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Theoretical and experimental analysis of the energy balance of extensive green roofs

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ABSTRACT

This paper analyzed the energy balance of extensive green roofs and presented a simple but practical energy balance model. Field experiment justified the validation and accuracy of this model. Experimental results demonstrated that within 24 h of a typical summer day, when soil was rich in water content, solar radiation accounted for 99.1% of the total heat gain of a *Sedum lineare* green roof while convection made up 0.9%. Of all dissipated heat 58.4% was by the evapotranspiration of the plants–soil system, 30.9% by the net long-wave radiative exchange between the canopy and the atmosphere, and 9.5% by the net photosynthesis of plants. Only 1.2% was stored by plants and soil, or transferred into the room beneath.

1. Introduction

Many comprehensive environmental problems have occurred in modern cities. Installing green roofs is now widely considered as an effective strategy to solve these problems. Green roofs can mitigate the urban heat island (UHI) effect [1,2], improve the energy efficiency of buildings [3–7], reduce stormwater runoff [8–10], increase biodiversity [11,12], purify water and air [9,13,14], as well as elongate the life span of roofs [1,14]. Because of the benefits mentioned above, green roofs have become a focus of current researches. Of the main values – elongated roof life span, reduced stormwater runoff and improved building energy efficiency – thermal benefits are the most attractive [15].

Green roofs can dissipate the absorbed heat by several effective ways and thereby reduce the heat transferred into the rooms beneath. Wong et al. [1], Theodosio [3], Barrio [4], Takakura et al. [16], Onmura et al. [17] and Sailor [18] studied the energy balance of green roofs and concluded that the dominant way for green roofs to dissipate the absorbed heat was evapotranspiration. But some early studies revealed that the thermal radiation from leaves was the key [19,20]. This dispute has not been settled yet.

Barrio [4], Sailor [18] and Kumar and Kaushik [21] presented different mathematical models for analyzing the energy flows and balance of green roofs. These models can be integrated into building energy simulation programs (such as EnergyPlus) but fail to account for every possible pathway – such as photosynthesis and respiration of plants – that may play an important role in the energy balance of green roofs. In addition, these models include many complicated algebraic or even partial differential equations, which are difficult to solve directly. Thus these models should be improved for better accuracy and greater practical implications.

Extensive green roofs are the most widely used green roofs due to their low costs, light weight, shallow soil layer and independence from delicate maintenance. Plants adopted on extensive green roofs are mainly turf and shrubs, and *Sedum* plants are most widely used [18,22–24]. This paper was focused on the energy balance of extensive green roofs, analyzed every energy incoming and outgoing pathway that might be important, and presented a simple but practical mathematical model. A field experiment was also carried out to justify the validation and accuracy of this model. Relative importance of every pathway was obtained.

2. Theoretical analysis

2.1. Basic energy balance equation

The proposed energy balance model for extensive green roofs is established with the following prerequisites:

(a) The lawn, with 100% leaf coverage, is considered as a diffuse gray body.
(b) Thermal effects of plants' metabolism except for photosynthesis, respiration and transpiration, and thermal effects of microorganism in the soil are negligible.
(c) The conditions with precipitation and dew are not included.

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Nomenclature

c_p	specific heat of plants (J kg^{-1} K^{-1})
c_s	specific heat of soil (J kg^{-1} K^{-1})
$\Delta_f H_m^{\theta}(25\,^{\circ}\mathrm{C})$	standard molar enthalpy of formation at 25 °C (J mol^{-1})
$\Delta_r H_m^{\theta}(25\,^{\circ}\mathrm{C})$	standard molar enthalpy of reaction at 25 °C (J mol^{-1})
h	convection heat transfer coefficient (W m^{-2} K^{-1})
l	latent heat of vaporization (kJ kg^{-1})
$M_{C_6H_{12}O_6}$	molar mass of glucose (kg mol^{-1})
M_{CO_2}	molar mass of carbon dioxide (kg mol^{-1})
n_i	chemical stoichiometric number
q_{cv}	heat transferred by convection (W m^{-2})
q_{em}	heat loss by emission (W m^{-2})
q_{ep}	heat loss by evaporation (W m^{-2})
q_{et}	heat loss by evapotranspiration (W m^{-2})
q_{lr}	heat gain from long-wave radiation (W m^{-2})
q_{ps}	solar energy converted by photosynthesis (W m^{-2})
$q_{ps,net}$	thermal effect of net photosynthesis (W m^{-2})
q_{rp}	heat generation by respiration (W m^{-2})
q_{sp}	heat storage by plants (W m^{-2})
q_{sr}	heat gain from solar radiation (W m^{-2})
q_{sri}	incident solar radiation (W m^{-2})
q_{ss}	heat storage by soil (W m^{-2})
q_{tf}	heat transferred into the room (W m^{-2})
q_{tp}	heat loss by transpiration (W m^{-2})
R_{ep}	evaporation rate (kg m^{-2} s^{-1})
R_{et}	evapotranspiration rate (kg m^{-2} s^{-1})
R_{tp}	transpiration rate (kg m^{-2} s^{-1})
TC	transpiration coefficient
t_a	ambient air temperature (°C)
t_d	dew point (°C)
t_p	plant temperature (°C)
t_s	soil temperature (°C)
v	wind speed above the canopy (m s^{-1})

Greek letters

α_l	long-wave absorptivity of the lawn
α_s	short-wave absorptivity of the lawn
ε	emissivity of the lawn
ρ_p	areal density of plants (kg m^{-2})
ρ_s	areal density of soil (kg m^{-2})
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
$\nu_{net,C_6H_{12}O_6}$	net photosynthetic rate in glucose (kg m^{-2} s^{-1})
ν_{net,CO_2}	net photosynthetic rate in carbon dioxide (kg m^{-2} s^{-1})
$\nu_{ps,C_6H_{12}O_6}$	photosynthetic rate in glucose (kg m^{-2} s^{-1})
$\nu_{rp,C_6H_{12}O_6}$	respiratory rate in glucose (kg m^{-2} s^{-1})
τ	time (s)
$\Delta\tau$	time interval (s)

(d) The green roof is large enough to assume horizontal homogeneity and apply one-dimensional (vertical) analysis.

Considering plants and soil as the system, structural roof and ambient air as the environment, the energy exchanges between the plants–soil system and the environment are obtained and illustrated in Fig. 1. According to the first law of thermodynamics,

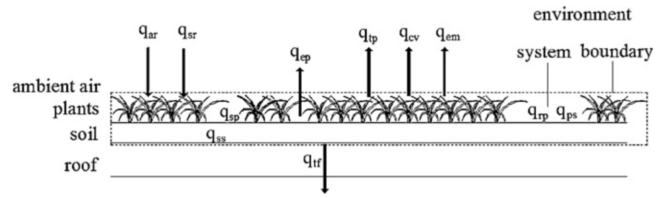

Fig. 1. Energy exchange between an extensive green roof and its environment.

the following energy balance equation is obtained:

$$q_{sr} + q_{lr} + q_{cv} + q_{em} + q_{tp} + q_{ep} + q_{sp} + q_{ss} + q_{tf} + q_{ps} + q_{rp} = 0 \qquad (1)$$

where q_{sr} is the heat gain from solar radiation, q_{lr} the heat gain from long-wave radiation, q_{cv} the heat transferred by convection, q_{em} the heat loss by emission, q_{tp} the heat loss by transpiration, q_{ep} the heat loss by evaporation, q_{sp} the heat storage by plants, q_{ss} the heat storage by soil, q_{tf} the heat transferred into room, q_{ps} the solar energy converted by photosynthesis and q_{rp} the heat generation by respiration. The unit of all the terms in Eq. (1) is W m^{-2}, and the positive values represent heat gain while the negative ones represent heat loss or storage. The first eight terms in Eq. (1) can be calculated by methods summarized in Table 1 (Eqs. (3) and (4) were recommended by Meng et al. [25] and Feng and Chen [26] respectively). The unit area for the terms is 1 m^2 soil or total leaf area above 1 m^2 soil.

2.2. Calculation methods for photosynthesis and respiration

The calculation methods for the thermal effects of photosynthesis and respiration have not yet been reported in the literatures concerning the energy balance of green roofs. Based on the relevant theories in the field of Plant Physiology and Physical Chemistry, the thermal effects of photosynthesis and respiration are attempted to be calculated quantitatively.

2.2.1. Calculation method for photosynthesis

Photosynthesis in plants synthesizes organic compounds (mainly carbohydrates) by combining carbon dioxide and water, and the energy needed for this biochemical process is from solar radiation. This indicates that photosynthesis can convert solar energy into chemical energy and thus q_{ps} is negative. The overall process of photosynthesis can be depicted by Eq. (10):

$$6CO_2(g) + 12H_2O^*(l) \xrightarrow{h\nu} C_6H_{12}O_6(s) + 6O_2^*(g) + 6H_2O(l) \qquad (10)$$

The thermal effect of this reaction at a given temperature equals to the standard molar enthalpy of this reaction at the given temperature. At 25 °C it can be calculated by:

$$\Delta_r H_m^{\theta}(25\,^{\circ}\mathrm{C}) = \sum n_i\, \Delta_f H_m^{\theta}(25\,^{\circ}\mathrm{C}) \qquad (11)$$

Table 1
Calculation methods for the first eight terms in Eq. (1) (Eqs. (3) and (4) were recommended by Meng et al. [25] and Feng and Chen [26] respectively).

$q_{sr} = q_{sri}\alpha_s$	(2)
$q_{lr} = \alpha_l\sigma(t_a + 273.15)^4(0.802 + 0.004t_d)$	(3)
$q_{cv} = (5.7 + 3.8v)(t_p - t_a)$	(4)
$q_{em} = \sigma\varepsilon(t_p + 273.15)^4$	(5)
$q_{tp} = R_{tp}l$	(6)
$q_{ep} = R_{ep}l$	(7)
$q_{sp} = \rho_p c_p \frac{dt_p}{d\tau}$	(8)
$q_{ss} = \rho_s c_s \frac{dt_s}{d\tau}$	(9)