation.

Regarding variation in sensible heat rate it was observed that for different soil compositions the sensible heat rate was the same. Differences in the latent heat flux were not observed in the extensive green roofs but were observed in comparison of the semi-intensive roofs specifically for greater LAIs, that is case SC3VC8 with SC4VC8.

c. Impact of LAI and plants' height

The simulations in EnergyPlus considered LAI values of 0.5, 1, 2 and 5 and plant height for extensive green roofs 15cm and for semi-intensive green roofs 35cm. According to the figures 4 and 5 as LAI increased the sensible heat decreased, especially in extensive roofs. Heat storage was only slightly decreased for LAI variation of 0.5 to 2 but greatly decreased for a LAI of 5. Absolute value of latent heat was also increased with increasing LAI.

It is well know that the height of the plants has a large influence on leaf temperature. Moreover, short vegetation present in extensive green roofs is aerodynamically smooth and dissipates heat leas effectively, resulting to higher leaf temperatures than that of air and that gave reasoning to why net radiation of extensive roofs reached a higher peak than net radiation of semi-intensive roofs, cases SC1VC1 with SC3VC5. Tall vegetation is aerodynamically rough and the temperature of the leaves is close or lower to that of the air. In Singapore where wind speed is mainly low the heat may not easily be carried away from leaves, creating a more stable leaf temperature.

Comparing different LAI factors it was noticed that as LAI increased, the latent heat dissipated to the atmosphere also increased, whereas the sensible heat and the heat storage decreased. Moreover, it was noticed that for semi-intensive green roofs for thicker soil the latent heat was generally close to zero, except for the LAI of value 5 (SC3VC8 and SC4VC8). For higher LAI, denser green roofs, the soil evaporation is negligible compared to the evapotranspiration of the vegetation.

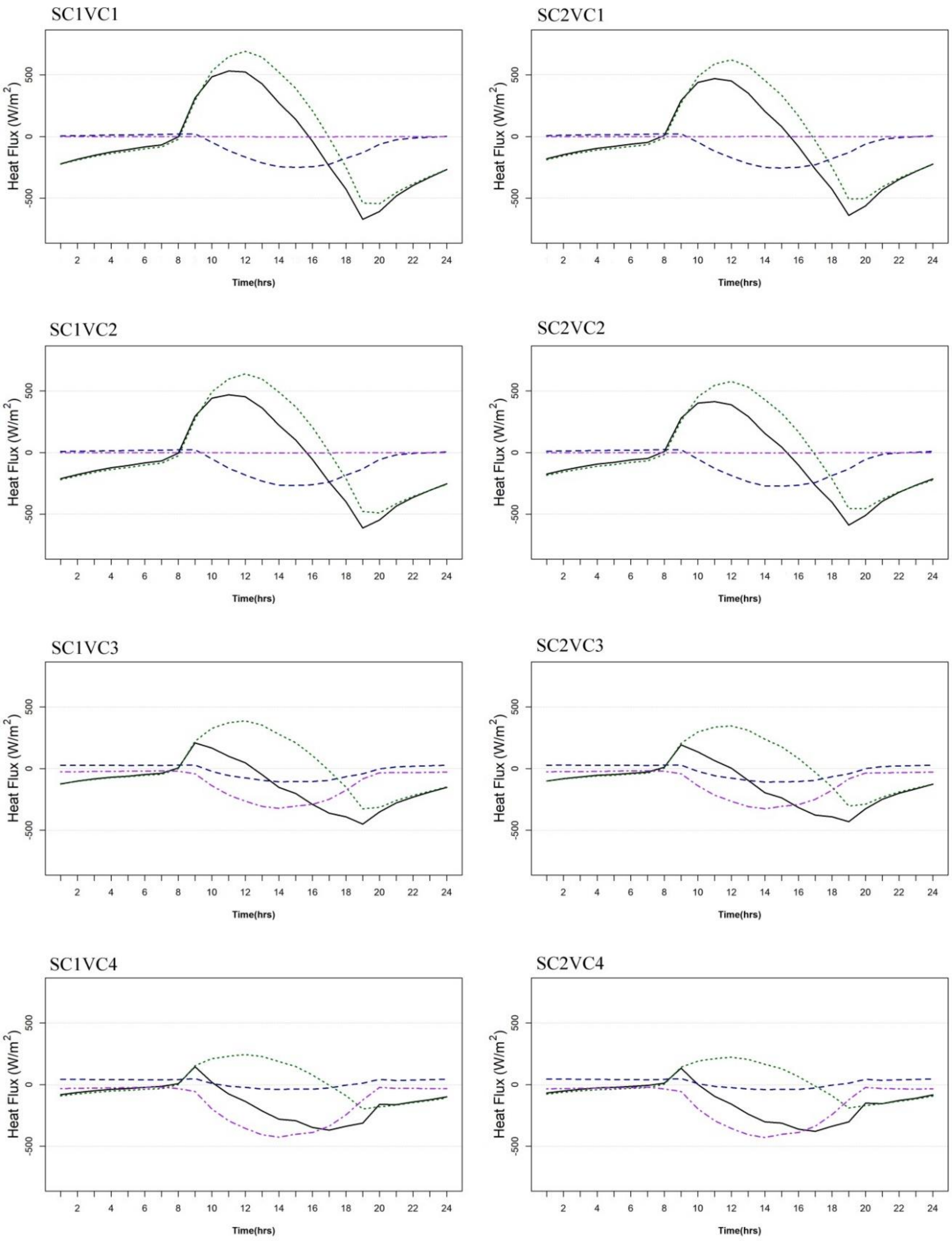

Figure 4: Diurnal profiles for net radiation (black solid line), heat storage (green dotted line), sensible heat flux (blue dash line) and latent heat flux (purple dot-dash line) for the different extensive green roof scenarios

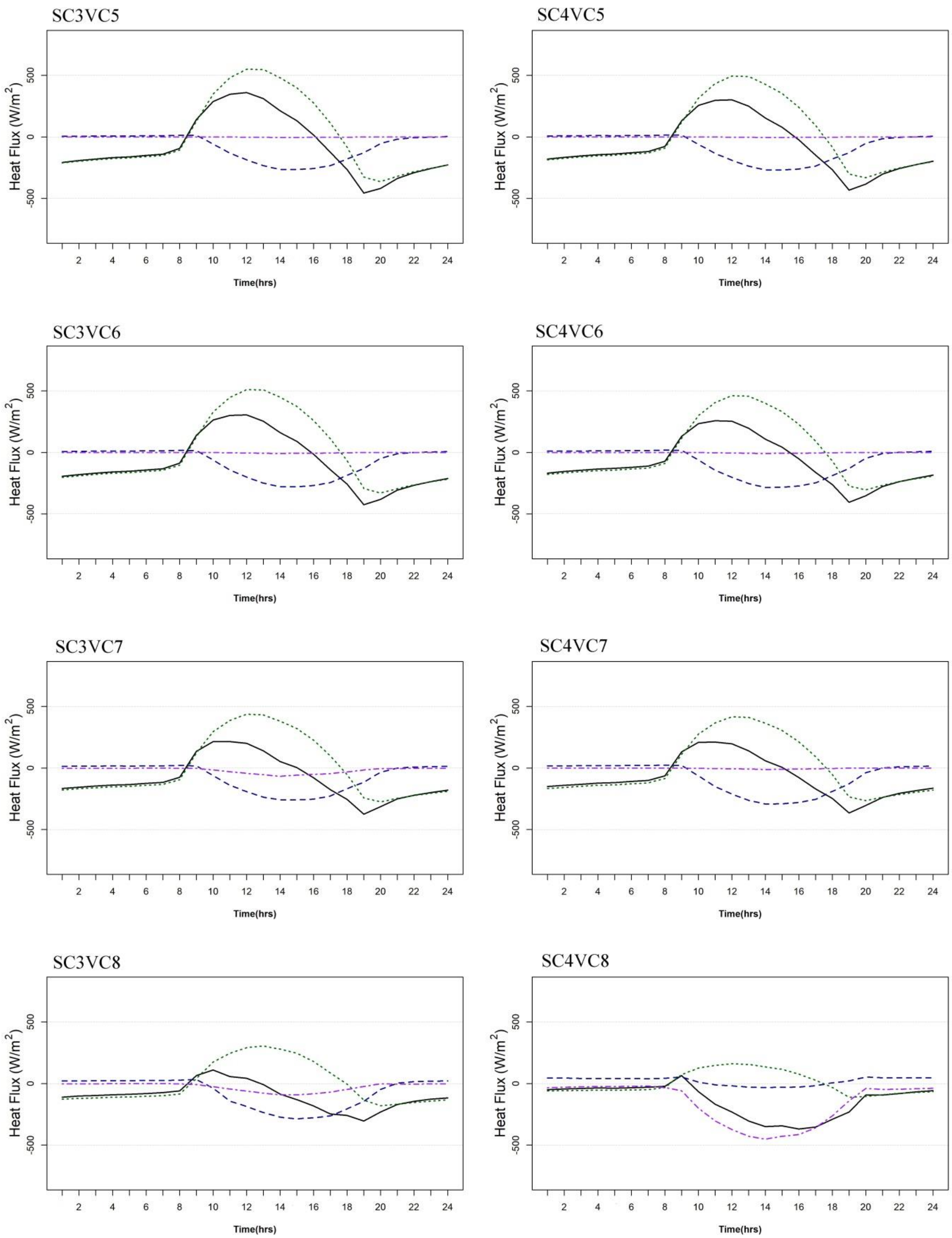

Figure 5: Diurnal profiles for net radiation (black solid line), heat storage (green dotted line), sensible heat flux (blue dash line) and latent heat flux (purple dot-dash line) for the different semi-intensive green roof scenarios

d. Comparison with diurnal heat fluxes of conventional roof

Surface heat fluxes follow a variating diurnal cycle and this is illustrated in figure 6 for the conventional roof. The graph indicated a higher thermal storage for conventional roof reaching a peak of 727W/m^2 at noon, whereas the most intensive green roof scenario SC4VC8 had a heat storage peak of 160W/m^2. The diurnal profile was consistent with the expected values as it showed high heat storage and a small lag in the sensible heat released back to the atmosphere, and thus contributing to the UHI which is generally more pronounced in the late afternoon. Sensible heat reached a maximum of 117W/m^2 at 6:00am and a minimum of -872W/m^2 at 2pm showing the release of heat into the atmosphere. The net radiation maximized at 257W/m^2 at 10:00am and was minimized at -482W/m^2 in the late afternoon at 5:00pm, resulting to the maximum release of energy to the atmosphere.

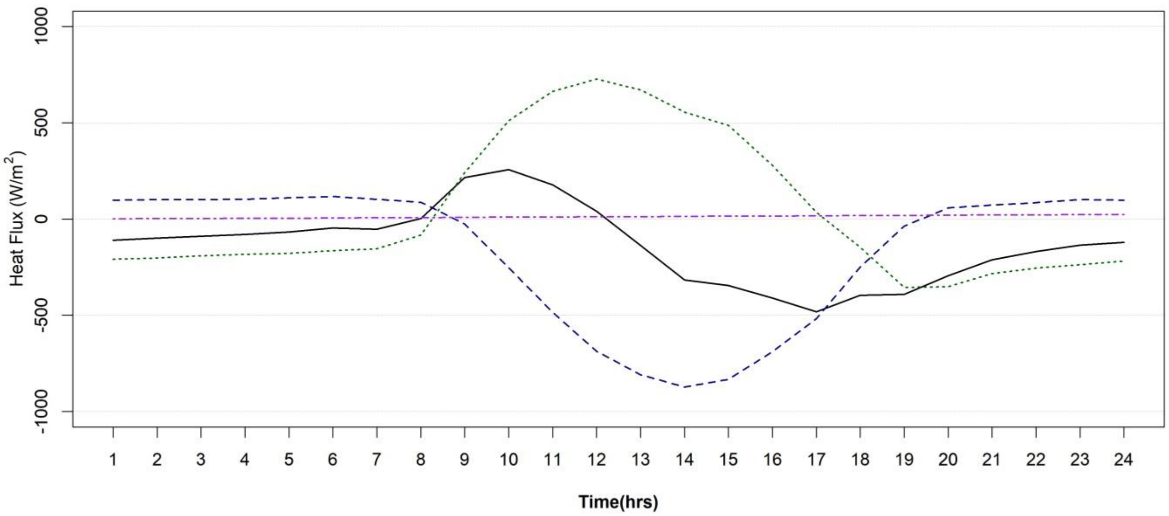

Figure 6: Diurnal profile of conventional roof's heat fluxes for net radiation (black solid line), heat storage (green dotted line), sensible heat (dash blue line) and latent heat (dot dash purple line)

CONCLUSIONS

The evidence from the simulations of this study support the idea of green roofs in the urban environment as it was shown the general decrease of the net radiative heat flux of green roofs compared to the conventional roof. It was particularly shown a great decrease of the heat storage of green roofs and a small decrease in the sensible heat flux which is the main precursor of higher urban temperatures.

Insight has been gained with regard to the effect of LAIs, soil composition and soil thickness on each heat flux, showing the small effect of soil composition on the variating heat fluxes, but the greater effect of soil thickness and LAIs. These findings added to the growing body of literature on green roofs, encouraging further investigation upon the maximum load of green roofs on existing buildings. The results showed a decrease of the thermal storage of up to 550W/m^2 for green roof compared to the conventional roof and a decrease of the sensible heat released back to the atmosphere in the late afternoon.

Future work could be the study of green roofs’ response under extremely high temperatures and to identify the best roof properties in countries of greater seasonal variability in meteorological parameters. It is important to identify the correct balance between soil thickness, leaf area index and soil composition to counteract with cold weather but also to provide essential urban cooling under heatwave conditions. Climatic conditions like rainfall, drought and heatwaves govern the choice of vegetation species for green roofs and dictate the frequency of irrigation so collaborations of researchers of diverse backgrounds would provide more accurate analysis of all the implicated parameters.

REFERENCES

1. Chan, A.L.S., Chow, T.T., 2013. Energy and economic performance of green roof system under future climatic conditions in Hong Kong. Energy Build. 64, 182–198. doi:10.1016/j.enbuild.2013.05.015
2. Jaffal, I., Ouldboukhitine, S., Belarbi, R., 2012. A comprehensive study of the impact of green roofs on building energy performance. Renew. Energy 43, 157–164. doi:10.1016/j.renene.2011.12.004
3. Li, D., Bou-Zeid, E., Oppenheimer, M., 2014. The effectiveness of cool and green roofs as urban heat island mitigation strategies. Environ. Res. Lett. 9, 55002. doi:10.1088/1748-9326/9/5/055002
4. Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K.K.Y., Rowe, B., 2007. Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. Bioscience 57, 823–833. doi:10.1641/B571005
5. Quezada-Garcia, S., Espinosa-Paredes, G., Escobedo-Izquierdo, M.A., Vazquez-Rodriguez, A., Vazquez-Rodriguez, R., Ambriz-Garcia, J.J., 2017. Heterogeneous model for heat transfer in Green Roof Systems. Energy Build. 139, 205–213. doi:10.1016/j.enbuild.2017.01.015