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Influence of plant coverage on the total green roof energy balance and building energy consumption

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ABSTRACT

This study quantifies the influence of green roof plant coverage on the building energy consumption and the substrate energy balance components. The analysis started with the implementation of a green roof model that accounts for the effects of plant coverage into the U.S. Department of Energy (DOE) building energy simulation program, EnergyPlus. Using the DOE reference building models, thirty different cases were simulated considering different green roof plant coverage, building type, and building age for two different climates. The results indicated that the green roof substrate surface temperature decreases with increasing plant coverage. This temperature decrease is primarily due to the decrease in the amount of absorbed solar radiation on the substrate surface and also an increase in the substrate surface evaporation. For the base-case simulation, due to the plant shading effects, the total daily received radiation at the bare-soil surface is 32% (6.2 kWh m^{-2}) higher than that at the fully-covered green roof substrate surface. Furthermore, the annual cooling (heating) load decreases (increases) with the rate of 13 (0.88) kWh m^{-2} of plant coverage area. The aim of this study is to show the importance of considering plant coverage in green roof simulations and building energy demand predictions.

1. Introduction

As the human population grows, many more natural surfaces turn into impervious surfaces to support infrastructure development for the city dwellers [1,2]. Replacing the natural land cover with buildings and impervious surfaces changes the local energy balance due to different radiative and thermal properties of the newly-introduced materials. These modifications create a different microclimate in the urban areas compared to the microclimate in the rural areas. Turning traditional black flat roofs that constitute about 20–25% of the urban surfaces [3] into green roofs is one of the potential solutions to restore some of natural habitats destroyed in the process of developing city infrastructure. Green roofs are one of the oldest and well-known techniques to reduce the negative effects of urbanization and have been recognized as one of the urban heat island (UHI) mitigation strategies [4]. Green roofs can mitigate the effects of impervious surfaces such as storm water runoff [5,6], and higher surface and ambient air temperatures [7,8]. Therefore, green roofs offer multiple benefits to cities from the water and energy flow perspectives. Urban- and building-scale benefits and positive effects of green roofs have been explored in several studies using numerical simulations, field measurements and laboratory experiments [9–16]. In their lifecycle, green roofs are not continuously fully-covered with plants resulting in heterogeneity along the green roof surfaces. Heterogeneity in roughness, shading, and soil moisture content creates nonuniformity in energy and mass transport over green roofs. In practice, to reduce the green roof heterogeneity and to speed plant growth rate at the initial period of a green roof lifecycle, pre-cultivated vegetation mats are used [17]. Therefore, studying the green roof heterogeneity and plant coverage effects on the green roof energy balance and building energy consumption is required to understand the performance of green roofs.

An extensive literature review indicates that despite a long history of valuable studies in the area of green roofs, the effects of the green roof plant coverage (defined as the percentage of the roof area covered with plants to the total green roof area) have not been studies, quantitatively.

Most of the detailed existing green roof models account for the effects of the plant canopy height and density [18–20], but due to the horizontally-homogeneous assumptions, heterogeneity effects along the green roof surfaces are neglected. Heterogeneity in green roof plant coverage is explicitly considered in a recently developed model by Tabares-Velasco and Srebric [14] (hereinafter

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Nomenclature

C_p	specific heat of air, J kg^{-1} K^{-1}
e_{air}	vapor pressure in the air, kPa
e_{soil}	saturated vapor pressure at the soil/substrate temperature, kPa
h_{conv}	convective heat transfer coefficient for plant layer, W m^{-2} K^{-1}
h_{por}	convective heat transfer coefficient for porous media (plants), W m^{-2} K^{-1}
h_{sub}	total convective heat transfer coefficient for green roof substrate, W m^{-2} K^{-1}
k_l	longwave extinction coefficient
k_s	shortwave extinction coefficient
LAI	leaf area index [(leaf area)/(soil surface)]
$LMST$	Local Mean Sidereal Time
LW_{net_Plant}	thermal radiative exchange between the plant layer and the soil surface absorbed by the soil surface, W m^{-2}
LW_{net_Sky}	thermal radiative exchange between the sky and the soil surface absorbed by the soil surface, W m^{-2}
Q_E	substrate surface latent heat flux, W m^{-2}
Q_{E_bare}	substrate latent heat flux of the uncovered portions of the green roofs, W m^{-2}
$Q_{E\_covered}$	substrate latent heat flux of the covered portions of the green roofs, W m^{-2}
Q_G	conductive heat flux through green roof substrate and roof construction, W m^{-2}
Q_S	substrate surface sensible heat flux, W m^{-2}
r_a	aerodynamic resistance to mass transfer, s m^{-1}
r_{sub}	substrate surface resistance to mass transfer
R_s	total shortwave radiation received at the substrate surface, W m^{-2}
SW_{net}	substrate surface net absorbed shortwave radiation, W m^{-2}
T_{plant}	plant temperature, K
T_{sky}	sky temperature, K
VWC	substrate average volumetric water content, m^3 m^{-3}
VWC_{sat}	substrate maximum volumetric water content, m^3 m^{-3}

Greek

γ	psychrometric constant, kPa K^{-1}
δ_f	plant coverage (PC)
ε_g	soil emissivity
ε_p	plant emissivity
ε_s	sky emissivity
ρ	air density, kg m^{-3}
τ_{lw}	longwave transmittance of a plant canopy
τ_{sw}	shortwave transmittance of a plant canopy

GR-TS2012). GR-TS2012 is a physically-based, quasi-steady state heat and mass transfer green roof model that introduced the plant coverage as a percentage of the total green roof area. The aim of the current study is to use a modified version of GR-TS2012 to explore and quantify the effects of plant coverage on the extensive type green roof surface energy balance and further explore its influence on the energy demand in buildings. Therefore, GR-TS2012 was implemented into EnergyPlus, the U.S. Department of Energy (DOE) building energy simulation program [21]. If successfully implemented, this simulation module can enable numerical calculations of green roof plant coverage impacts on the building energy consumption. Therefore, beyond the model implementation, this study validated the module with data from measurements and conducted simulations of thirty different cases considering different green roof plant coverage, building type, and building age for two different climates. Overall, the study deployed a detailed green roof model in a comprehensive way to quantitatively evaluate impacts of the green roof plant coverage on the total green roof energy balance and the thermal performance of a building.

2. Model description

This study uses a quasi-steady state heat and mass transfer green roof model that was developed from data collected in a “Cold Plate” apparatus set in an environment chamber [22]. The detailed description of this model, which in this paper is referred to as GR-TS2012, is available in the literature [14]. This model is fully validated with laboratory and field experimental data including both heat fluxes and surface temperature fields [14,23]. The unique characteristic of this physically-based model is the ability to simulate partially-exposed/partially-covered, including bare-soil and fully-covered green roofs by taking into account the plant coverage percentage. GR-TS2012 was originally implemented in the Engineering Equation Solver (EES) software to solve the heat and mass transfer equations between the sky, plants and substrate. In order to investigate the effects of a green roof plant coverage on building energy performance in this study, GR-TS2012 was integrated into the U.S. Department of Energy (DOE) building energy simulation software, EnergyPlus [21]. EnergyPlus is one of the most advanced building energy simulation models that is supported by DOE for analyzing the energy consumption of buildings. EnergyPlus is a stand-alone building energy simulation model that simulates the hourly energy consumption of a building conditional on user-specified internal loads, building construction, and weather. More information about EnergyPlus can be found in the corresponding DOE publications [24,25]. For implementing GR-TS2012 into EnergyPlus, GR-TS2012 was written in FORTRAN and later in C++ language. In its new format, the energy balance equations for plants, bare soil surface, and substrate surface under the plant layer were solved iteratively for their temperatures by Newton's method. Furthermore, using the plant coverage percentage, the area-averaged soil surface temperature is calculated as the roof surface temperature. The volumetric water content (*VWC*) in the substrate layer is simulated by the moisture-tracking subroutine of EnergyPlus that accounts for precipitation, irrigation, evapotranspiration, and runoff [20]. Similar to the existing ‘Ecoroof’ model option in EnergyPlus, in the current model, the user is allowed to specify a green roof layer as the outer layer of a rooftop construction [20]. Besides the ‘Ecoroof’ inputs that include growing media depth, soil physical and thermal properties, plant canopy density, stomatal resistance, and soil moisture conditions, additional parameters are required for the new green roof model. The new parameters are the plant coverage representing the percentage of green roof area covered with plants, the substrate VWC at field capacity, as well as the shortwave and longwave extinction coefficients [26]. GR-TS2012 requires additional inputs, but they are crucial in accounting for thermal effects of partially covered green roofs.

To verify the implementation of the green roof model into EnergyPlus, the model was tested against field data from a green roof installed on a commercial building roof in Chicago, IL, the same case that was used in the previous field validation study of GR-TS2012 [23]. Recreation of the GR-TS2012 validation study verified that the implemented model into EnergyPlus works as expected.