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Development of databases for facilitating green roof energy simulation assessments

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Abstract

Assessments of the energy performance of green roofs have traditionally been performed with experimental and modelling procedures. Experimental green roof energy studies have significant disadvantages (expensive, time-consuming, cannot be generalised, etc.). On the other hand, modelling studies are often done with over-simplified models (for example, by ignoring the effect of moisture flows in the green roof layers) or with detailed models that require inputs which are often difficult to be obtained in practice and may involve a certain degree of uncertainty. This paper describes the methodologies for the development of databases that include data inputs that could be used within building simulation programs for green roof energy performance appraisals. The methods described are based on the data model used by a new green roof model within the ESP-r simulation program; however several of these data could also be used by other detailed models. Where applicable, data are used from the literature and measurements are also taken for input model variables that affect the heat and moisture flows in the plant, air canopy and soil layers. Measurement methods are also described in the paper. The availability of such databases could facilitate the appraisals of green roofs within whole building integrated energy simulations and the methodologies described in this paper could be replicated by researchers in order to include additional green roof data for modelling alternative green roof types.

Keywords

energy, simulation, assessments, development, facilitating, databases, green, roof

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Development of Databases for Facilitating Green Roof Energy Simulation Assessments

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ABSTRACT

Assessments of the energy performance of green roofs have traditionally been performed with experimental and modelling procedures. Experimental green roof energy studies have significant disadvantages (expensive, time-consuming, cannot be generalised, etc.). On the other hand, modelling studies are often done with over-simplified models (for example, by ignoring the effect of moisture flows in the green roof layers) or with detailed models that require inputs which are often difficult to be obtained in practice and may involve a certain degree of uncertainty. This paper describes the methodologies for the development of databases that include data inputs that could be used within building simulation programs for green roof energy performance appraisals. The methods described are based on the data model used by a new green roof model within the ESP-r simulation program; however several of these data could also be used by other detailed models. Where applicable, data are used from the literature and measurements are also taken for input model variables that affect the heat and moisture flows in the plant, air canopy and soil layers. Measurement methods are also described in the paper. The availability of such databases could facilitate the appraisals of green roofs within whole building integrated energy simulations and the methodologies described in this paper could be replicated by researchers in order to include additional green roof data for modelling alternative green roof types.

KEYWORDS

Green roof simulation; Input model data; Soil properties; Vegetation characteristics

INTRODUCTION

A control volume model has been developed and has been placed within the structure of the ESP-r simulation tool (Clarke 2001) in order to assess the energy benefits and

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moisture retention characteristics of green roofs. Green roof simulation developments have been reported in the literature (Sailor 2008), (Jaffal et al. 2012) and (Tabares-Velasco and Srebric 2012) but the new model in ESP-r offers a detailed alternative that, amongst the many new additions which will be reported elsewhere, takes into account time-varying changes of plant physical characteristics and quantifies the water retention capability of the green roof. Such detailed treatment of the plant and soil layers in a green roof requires detailed input data that can be difficult for building professionals to obtain since they are often unfamiliar with the relevant plants and soil concepts. This paper presents the development of a database with inputs that could be used by the green roof model. The green roof mathematical model will be described elsewhere and this paper will only give a brief overview of the model's structure in order to discuss the relevant to the input data issues.

The model couples thermal and moisture exchanges for each control volume. A set of energy balance equations which define the rate of temperature changes is solved for every control volume and has the following general form:

$$F1\,\frac{dT}{dt} = F2 \qquad (1)$$

where F1 is thermal storage function [J/m^{2}K] and F2 is a thermal flux function [W/m^2], which may contain some or all of the following (depending on the control volume): solar radiation, long wave exchange with objects in view, convection, conduction and latent heat exchange due to vapour flow (e.g. evaporation). Similarly the moisture balance equation has the following generic format and it is solved for the soil control volumes (moisture exchanges within the plant's canopy are considered separately in the model):

$$G1\,\frac{d\psi}{dt} = G2 \qquad (2)$$

This is a representation of Richard's equation (Celia et al. 1990), where G1 is a moisture storage function [m^{-1}], G2 is a moisture flux function [s^{-1}] and ψ is the matric potential [m]. Here G2 is a non-linear function (as defined in Richards equation) as opposed to F2 of equation 1 which is a linear function. Non-linearities brought about by radiation exchanges in F2 are linearized by way of techniques explained by Clarke (2001) .

Both thermal and moisture balance equations are discretised and solved simultaneously for all control volumes in an implicit formulation. The following sections discuss the plant and soil related input data that are needed for the solution of these equations and the green roof simulations in general. Table 1 lists all the input parameters for the new green roof model together with suggested default values. It is worth noting that the model is able to handle time-varying ("scheduled" in Table 1) plant morphology and "fraction of vegetation coverage" inputs in order to better represent the dynamic changes of plants during the simulations.

Table 1. *Listing of user input data required for the green roof model*

Classification	Input parameter	Default value used in code
Plant morphology (static or scheduled)	plant height [m]	0.3
	leaf area index (LAI)	4
	leaf characteristic dimension (average width) [m]	0.015
	leaf thickness [m]	0.0008
Plant thermal properties	leaf density [kg/m^3]	400
	leaf specific heat [J/kg K]	2000
Plant moisture exchange	minimum stomata resistance [s/m]	120
	plant wilting point [m]	-80
Soil texture class and related thermal moisture properties	saturated moisture content [m^3/m^3]	0.45
	residual moisture content [m^3/m^3]	0.067
	saturated hydraulic (moisture) conductivity [m/s]	2.89e-06
	moisture retention curve factors n[-] and α [m^{-1}]	1.4, 0.02
	soil organic fraction [-]	0.1
	soil mineral fraction [-]	0.45
	soil clay fraction [-]	0.02
Radiation related	solar reflectivity of canopy [-]	0.25
	solar reflectivity of ground	0.15
	solar reflectivity and transmissivity at leaf tissue level [-]	0.3, 0.2
	emissivity of leaves [-]	0.96
	emissivity of ground [-]	0.95
	coefficient of extinction for long wave radiation [-]	0.829
weather file: precipitation data	hourly precipitation data for the location [mm/h]	TRMM data (Liu et al. 2012)
General/site related	location altitude [m]	100
	fraction of vegetation coverage (static or scheduled) [-]	0.95
	substrate (soil) height [m]	0.3
	irrigation schedule	0

DATA FOR PLANTS IN THE GREEN ROOF MODEL

Leaf Area Index (LAI)

Leaf area index represents how dense a canopy is in blocking solar radiation from reaching the ground. A 0 value represents bare ground while a value 3-5 is common for shrub covers that are normally found in green roofs. An LAI of 5 is assigned to fairly dense roofs. Experimental observations confirm these values reported in literature (Yu 2006) and (Allen et al. 1998). The main factors affecting LAI are the plant type and the plant's phase of development. For deciduous plants leaf area index will change over season. Agricultural crops with short life span of 3 to 4 months are also reported to be used in green roofs. They show distinctive variation of LAI over the life span as reported in FAO's (Food and Agriculture Organization of the UN) crop evapotranspiration guide (Steduto et al. 2012) and by van Walsum and Supit (2012) . For evergreen types of shrubs usually found in intensive green roofs, pruning and maintenance have more influence than seasons and stage of development.

LAI field measurements were conducted with Delta-T Devices Sun Scan Canopy Analysing System (type SS1) by measuring total photosynthetically active radiation (PAR) above canopy and comparing it with the measured PAR below canopy. Manufacturers' accuracy is ±10% which can be compromised at poor sun light and for plant morphology with vertical leaves. The results from these measurements are presented in Table 2 together with the rest of the plant-related input data.
A rule of thumb that is reported by Allen et al. (1998) states that LAI for clipped grass can be estimated as 24h, where h is the height of grass in m.

Canopy physical dimensions

Canopy height depends on the plant species and the literature could be used for sourcing relevant data (Snodgrass and Snodgrass 2006). However, for green roof plants that are maintained with often limited soil height and are occasionally trimmed to maintain aesthetics, height becomes a site specific parameter. From site measurements on an existing intensive green roof in China, we found heights of 0.4 to 0.7m for shrub type of plants. For green roofs with grass, the common height is around 0.06m for a well maintained lawn (Aldous and Chivers 2002).
Leaf characteristic dimension, which is used for the aerodynamic resistance calculation within canopy, is the leaf width. Leaf width is dependent on the plant species and from site measurements we found that for the specific plants of Table 2 it varies from 10 to 30mm.
Leaf thickness is also plant species dependent. Values of 0.3 to 0.6mm were observed for the plants in the site measurement. If unknown a value 0.5mm could be used (as found from experimental observations), which is a representative value for shrub type of plants.

Plant thermal characteristics (specific heat and density)

These inputs are not often reported in the literature. The literature (Stahghellini 1987) gives for example a generic value of 3500 J/kgK for specific heat and 700 kg/m^3 for density, which is an estimate based on the fact that plant tissues consist of 70-80% water. The ASHRAE Refrigeration Handbook (ASHRAE 2010) contains a detailed table for the specific heat of fruits and vegetables.

Minimum stomatal resistance

Stomata are the small openings on leaf surface through which exchange of O_2, CO_2 and water vapour occurs (Frankenstein and Koenig 2004, Campbell and Norman 1998). The size of the stomata opening and their resistance to vapour flow depends on light levels, water availability, ambient CO_2 concentration, air pollution and healthy state of plant. The measurement of actual stomata resistance is done in field tests under the most ideal conditions (bright day light, after irrigation and when it is windy). A cycling porometer from Delta-T is used for the measurements of this study (accuracy: ±20%). To get the minimum stomata resistance, measurements were done under favourable conditions for plants. The method of getting stomata resistance is by measuring the time taken by a plant leaf to release water vapour to a chamber in the head of the instrument so that the relative humidity inside changes by a fixed step. Prior to the leaf measurement, the instrument is calibrated with a calibration plate containing pores of known resistances. The calibration was done on site to have similar conditions for calibration plate and leaf. Data collected from plants at the CSET green roof at the University of Nottingham in Ningbo is given in Table 2.

Table 2.*Summary of data collected from a selection of green roof plants*

Plant Name	LAI	Height [m]	Leaf Angle [deg]	Leaf width [mm]	Leaf thickness [mm]	Minimum stomata resistance [s/m]
Camellia Sasanqua	2.18	0.4	45	23.4	0.56	288
Rhododendron	1.85	0.5	60	30.0	0.5	161
Ligustrum Japonicum 'Howardii'	4.93	0.48	60	20.2	0.46	172
Viburnum Dilatatum (Thunb)	6.28	0.7	30	31.2	0.54	212
Lorpetalum Chinense var. Rubrum	5.27	0.7	30	21.0	0.32	228
Buxus sinica	4.03	0.45	60	11.2	0.42	165
Lawn	1.4	0.06	60	4	0.6	NA

Note: Lawn LAI is an estimate based on rule of thumb; the stomata resistance is not available in this case due to instrument leaf size limitation

SOIL INPUT DATA

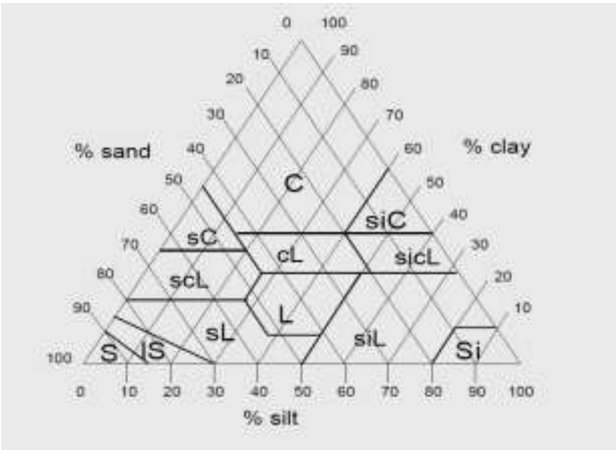
The relation between soil's matric potential (ψ) and moisture content (θ) is defined by a water retention curve and is specific to a soil of certain texture. The equation that represents the water retention curve (van Genuchten 1980) is shown below.

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha|\psi|)^n]^{1-\frac{1}{n}}} \qquad (3)$$

where θ(ψ) is the moisture content [m^3m^{-3}]; ψ is matric potential [m]; θs is the saturated moisture content [m^3m^{-3}]; θr residual moisture content [m^3m^{-3}]; α is an index related to the inverse of the air entry suction, α>0 [m^{-1}], and, n is an index which is a measure of the pore-size distribution, n>1(dimensionless).

The terms that define equation 3 (θr, θs, α and n) are the main soil input data for the model. These parameters together with the soil saturated moisture conductivity are obtained by determining the soil texture class, which in turn is obtained by analysing the particle size distribution of soil. These procedures are demonstrated below.

Size distribution of soils constituents were obtained using a Bettersize2000 laser particle size analyzer (accuracy 1% for mass median diameter). The components can be classified according to size (Leij 1996): sand diameter is >50µm; silt is between 2 and 50 µm and clay is of size <2µm. The result for the soil sample test at CSET's green roof in China was found to be: 22.2% clay, 67.17% silt and 10.63% sand. Reading from the soil texture class triangle (Figure 1), the soil texture is identified as 'silt-loam'. The soil properties can afterwards be determined for any of the 12 soil texture classes from the table of properties published by Carsel and Parrish (1988) and reproduced in Table 3.



S	Sand
lS	loamy Sand
sL	sandy Loam
scL	sandy clay Loam
Si	Silt
SiL	silt Loam
cL	clay Loam
L	Loam
sicL	silty clay Loam
sC	sandy Clay
siC	silty Clay
C	Clay

Figure 1. *USDA soil triangle and textures classes* (Leij 1996)

Table 3. *Soil characteristics according to texture class (Carsel and Parrish 1998)*

Texture Class	Residual moisture content θr [m3/m3]	Saturated moisture content θs [m3/m3]	Index α [1/cm]	Index n [-]	Saturated moisture conductivity Ks [cm/day]
Sand	0.045	0.43	0.145	2068	712.80
Loamy sand	0.057	0.41	0.125	2.28	350.16
Sandy Loam	0.065	0.41	0.075	1.89	106.08
Loam	0.078	0.43	0.036	1.56	24.96
Silt	0.034	0.46	0.016	1.37	6.00
Silt loam	0.067	0.45	0.020	1.41	10.80
Sandy clay loam	0.100	0.39	0.059	1.48	31.44
Clay loam	0.095	0.41	0.019	1.31	6.24
Silty clay loam	0.089	0.43	0.010	1.23	1.68
Sandy clay	0.100	0.38	0.027	1.23	2.88
Silty clay	0.070	0.36	0.005	1.09	0.48
Clay	0.068	0.38	0.008	1.09	4.80

REMAINING MODEL INPUT DATA

Emissivity of most natural materials is between 0.95 and 1. The default values used in the model are 0.95 for soil and 0.96 for plant (Campbell and Norman 1998).

The coefficient of extinction k (for short and long wave radiation) together with LAI is used for calculating the interception of radiation heat exchanges by the canopy as

per Beer's law (Campbell and Norman 1998): $I/Io = e^{-(k\,LAI)}$
where Io is the incident radiation on the roof and I is the transmitted radiation through the canopy. Extinction coefficient for short wave radiation can be calculated from the extinction coefficient for long wave (Barrio 1998) and it is not therefore a user input for the model. Extinction coefficient for long wave (k_l) is dependent on the leaf angle (Stahghellini 1987): $k_l = 1$ for horizontal leaf distribution, 0.829 for 45^o leaf distribution, 0.436 for vertical leaf distribution and 0.684 for spherical leaves.
Plant wilting is a measure of the ability of plant to survive in low moisture soil. (Simunek et al. 2005) use the value of -80 m suction pressure.

CONCLUSION AND IMPLICATIONS

Methods have been outlined for obtaining the required set of plant and soil data for a new green roof simulation model which requires extensive input data. Significant relevant sources from the literature were found and green roof input data were extracted from these sources, which among others include studies in soil-plant-atmosphere and environmental domains. The experimental methodologies for measuring the plants' Leaf Area Index and minimum stomatal resistance, and also the soil's texture classification have been demonstrated. Future studies will assess the sensitivity of simulation results to some of these inputs and will investigate the possibilities for using fewer inputs in simulations. This paper is expected to facilitate the simulation of green roofs by practitioners who are not familiar with the properties of plants and soils by providing direction for source of information in these domains. While the green roof model has been implemented in the ESP-r and the inputs presented here match the specific model's requirements, the data are purely physical and other green roof models could also benefit.

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