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A green roof model for building energy simulation programs

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Abstract

A physically based model of the energy balance of a vegetated rooftop has been developed and integrated into the EnergyPlus building energy simulation program. This green roof module allows the energy modeler to explore green roof design options including growing media thermal properties and depth, and vegetation characteristics such as plant type, height and leaf area index. The model has been tested successfully using observations from a monitored green roof in Florida. A preliminary set of parametric tests has been conducted on prototypical 4000 m^2 office buildings in Chicago IL and Houston TX. These tests focus on evaluating the role of growing media depth, irrigation, and vegetation density (leaf area index) on both natural gas and electricity consumption. Building energy consumption was found to vary significantly in response to variations in these parameters. Further, this response depended significantly on building location (climate). Hence, it is evident that the green roof simulation tool presented here can serve a valuable role in informing green roof design decisions.

Keywords: Green roof; Ecoroof; Energy model; EnergyPlus; Building energy; Simulation

1. Introduction

A green roof (or ecoroof) is a roof that contains a soil (growing media) and vegetation layer as its outermost surface. The construction between the growing media and the roof structure varies, but typically includes a drainage layer, a root barrier, and a waterproof membrane. Green roof growing media depth is typically between 10 and 30 cm, although some implementations (referred to as intensive green roofs) have deeper soils capable of sustaining large shrubs and even trees. The thinner implementations (typically < 20 cm), known as extensive green roofs, are more common, but can only sustain smaller plants and ground cover.

While green roofs have been in use for centuries, there recently has been a surge in interest in installing green roofs in both retrofit and new construction applications. Potential benefits of green roofs include aesthetic appeal, habitat, storm water reduction, and energy savings. It is the energy savings aspect of green roofs that motivates the present work. Specifically, while the potential energy savings of green roofs is widely touted as an important benefit it has not been studied in much detail with few exceptions. Field studies generally have been limited to evaluating summertime effects of green roofs with a focus on surface temperatures [1,2]. While the study by DeNardo [3] investigated green roof performance throughout the year, that study also limited its energy analysis to measurements of surface temperatures. With respect to predictive models of the energy performance of green roofs there have been several studies that have used field measurements to parameterize simplified mathematical models [4,5]. Each of these studies, however, invoked simplifications with respect to the effects of evapotranspiration and time-varying soil thermal properties. Both studies were also limited in scope to the air conditioning energy savings potential in summer.

There is a growing need for comprehensive design tools that can be used by developers and architects to assess the potential benefits of green roofs and assist in the design process. In this paper we present a new resource to inform this design process. Specifically, we have implemented a physically based model of the energy balance of green roofs in a module incorporated in EnergyPlus—the cutting edge building energy simulation software developed by the US Department of Energy. The

Abbreviations: BATS, biosphere, atmosphere transfer scheme; BLAST, building loads analysis and system thermodynamics; CTF, conduction transfer functions—transient conduction solution method; DOE-2, department of energy building energy analysis tool; FASST, fast all-season soil strength model; GRP, green roof project at University of Central Florida; HVAC, heating, ventilation, and air-conditioning; SiB, simple biosphere model; TMY, typical meteorological year.

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Nomenclature

C_{eg}	latent heat flux bulk transfer coefficient at ground layer
C_f	bulk heat transfer coefficient
C_{hg}	sensible heat flux bulk transfer coefficient at ground layer
C_{hnf}	near-neutral transfer coefficient at foliage layer
C_{hng}	near-neutral transfer coefficient at ground layer
$C_{p,a}$	specific heat of air at constant pressure (1005.6 J/kg K)
$C_{1,f/g}$, $C_{2,f/g}$, $C_{3,f/g}$	coefficients in linearized temperature equations for foliage/ground
e^*	saturation vapor pressure (Pa)
f_1	multiplying factor for radiation effect on stomatal resistance
f_2	multiplying factor for moisture effect on stomatal resistance
f_3	additional multiplying factor for stomatal resistance
F_f	net heat flux to foliage layer (W/m^2)
F_g	net heat flux to ground surface (W/m^2)
g_d	plant specific characteristic related to stomatal resistance
H_f	foliage sensible heat flux (W/m^2)
H_g	ground sensible heat flux (W/m^2)
$I_s^{\downarrow}$	total incoming short-wave radiation (W/m^2)
$I_{ir}^{\downarrow}$	total incoming long-wave radiation (W/m^2)
K_v	von Karmen constant (0.4)
l_f	latent heat of vaporization at foliage temperature (J/kg)
l_g	latent heat of vaporization at ground temperature (J/kg)
L_f	foliage latent heat flux (W/m^2)
L_g	ground latent heat flux (W/m^2)
LAI	leaf area index (m^2/m^2)
M_g	moisture saturation factor
q_a	mixing ratio for air
q_{af}	mixing ratio for air within foliage canopy
$q_{f,sat}$	saturation mixing ratio at foliage temperature
$q_{g,sat}$	saturation mixing ratio at ground temperature
r_a	aerodynamic resistance to transpiration (s/m)
r_s	foliage leaf stomatal resistance (s/m)
$r_{s,min}$	minimum leaf stomatal resistance (s/m)
r''	surface wetness factor
R_{ib}	bulk Richardson number
R_v	gas constant for water vapor (461.53 J/kg K)
T_a	the air temperature at the instrument height (Kelvin)
T_{af}	air temperature with in the canopy (Kelvin)
T_f	foliage temperature (Kelvin)
T_g	ground surface temperature (Kelvin)
W	wind speed above canopy (m/s)
W_{af}	wind speed with in the canopy (m/s)
z	height or depth (m)
Z_a	instrument height (m)
Z_d	displacement height (m)
$Z_{o,f}$	foliage roughness length scale (m)

Greek letters

α_f	albedo (short-wave reflectivity) of the canopy
α_g	albedo (short-wave reflectivity) of ground surface
Γ_h	stability factor
ε_f	emissivity of canopy
ε_g	emissivity of the ground surface
ε_1	$\varepsilon_g + \varepsilon_f - \varepsilon_f\varepsilon_g$
ρ_a	density of air at instrument height (kg/m^3)
ρ_f	density of air at foliage temperature (kg/m^3)
ρ_{af}	density of air at foliage temperature (kg/m^3)
ρ_{ag}	density of air at ground surface temperature (kg/m^3)
θ	moisture content
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/m^2 K^4)
σ_f	fractional vegetation coverage

Subscripts

a	air
af	air within the foliage layer
avg	average
e	latent heat flux term
f	foliage surface
g	ground surface
h	sensible heat flux term
ir	infrared (or long-wave)
max	maximum
n	current time step
$n + 1$	future time step
r	residual
sat	saturation value
S	short-wave

green roof model accounts for long-wave and short-wave radiative exchange within the plant canopy; plant canopy effects on convective heat transfer; evapotranspiration from the soil and plants; heat conduction (and storage) in the soil layer; and moisture-dependent thermal properties. The model formulation is based on the Army Corps of Engineers' FASST vegetation models [6,7], drawing heavily from two models used extensively in the atmospheric modeling communities—the Biosphere Atmosphere Transfer Scheme (BATS) [8] and the Simple Biosphere model (SiB) [9]. It simultaneously solves for soil surface (T_g) and foliage (T_f) temperature each time step.

As implemented in EnergyPlus the green roof module allows the user to specify "ecoroof" as the outer layer of a rooftop construction. The user then can either accept default values or specify various parameters of the green roof construction including growing media depth, thermal properties, plant canopy density, plant height, stomatal conductance (ability to transpire moisture), and soil moisture conditions (including