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Effects of plant and substrate selection on thermal performance of green roofs during the summer

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ABSTRACT

Green roof assemblies influence the total roof surface energy balance for a building. The energy balance for a green roof depends mostly on the selection of plants and substrates suitable for the building's location. This study measured thermal properties of common green roof materials and selected two types of plants and substrates to simulate transient thermal performance of different green roof assemblies. The selected plants and substrates have the highest and lowest reflectivity values to establish upper and lower bounds of thermal performance. The simulations use a previously developed green roof model including weather data for four cities representing different climate zones in the U.S. Based on the simulations, substrate heat fluxes and net radiation fluxes are compared for five days in July of the typical meteorological year. The results show that green roof assemblies receive net radiation fluxes that differ by 20%, and peak net radiation fluxes that differ by 16%, due to their different spectral reflectivity values. However, the substrate heat fluxes are similar for different green roof assemblies, as a roof insulation layer diminished this flux. Overall, the material selection of green roof assemblies is more important for buildings located in climate zone 4 or 5 than buildings located in climate zone 2 or 3, where limited water availability for evapotranspiration during hot, dry summers results in little thermal performance variability. Independent of the climate zones, simulation results show that the plant type has an important effect on the net radiation.

1. Introduction

Green roofs have been gaining popularity as a sustainable building technology with a range of benefits. Many buildings use green roofs to store rainwater and then gradually release it as a means of storm water management. Green roofs with appropriate plants can efficiently reduce runoff while providing natural filtration, and do not require watering [1]. Furthermore, by providing additional shading, evapotranspiration, and insulation compared to traditional reflective roof coverings, green roofs play an important role in the total roof surface energy balance used in building energy simulations. Green roofs can reduce the urban heat island effect, protect the building envelop from exposure to excessive daily temperature swings, and decrease cooling and heating requirements [2–4]. Finally, green roofs have life cycle benefits as they can last longer than conventional roofs with lower maintenance costs [5–7].

A typical green roof consists of three layers (from bottom to top): a drainage layer, a substrate layer (growing medium), and a plant layer. The substrate layer typically includes three main components: a lightweight inorganic aggregate, compost, and sand [6]. A green roof designer has many choices for substrates and plants based on local climate, material prices and aesthetic requirements. The substrate material's thermal properties, such as thermal conductivity [7] and specific heat capacity [6,8], can significantly vary between green roof components, causing varying influences on the green roof energy balance. In addition, substrate

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Nomenclature

C	volumetric specific heat, mJ/(m^3 K)
C_p	specific heat, mJ/(kg K)
ρ	density, kg/m^3
K	thermal conductivity, W/m K
$R_{sh,abs,plants}$	absorbed short wave or solar radiation by the plants
$R_{sh,abs,substrate}$	absorbed solar radiation by substrate underneath the plants
$Q_{IR,plants,sky}$	radiative heat transfer between plants and sky (W/m^2)
$Q_{IR,,subs,cov,sky}$	thermal radiation or radiative heat exchange between substrate and sky, W/m^2
$Q_{film,plants}$	heat transfer between plants and the surrounding environment (W/m^2)
Q_{IR}	long wave radiation between the plant and the top substrate layer (W/m^2)
$Q_{S,P}$	convective heat transfer between the top substrate layer and the surrounding air (W/m^2)
$Q_{substrate}$	conductive heat fluxes through green roof substrate (W/m^2)
$Q_{IR,sky}$	long wave radiation exchanged between substrate and sky (W/m^2)
$\tau_{plants,IR}$	long-wave transmittance of a canopy, 0.1256
ε_{plants}, $\varepsilon_{substrates}$	emissivity of plant and substrates
T_{plants}, T_{sky}, $T_{top,substrate}$, $T_{air,ref}$, T_{soil}	plants' average temperature, sky temperature, temperature of top layer of substrate, air temperature, substrate temperature, K
σ	Stefan–Boltzmann constant, 5.64 × 10^{-8} W/m^{2}K^4
$Q_{IR,S,P}$	radiative heat transfer between the plant layer and the top substrate layer, W/m^2
$Q_{convection,plants}$	sensible heat flux between plants and surround air by convection, W/m^2
$Q_{convection,substrate,cov}$	sensible heat flux between substrate underneath plants and surround air by convection, W/m^2
Q_E	soil evaporative flux, W/m^2
Q_{film}	heat transfer from the substrate to the environment by means of evaporation (Q_T), convective heat transfer ($Q_{S,P}$), and radiative heat transfer (Q_{IR}), W/m^2
Q_{sun}	incoming solar radiation, W/m^2 K
$Q_{s,s}$	sensible heat flux between green roof substrate and surround air by convection, W/m^2
$Q_{conduction}$	conductive heat flux through green roof substrate, W/m^2
h_{conv}	convective heat transfer for plant layer, W/m^2 K
h_{sub}	total convective heat transfer for green roof substrate covered by plants, W/m^2 K
h_{por}	convective heat transfer for porous media (plants), W/m^2 K
LAI	leaf area index [(leaf area)/(soil surface)]
ET	evapotranspiration, or latent heat flux by convection, W/m^2
γ	Psychrometric constant = C_pP/0.622i_{fg}
r_s	stomatal resistance to mass transfer, s/m
r_a	aerodynamic resistance to mass transfer, s/m
$e_{s,o}$	vapor pressure at the evaporative surface for the roofs with plants, kPa
e_{air}	vapor pressure of the air, kPa
VWC(h)	volumetric water content at pressure head h (cm), cm^3 cm^{-3}
θr, θs, θm	residual and saturated water contents, fictitious(extrapolated) parameter, cm^3 cm^{-3}
α	constant related to the inverse of the air-entry pressure, cm^{-1}
n, m	n is measure of the pore-size distribution, $m = 1 - 1/n$
$q_{j,\theta}$	heat flux for time θ, W/m^2
Y_n, X_n	CTF coefficient, W/m^2 K
$t_{j,\theta}$	surface temperature, C
φ_n	dimensionless flux coefficient

moisture levels can change seasonally and diurnally, causing temporal variability for thermal conductivity and specific heat capacity. When a green roof substrate goes from dry to saturated conditions, thermal conductivity and specific heat capacity increase significantly. Therefore, it is necessary to understand substrate composition and moisture levels to be able to accurately simulate the green roof thermal performance as a component in the total building energy balance. Appropriate plant selection considers the environmental conditions specific to the climate zone. Growth success of green roof plants is expected to be partially dependent on the similarity between the roof eco-region and the plant's native habitat [9]. For example, *Sedum* are common plants used in extensive green roofs, but a study reported that some *Sedum* species could have poor performance in hot and humid areas because they are not well adept to these conditions [10].

Building location and selection of green roof components play important roles in green roof thermal performance. However, when estimating the thermal performance of green roofs, most previous studies considered only location or green roof components [11,12]. The current study investigated the effects of different plant species and substrates on thermal performance of green roof buildings located in different climate zones. Based on the simulations, this study recommends a few strategies for green roof component selection in several climates to improve the thermal performance of green roofs.

This study analyzed seven plant species and five substrates commonly used in green roofs. The study approach is divided in two steps: (1) conduct experiments to measure and analyze thermal properties of plants and substrates; and (2) simulate and analyze thermal performance of different green roofs using the measured properties.

2. Experimental approach

This investigation used seven plant species and five substrate types to evaluate the effects of different plants and substrates on the thermal performance of a green roof. Fig. 1 shows a photo of selected plant species and substrates. The plant species shown in Fig. 1 are: 1) *Sedum spurium* (*Dragon's Blood*), 2) *Sedum hispanicum*, 3) *Sedum rupestre Angelina*, 4) *Sedum sexangulare*, 5)*Sedum tomentosum*, 6) a tray with mixed *Sedum* species, and 7) *S. spurium*. The substrate materials are: 1) Norlite (Norlite expanded shale aggregate, Norlite LLC Cohoes, NY), 2) Perlite, 3) Expanded clay (Garick LLC, Cleveland OH), 4) "Cellar market" (a custom blended locally sourced roof media composed of sandstone aggregate and