COMPARISON OF GREEN ROOF PLANTS AND SUBSTRATES BASED ON SIMULATED GREEN ROOF THERMAL PERFORMANCE WITH MEASURED MATERIAL PROPERTIES

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ABSTRACT

This study explores effects of green roof materials on green roof thermal performance based on simulated heat transfer through a roof assembly. A case study for a commercial building with a green roof located in Chicago, IL compares heat fluxes and net radiation for different plant and substrate materials. The investigation included a total of 35 cases based on combinations of seven types of plants and five types of substrates used in extensive green roofs. The green roof performance during one week in July was simulated employing a validated green roof model. ANOVA statistical analyses provide direct comparison of simulated heat fluxes and net radition with different plant and substrate types. The results show that both plant and substrate types are statistically important to the total heat fluxes, while only plant types affect the simulated net radiation. The interation effect of plant and substrate types is not statistically important. Specifically, the combination of a plant and a substrate with the highest albedo was chosen as the base case, and comparative analyses were conducted between the base case and other cases. The base case shows the best thermal performance in most simulated conditions. Therefore, in this case study it was sufficent to measure the thermal properties of selected green roof plants and substrates to determine the assembly with best expected thermal perfomance.

INTRODUCTION

Green roofs have been gaining popularity in building constructions due to a variety of benefits: (1) extended roof lifespan by protecting the roof (Saiz et. al 2006), (2) green roofs create pleasant living environments and reduce the storm water runoff (VanWoert et. al 2005), (3) improve the thermal performance of roofing systems both summer and winter (Tabares-Velasco and Srebric 2012; Zhao and Srebric 2012), and (4) reduce the urban heat island by affecting the microclimate, adoption of when adopted in a larger scale (Wong et. al 2003).

The design and selection of green roof materials can impact potential building energy savings (Celik et. al 2010; Jim and He 2010; Getter et. al 2011). Green roof typically consists of several layers from bottom to top: regular roof layer, drainage layer, substrate layer (engineering soil), and a vegetation layer. Specifically, the plant and substrate layers play an important role in the green roof thermal performance. Different plant species have different physiological properties, such as leaf area index (LAI) and foliage height. Therefore, the selection of plants could affect the green roof performance by both shading and evapotranspiration (Tabares-Velasco and Srebric 2012). The thermal properties of various substrates are different due to the differences in mineral composition, texture and shape of the soil (Côté and Konrad 2005). Differences in substrate properties such as thermal diffusivity and reflectivity can affect the heat transfer through a green roof assembly.

A few previous studies have investigated different properties of green roof materials. For example, a study compared different substrate and plant combinations in green roofs based on life cycle CO_2 and life cycle cost analyses (Kim et. al 2012). Another study examined thermal properties of green roofs based on parametric analyses, and concluded that compared to sparse red plants, dark green plants typically maintained lower surface temperatures (Niachou et. al 2001). Other studies measured the thermal properties of different substrates (Sailor et. al 2008 and Sailor et. al 2012) or assessed the effects of plant types on canopy air temperatures and penetrating heat fluxes (Kumar and Kaushik 2005). In addition, an experimental study measured the insulating effects of green roofs using different substrate and plant types (Celik et. al 2010). In total, this experimental study examined nine combinations of different green roof assemblies and measured the daily temperature differences between the green roof substrates and indoor air. The results showed that plant selection could affect the building energy consumption from green roof assemblies. Thus, previous studies have shown that the selection of green roof materials can affect the green roof performance. However, only a few studies investigated whether the effect of green roof materials on thermal performance for actual buildings is statistically significant. Therefore, there is a need for analysis to compare the green roof material properties that are needed for adequate simulation of green roofs.

The present study compares different green roof materials by simulating heat transfer in green roofs

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with different combinations of plants and substrates. Figure 1 shows a flowchart of this study.

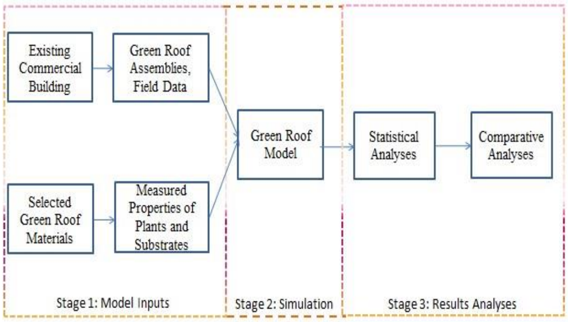

Figure 1 Research methodology flow chart

The first stage of this study was to collect input data for the green roof model. An existing green roof assembly on a commercial building provided validation of the green roof model (Tabares-Velasco et al. 2012). Another source of model inputs is the measured properties of commonly used green roof materials, including seven plant types and five substrate types. In the second stage, the validated green roof model enabled heat flux predictions for 35 combinations of selected plants and substrates in the same geographic location. The results analyses stage includes statistical and comparative analyses. The statistical analyses explored the effects of green roof material selection on green roof thermal performance. Furthermore, by comparative analyses, the simulation results provided a criterion for selection of green roof materials to improve overall thermal performance.

EXPERIMENTS AND MEASUREMENTS

Description of experimental green roof

The studied green roof resides on a commercial building located in Chicago, IL. From top to bottom, this green roof consists of the following material layers: (1) a plant layer, (2) a 7.5 cm substrate layer, (3) two layers of polypropylene fabric, (4) a 2.5 cm of thick foam drainage/protection board made from chunks of recycled closed cell polystyrene, and (5) 0.2 cm PVC waterproof membrane layer. The data aquisition system installed on this green roof includes: (1) a weather station to record the meterological data, (2) a variety of sensors to measure temperatures of different green roof layers, heat fluxes through the green roof, and water contents. The measured data were collected every minute and averaged every 15 minutes. Figure 2 shows the vertical cross-section details of the green roof and data acquisition system.

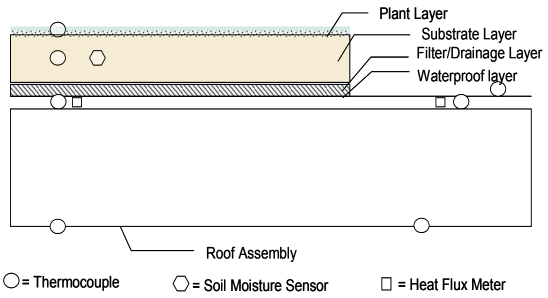

Figure 2 Sketch of green roof system data acquisition system

Description of green roof components

Table 1 shows the thermal properties and mineral composition for the selected substrates. The values shown for the substrate are averages of dry and saturated conditions. Table 2 shows the plant types and measured albedo. The albedo were assumed constant and did not change with volume water content during the simulation.

Thermal properties of the substrates were measured using a commercial transient heat flow probe (Decagon KD2 Pro) with an accuracy of ±10% (Decagon 2006). Reflectivities of substrates and plants were calculated from spectral reflectivity measurements using a portable spectrometer that measured the spectral reflectivity within the range of 400-2500nm.

Table 1
Properties and mineral composition of analysed substrates

SUBSTRATE PROPERTIES	MINERALS COMPOSITION
(1) Avondale	
Albedo: 0.13	Mainly quartz, SiO_2 (sand); trace leucite; trace dolomite (Ca-Mg carbonate) No distinct clay peaks.
Density: 800 kg/m^3	
Thermal conductivity: 0.40 W/(m K)	
Specific heat: 1373 J/(kg K)	
(2) Perlite	
Albedo: 0.13	Mainly quartz, SiO_2 (sand); trace dolomite (Ca-Mg carbonate); trace feldspar; trace cristobalite, another type of SiO_2. This is probably heated volcanic glass material mixed with sand.
Density: 621 kg/m^3	
Thermal conductivity: 0.31 W/(m K)	
Specific heat: 1348 J/(kg K)	
(3) Clay	
Albedo: 0.12	Mainly quartz, SiO_2 (sand); trace
Density: 682 kg/m^3	

Thermal conductivity: 0.32 W/(m K)	leucite; trace dolomite (Ca-Mg carbonate) No distinct clay peaks probably because of amorphization by heating.
Specific heat: 1065 J/(kg K)	
(4) Cellar	
Albedo: 0.11	Mainly quartz, SiO_2 (sand); moderate dolomite (Ca-Mg carbonate); moderate kaolinite clay; slight mica clay and slight chlorite clay. This is the only sample that definitely shows clays.
Density: 1347 kg/m^3	
Thermal conductivity: 0.93 W/(m K)	
Specific heat: 1113 J/(kg K)	
(5) Norlite	
Albedo: 0.08	Mainly quartz, SiO_2 (sand); trace feldspar; trace dolomite (Ca-Mg carbonate); trace leucite; No distinct clay peaks. This porous material is probably produced by vitrifying shale rock in a kiln.
Density: 863 kg/m^3	
Thermal conductivity: 0.46 W/(m K)	
Specific heat: 1246 J/(kg K)	

Table 2
Albedo of plants analysed

PLANT SPECIE	MEASURED PLANT ALBEDO
(1) Sedum Album	0.23
(2) Sedum Sexangular	0.22
(3) Sedum Hispanicum	0.18
(4) Sedum Reflexum	0.16
(5) Sedum Spurium D	0.15
(6) Sedum Spurium O	0.14
(7) Mixed sedum specifies	0.11

SIMULATION OF GREEN ROOFS

Description of green roof model

This study used a validated green roof model that calculates the combined heat and mass transfer processes between the sky, plants, and substrates to obtain the green roof's therrmal performance (Tabares-Velasco et al. 2012). The model also considers the plants' physiological changes that affect transpiration resulted from environemtanl properties such as humidity, solar radiation, wind speed and substrate water content. The model was previously validated with both quasi-steady state data collected in a "Cold Plate" apparatus under laboratory conditions and field data measured from an existing green roof on a building.

The model represents the plant layer as a porous media for convection heat and mass transfer processes. Therefore, the equations of energy balance for a green roof assembly could be expressed as:

$$R_{sh,abs,plants} = Q_{film,plants} + Q_{IR} \tag{1}$$

$$R_{sh,abs,substrate} = -Q_{IR} + Q_s + Q_{substrate} + Q_{IR,sky} + Q_E \tag{2}$$

Equation 1 describes the energy balance for the plant layer, where $R_{sh,abs,plants}$ is the absorbed solar radiation by the plants, Q_{IR} is the radiative heat transfer between the plant layer and the top substrate layer, and $Q_{film,plants}$ represents the heat transfer between plants and the surrounding environment by means of latent (transpiration) heat fluxes, convective and radiative heat transfer. Equation 2 shows the energy balance of the substrate below the plants, where $R_{sh,abs,substrate}$ is the absorbed solar radiation by substrate underneath the plants, Q_{IR} is the long wave radiation between the plant and the top substrate layer, Q_S is the convective heat transfer between the top substrate layer and the surrounding air, $Q_{substrate}$ is the conductive heat flux through green roof substrate, and $Q_{IR,sky}$ is the long wave radiation exchanged between the substrate and sky. Additional equations for each of the model components can be found in the literature (Tabares-Velasco and Srebric 2012).

Green roof model inputs

The main inputs to the green roof model include the following four groups of parameters:

(1) Outdoor weather conditions

The meteorological data were measured onsite for the experimental building and included outdoor dry bulb temperature, wind speed, relative humidity, solar radiation, as well as downward long wave radiation. The weather conditions were the same for all the simulated green roof assemblies.

(2) Conduction transfer functions (CTF)

Adding the conduction transfer functions (CTF) is important to simulate the thermal mass of the substrates. CTFs link current conduction heat fluxes to current and past surface temperatures as well as the past heat fluxes by CTF coefficients dependent on the wall or surface properties and time steps used in the heat flux calculations (ASHRAE 2005). This method is widely used in energy simulations for its simplicity and accuracy. EnergyPlus (U.S. Department of Energy) program provided the CTFs for each substrate type with a time step of 15 minutes. The present study used the average properties of dry and saturated substrates, since the CTF method only allows the use of constant physical-thermal properties, changes of substrates' thermal properties in response to water content change were neglected. However, it is important to mention that previous studies have shown the effects of variable thermal conductivity on the overall thermal performance of a green roof assembly is small, when comparing to the seasonal and hourly variation of evapotranspiration and radiation (Tabares-Velasco and Srebric 2009, Tabares-Velasco and Srebric 2011).

(3) Substrates' Volume Water Content (VWC)

Actual field measurement on the green roof building included soil moisture sensors. However, this data was not used in this numerical work, because the variation of plant and substrate types yielded differences of volumetric water content (VWC) due to the varied thermal and hydrothermal properties. Therefore, VWC used for each single case was calculated with a physically-based energy balance simulation module (Sailor 2008) in EnergyPlus, by assuming no irrigation during the simulated period with appropriate measured properties for each substrate.

(4) Other inputs

Additional model inputs used in this study are: (a) substrate thickness equals to 0.075m, (b) the indoor air temperature was set to 20°C, (c) the leaf area index (LAI) was 2.5, (d) minimum resistance to plant transpiration (stomatal resistance) was held constant for all plant types to a value of 700 s/m, (e) the measured properties of plants and substrates are shown in Table 1 and 2. LAI and stomatal resistance were based on a previous study for *Sedum spurium* (Tabares Velasco and Srebric2012). However, actual plant species might have a different stomatal resistance since stomatal resistance of succulent plants ranges from 450 to 1000 s/m (Jones 1992). In addition, this study only uses the green roof model to calculate the heat and mass transfer between the green roof and the outdoor environment as shown in Equation 1 and 2, and does not estimate the interaction with indoor environment and/or overall building energy consumption. The scope of this study is limited to heat flux and net radiation due to the paper space constrains.

DISCUSSION AND RESULT ANALYSIS

The study simulated the green roof performance of 35 cases with different combinations of plants and substrates for one week with 15-minute intervals. Among the simulated results, heat fluxes and net radiation were chosen as indicators to represent the green roof's thermal performance for the following reasons: one of the major advantages of green roofs is that they reduce building thermal loads by decreasing the heat transferred through the roofs, which is represented by heat fluxes; while net radiation indicates major incoming heat flux towards the green roof. In addition, this study used statistical methods to test whether the selection of green roof materials was statistically important to the overall green roof's thermal performance in terms of heat fluxes and net radiation. Ideally, the comparison would be done by having 35 different green roof samples. However, this represent an extensive task that would require testing for several months and significant resources. Thus the statisticaly anslysis is more suitable for comparing the impacts of the plant and substrate properties on greenroof performance.

Statistical analysis

Based on a 95% level of significance, the analyses of variance (ANOVA) were performed on each response variable (heat fluxes and net radiation) to test whether plant and substrate types, as well as their interaction is statistically important to the green roof performance. Table 3 shows the response variables and the independent variables. The interaction, represented as "plant*substrate" in Table 3, describes possible simultaneous influences of plant and substrate types on the response variables. Level indicates the number of groups for the independent variables (for example, the level is the number of plant types for the first independent variable) and type implicates whether the main effect of an independent variable can be considered random.

Table 3

Response and independent variables in ANOVA

RESPONSE VARIABLES	**INDEPENDENT VARIABLES**		
Heat fluxes	Name	Type	Level
	plant types	fixed	7
	substrate types	fixed	5
Net radiation	plant *substrate	fixed	n/a
	Time	random	673

ANOVA analysis of heat flux as a response variable indicates that both plant and substrate types have statistically significant effects on heat fluxes, since their corresponding p-values are smaller than 0.05. However, in the case of net radiation, only plant types have a significant effect with a p-value close to 0, while the p-value of substrate types are larger than 0.05. This is probably due to the large LAI (2.5) which indicates large leaf area over the substrate, and the leaves block the interaction between the substrate, sky and the sun.

ANOVA analyses of heat fluxes and net radiation show that both p-values of the interaction effects of the two independent variables (i.e. plant types and substrate types) are larger than 0.05, suggesting that the interaction effects are not significant for either response variable (i.e. heat fluxes and net radiation). To further investigate effects of specific green roof materials, analyses were conducted for both response variables as follows.

Effects of green roof materials on heat fluxes

In the following analyses, the base case consists of a green roof containing plant (1) and substrate (1) which represents a combination with the highest albedo (*S. album* and avondale substrate shown in Table 1 and 2).

Figure 3 shows the calculated conductive heat flux differences between the base case (substrate (1)) and all other cases. All simulated green roof cases used the same plant type (plant (1)). Negative heat fluxes indicate outward heat fluxes from the building, while positive values indicate inward heat fluxes into the building through the roof assmblies. Figure 3 includes simulation results within a period of 24 hours rather than a week to avoid crowded lines. As shown in Figure 3, the simulated heat fluxes vary in accordance with the changes of solar radiation (Q_{sun}) with a time hysteresis, which is due to absorbed solar radiation and heat storage by substrates. Since solar radiation is the major heat drive during the day, the differences of heat fluxes caused by substrates are stronger and mostly positive. However, at night the differences decrease to negative values, suggesting that the differences of heat fluxes among various substrate types first eliminate, then become large again.

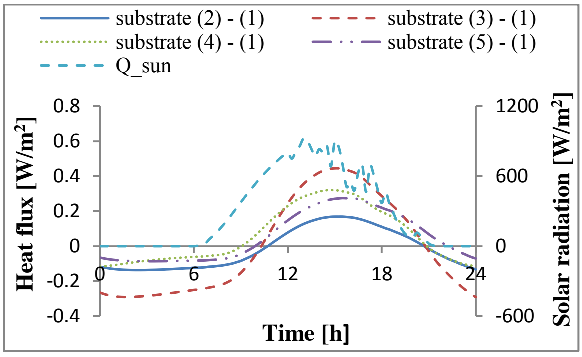

Figure 3 Comparison of solar radiation (Q_{sun}) and simulated heat fluxes with varied substrate types during 24 hours in July (all cases use plant (1))

To further investigate which substrate type enables better green roof thermal performance during the whole simulation period, Figure 4 compares heat fluxes of substrate (1) and (3). These two were selected since Figure 3 shows that the largest difference exists between these two substrate types. The results show that substrate (1) has the smallest heat fluxes during the simulated period, and the largest heat flux difference between (1) and (3) is about 10%, as seen in Figure 3 and 4.

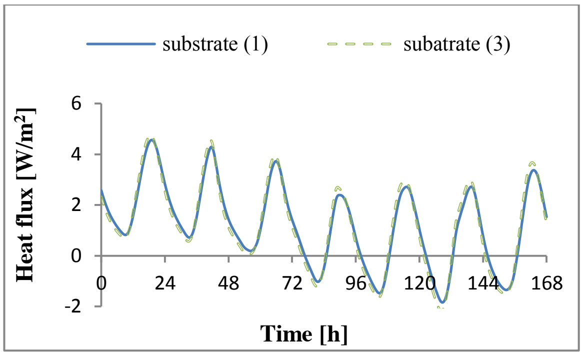

Figure 4 Comparison of simulated heat fluxes for substrate (1) and (3) during 1 week in July (both cases use plant (1))

Figure 5 shows simulated heat flux differences of different plant types with identical substrate types (substrate (1)). The results indicate that differences of heat fluxes increase while the differences of plants' albedo decrease: plant (7) and (1) have the largest differences of heat fluxes as there is the largest difference between their albedo (0.11 of plant (7) compared to 0.23 of plant (1)); while heat flux differences between plant (2) and (1) is quite small with minimal albedo difference between these two plants (0.22 of plant (2) compared to 0.23 of plant (1)). The time hysteresis between the solar radiation and the differences of heat fluxes is also shown during the day. The differences of heat fluxes become 0 at night, indicating that the effects of plant types on heat fluxes are negligible at night.

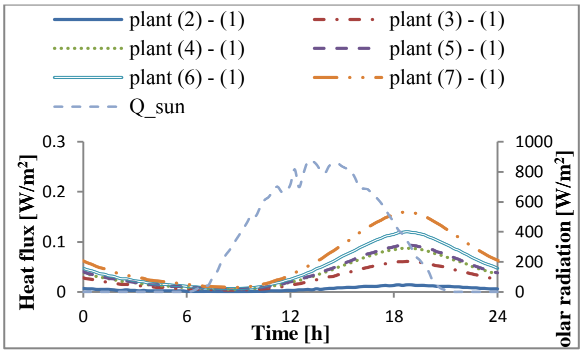

Figure 5 Comparison of solar radiation (Q_{sun}) and simulated heat fluxes through green roof with varied plant types during 24 hours in July (all cases use substrate (1))

Figure 6 shows simulated heat fluxes of plant (1) and plant (7): when the heat fluxes are positive, plant (1) has the smallest heat flux and thus the best green roof performance; however, when the heat fluxes become negative, plant (7) has the best green roof perfomance while plant (1) has the worst. The largest heat flux difference between the two cases is about 5%, as from Figure 5 and 6.

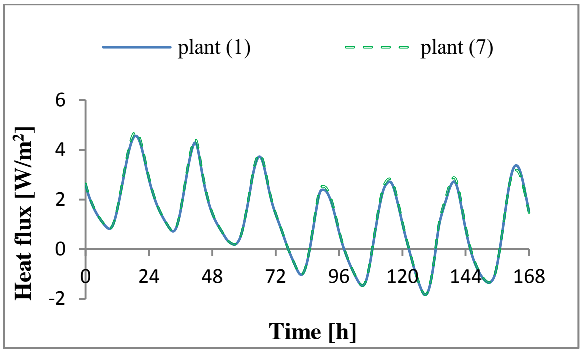

Figure 6 Comparison of simulated heat fluxes for plant (1) and (7) during 1 week in July (both cases use substrate (1))

From Figure 3 to 6, it can also be concluded that substrate types have more significant influences on heat fluxes than that of plant types, because the range of heat flux differences shown in Figure 3 is larger than that in Figure 5.

Effects of green roof materials on net radiation

Net radiation was the other response variable to represent the green roof performance in this paper. Since statistical analyses have proved that only the plant types are significantly important to net radiation, the following analyses only employ plant types as the variable interested.

Figure 7 presents the simulated net radiation differences between the base case and other cases. From these results, one can conclude that the differences in plant albedo are proportional to the net radiation differences. Net radiation differences between plant (7) and plant (1) is the largest since albedo difference of plant (7) and (1) is the largest among all plant types. Figure 8 shows the simulated results of plant (1) and (7): when the net radiation is positive, plant (7) has the largest net radiation during the day. However, plant types make negligible difference between cases during the night, and the largest net radiation difference between (1) and (7) is about 15%, as from Figure 7 and 8.

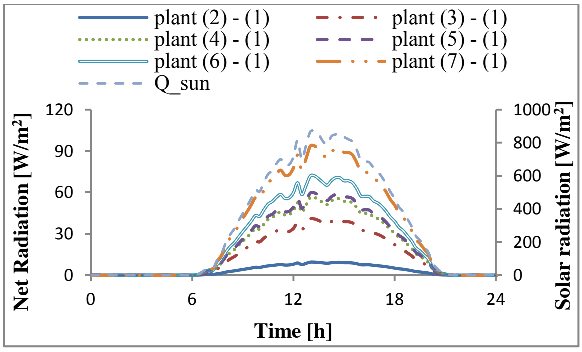

Figure 7 Comparison of solar radiation (Q_{sun}) and simulated net radiation with varied plant types during 24 hours in July (all cases use substrate (1))

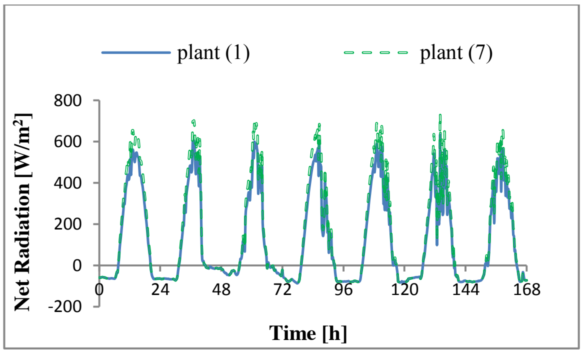

Figure 8 Comparison of net radiation for plant (1)and (7) during 1 week in July (both cases use substrate (1))

CONCLUSION

This paper presents a simulation study of different plant and substrate types commonly used in green roof assemblies. The analyses of variance show that both plant and substrate types could significantly affect the total heat fluxes through the green roof. However, only the plant types statistically influence the simulated net radiation. In addition, the interaction effect of plant and substrate type is not significant for either response variable. By taking the combination of plant (1) and substrate (1) as the base case, the analyses focus on the comparisons between the base case and other cases. Both the heat fluxes and net radiation change in accordance with the solar radiation; while the heat fluxes change with a time hysteresis due to heat storage of substrates. Table 4 presents the comparison results of different green roof assemblies, and the thermal performance of the base case is the best under different conditions.

Table 4
Comparison of green roof materials under different Conditions

PLANT TYPE	SUBSTRATE TYPE	LOWEST HEAT FLUX	LOWEST NET RADIATION
Varied	Identical	Plant (1) & Substrate (1)	Plant (1) & Substrate (1)
Identical	Varied	Plant (1) & Substrate (1)	Negligible difference between cases

In addition, the analyses show that the substrate types contribute more to the differences of simulated heat fluxes between cases, while only the plant types play an important role in the differences of simulated net radiation. This finding highlights the significance of thermal storage for substrates and shading for plants in the overall thermal perfomance of green roofs. In summary, the selection of green roof materials could affect the green roof thermal performance as high as 15%. However, more comprehensive studies considering different leaf area indexes and plant stomatal resistances are needed.

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