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Influence of soil water content on thermal performance of green roofs

Gwiza, Chingamidzai

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3 METHODOLOGY

3.1 Overview of experimental series

Soil is a coarse medium comprised of solid, gaseous and liquid phases. The SWC of soil indicates the amount of water present in the soil. The units of SWC are either on a volume basis, $m^3.m^{-3}$ (cubic meter water per cubic meter of bulk soil volume) or on a mass basis, $kg.kg^{-1}$ (kg water per kg dry soil). In both cases, the value is dimensionless and is usually multiplied by 100 so as to express it as a percentage (Gardner *et al*, 1986). In this study, SWC is measured as volumetric water content (VWC). VWC is defined as the ratio of the volume of contained water in a soil compared to the whole soil volume (Allaby and Allaby, 1999).

In order to answer the research questions, a small scale direct application extensive green roof was built in Johannesburg, South Africa. The behaviour of T_{ave} (the average daily temperature incident on the roof) and A (the amplitude of daily temperature fluctuations incident on the roof) as a function of SWC was determined by logging temperature and VWC time series data for the green roof over a two month period to ensure sufficient variation in SWC. Measurements were taken over the wet summer months of December 2011 and January 2012.

In addition to VWC data, the bulk density of the soil was also measured in order to calculate C_v (see Equation 2-2) as a function of VWC. In order to calculate K_q as a function of VWC, D_q needed to be determined (see Equation 2-4). Lastly, in order to determine the effect of evapotranspiration on the thermal performance of the green roof, and the effect of VWC on evapotranspiration, a second green roof without vegetation was built. This allowed distinction between the influence of soil and vegetation on the thermal performance of the green roof.

Details of these experiments are given in the following sections.

3.2 Experimental setup: Outdoor research facility

3.2.1 Layout and instrumentation

Two direct application extensive green roof test beds were used in this study: one with vegetation (Figure 3-1 a), the other without (Figure 3-1 b). Both beds were the same size (1.86 m × 1.74 m × 0.22 m). A third control box (Figure 3-1 c) of the same size was used to simulate a conventional tiled roof. The test beds were slanted to one side, and a hole was drilled in one corner to allow for sufficient drainage.



(a) (b) (c)

Figure 3-1: The three outdoor test beds: (a) green roof with vegetation, (b) green roof without vegetation, (c) control.

Measurements taken on the roof included VWC and temperature readings. Temperature was measured with J-type thermocouples. The thermocouples were coated with epoxy to protect them from weathering. Soil water sensors (Decagon EC-5) were installed to gauge the VWC of the soil. All the instruments were connected to an Agilent data logger and readings were taken every two minutes. The positioning of the thermocouples and soil water sensors are indicated in Figure 3-2.

3.2.2 Soil type

Typical green roof soils consist of a light inorganic aggregate, sand and compost. The appropriate soil composition differs by locality and design of the green roof (Sailor *et al*, 2008). For this investigation, the soil aggregate choices were based on the suggestions given by Clive Greenstone from the eThekweni Greenroof Pilot Project (personal communication,

2011). A sandy loam soil was used in this study. The experimental soil was composed of a mixture of soil and vermiculite (a type of clay mineral with medium shrink-swell capacity, used as a soil conditioner/amendment). Soil conditioners are added to soil to improve plant growth, as well as correct the soil's deficiencies in structure and/or nutrients. Vermiculite also improves drainage. No compost was used because the plants thrived in the latter mixture.

3.2.3 Vegetation type

The plant species *Plectranthus neochilus* was used. In a previous investigation carried out in the same outdoor research facility (Opeka and Martin, 2010) it was noted that the species easily established itself and could survive on the roof better than the other plant species tested.

Table 3-1: Key to Figure 3-2.

	Bidum
	Root barrier
	Drainage layer
	1000 µm plastic (to protect waterproofing)
A	Soil moisture sensor 1
B	Soil moisture sensor 2
1-13	Thermocouples and their positions in the green roof setup
2	Thermocouple under the vegetation canopy – Box 1 (UVC)
6	Thermocouple under the soil – Box 1 (UV)
7	Thermocouple on top of the soil – Box 2 (TS)
11	Thermocouple under the soil – Box 2 (US)
13	Thermocouple below the tiles – Box 3 (UC)

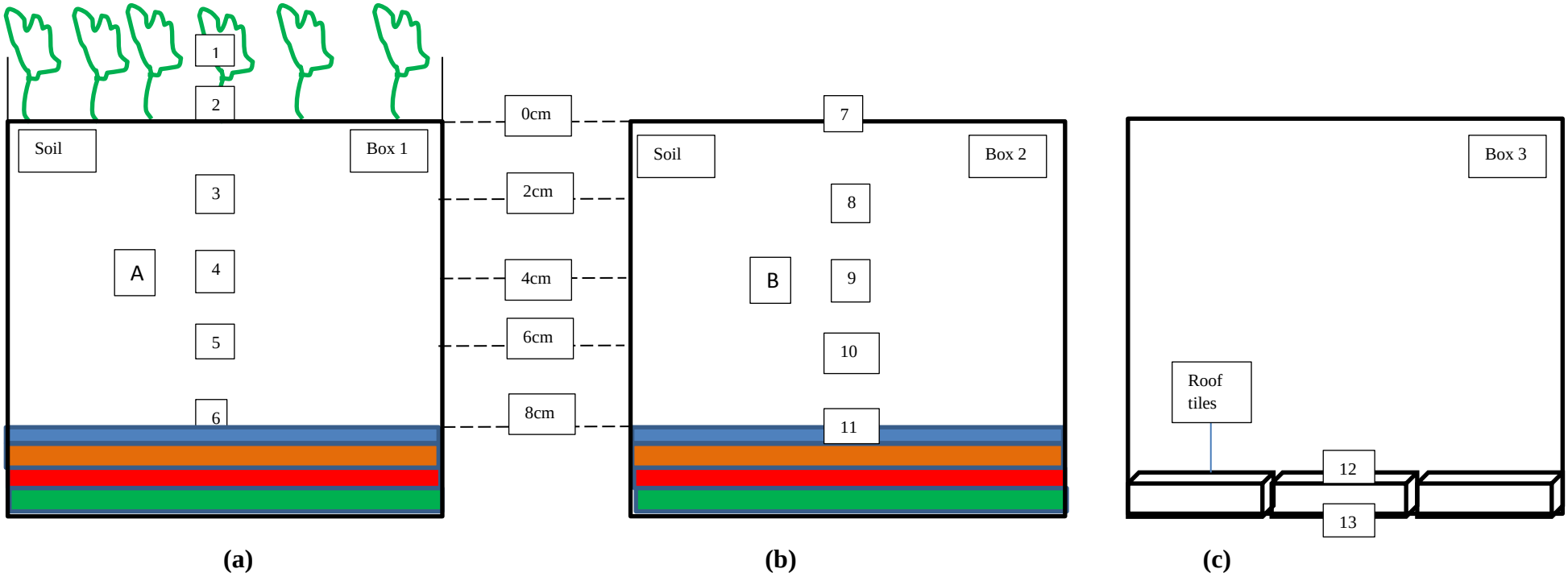

Figure 3-2: Location of thermocouples and soil water sensors. (a) Green roof with vegetation (Box 1), (b) green roof without vegetation (Box 2), (c) control (Box 3). The key to the diagrams is shown in Table 3-1.

3.3 Experimental setup: Laboratory experiments

3.2.1 Soil bulk density tests

The core method (Blake and Hartge, 1986) was used to take soil samples from the roof. This method involved inserting a core of known volume into the soil. The sample was then oven-dried at 105°C for 24 hours and then weighed to obtain the dry soil mass. The bulk density ρ_b (kg.m^{-3}) was calculated as:

$$\boldsymbol{\rho_b} = \frac{\boldsymbol{mass\ of\ dry\ soil\ (kg)}}{\boldsymbol{volume\ (m^3)}} \qquad \text{Equation 3-1}$$

3.2.2 Soil specific calibration of Decagon sensors

Decagon EC-5 sensors were installed to gauge the VWC of the soil. According to the soil sensor calibrations tests done by Decagon Devices (2009), the following equation will universally suit all mineral soils:

$$\boldsymbol{VWC = 11.9 \times 10^{-4}\, mV - 0.401} \qquad \text{Equation 3-2}$$

This equation however, did not give realistic results for the soil in use. The following calibration method was used to get an equation which is specific to the experimental soil.

Calibration Method (Decagon Devices, 2011):

1. Collect approximately 4 litres of bulk soil.
2. Air-dry the soil and pass the soil through a 2-5 mm sieve to remove large objects.
3. Pack the full soil volume into the calibration container at approximately the field bulk density and insert the EC-5 sensor vertically into the soil.
4. Excite the sensor with 2.5 to 3.6 excitation voltage.
5. Collect the raw data from the sensor (no calibration applied). Repeat the above steps once or twice to obtain repeatable insertion quality.

6. Record the sensor readings.
7. Without removing the EC-5 sensor, collect a volumetric soil sample by inserting the soil sampler fully into the undisturbed soil near the sensor.
8. Remove the sampler; making sure that the soil core inside is intact. Shave excess soil from the end(s) with a flat edge, and re-fill any small voids that may have occurred.
9. Place the entire soil core into a drying container and cap the container. Any water loss from the soil between sampling and the first weighing introduces error to the volumetric water content calculation.
10. Measure the mass of the wet soil + container (no lid).
11. Wet the calibration soil. Add about 1 mL of water for every 10 mL of soil volume (increases VWC by 10%). Add the water to the soil as evenly as possible. Thoroughly mix the soil to obtain a homogenous distribution of water.
12. Record the sensor readings.
13. Repeat steps 7 to 12 until the soil is almost saturated. This generally yields 4-6 calibration points.
14. Dry the volumetric soil samples by placing all of the already-weighed, wet samples into an oven at 105°C for 24 hours.
15. After 24 hours remove the soil drying containers from the oven and allow the soil and containers to cool.
16. Measure the mass of the dry soil + containers (without lids).
17. The volumetric water content is defined as the volume of water per volume of bulk soil.

Simple linear regression was used to determine the relationship between VWC and sensor output. The calibration function used in this study is as follows:

$$\boldsymbol{VWC = 1.368 \times 10^{-3} mV - 0.1343} \qquad \text{Equation 3-3}$$

3.2.3 Calibration of the J-type thermocouples

Prior to field installation, temperature calibrations of the thermocouples were performed. The thermocouples (connected to a data logger), together with a thermometer (to monitor temperature) were placed in ice. The temperature was increased in increments of 5°C to 20°C

by adding boiling water. Thermocouple output and temperature data (from the thermometer) were recorded. Stirring was done occasionally to maintain uniform temperature throughout the container. To derive the relationships between measured temperature and temperature readings of the thermocouples simple linear regression analyses were done (Gomez and Gomez, 1984). The calibration equations found were used to correct field recorded temperature readings.

3.4 Calculation methods

3.2.1 Volumetric heat capacity (C_v)

The C_v of soil is dependent on the SWC, the mineral and organic matter composition of the soil, as well as soil bulk density. The specific heat of water is defined as the heat required to raise 1g of water by 1^oC whereas the specific heat of the soil solid is the amount of heat needed to raise 1g of solids by 1^oC ($J.kg^{-1}.{}^oC^{-1}$). The solid specific heat of most mineral soils is about ($0.84\ J.kg^{-1}.{}^oC^{-1}$), but the specific heat of soil is composed of both the water and solid components. The following was adapted from Hanks and Ashcroft (1980):

$$\boldsymbol{C_v = \rho_{wet\ soil} * c_p = \rho_b(1 + \theta_m)c_p} \qquad \text{Equation 3-4}$$

in which C_v is heat capacity based on volume, ρ_b is the soil bulk density ($kg.m^{-3}$), θ_m is mass water content ($\theta_m = (\theta_v \rho_w)/\rho_b$), and c_p is the specific heat. The specific heat of soil is the sum of the solid and water components; therefore C_v can also be written as (Hanks and Ashcroft,1980):

$$\boldsymbol{C_v = \rho_b\left(c_{pav} + \theta_m c_{pw}\right)} \qquad \text{Equation 3-5}$$

Where c_{pw} is the specific heat of water ($4.18\ kJ.kg^{-1}.{}^oC^{-1}$) and c_{pav} is the mean specific heat capacity of the solid components. c_{pav} differs from mineral to mineral but averaged over all soil constituents, it is approximately $0.84\ kJ.kg^{-1}.{}^oC^{-1}$. Equation 3-5 therefore becomes:

$$\boldsymbol{C_v = \rho_b(0.8 + 4.2\,\theta_m)\frac{kJ}{kg℃}} \qquad \text{Equation3-6}$$

in which ρ_b must have units of kg.m^{-3}.

$\theta_m = (\theta_v \rho_w)/\rho_b$,

thus substituting into Equation 3-6 gives $C_v = \rho_b(0.8 + 4.2\ \frac{\theta_v \rho_w}{\rho_b})$. The density of water is 1000 kg.m^{-3} therefore:

$$\boldsymbol{C_v = 0.8 \times 10^3\ \rho_b\ + 4.2 \times 10^6\ \theta_v\ \frac{J}{m^3.℃}}$$ Equation 3-7

Equation 3-7 was used to calculate values for C_v in this study.

3.2.2 Thermal diffusivity (D_q)

D_q is defined as the ratio of heat conducted to heat stored per unit volume (m^2.s^{-1}). The method used to estimate D_q is based on that reported by Carslaw and Jaeger (1959), and Richards (1952) (cited in Taylor and Ashcroft, 1972). It is centred on an investigation of temperature oscillations near the Earth's surface. Soil surface temperatures are believed to fluctuate with simple harmonic oscillations (Taylor and Ashcroft, 1972). Measurements in the field are taken at two depth, z_1 and z_2, in a way that enables the ascertainment of (i) the temperature wave amplitudes, $\mathring{A}_1$ and $\mathring{A}_2$ or (ii) the time lag, t_1-t_2 , which is the required time period for the maximum (or minimum) temperature to travel the distance between z_1 and z_2 . D_q calculations are then done based on those done by Jackson and Kirkham (1958) (cited in Taylor and Ashcroft, 1972). τ is the period of the temperature wave. The first method uses the temperature wave amplitudes, $\mathring{A}_1$ and $\mathring{A}_2$:

$$\boldsymbol{D_q = \pi\ (z_2 - z_1)^2 / \tau[2.303 \log\left(\frac{\mathring{A}_1}{\mathring{A}_2}\right)]^2}$$ Equation3-8

Whilst the second method uses the time lag, $t_1 - t_2$, for the maximum (or minimum) temperature:

$$\boldsymbol{D_q = \frac{\tau(z_2 - z_1)^2}{4\pi(t_2 - t_1)^2}}$$ Equation3-9

It must be noted that these two methods have limitations, because D_q is not constant because soil thermal properties are constantly changing. Taylor and Ashcroft (1972) used the following illustration to explain this statement (Table 3-2).

Table 3-2 Data used by Taylor and Ashcroft (1972) to illustrate the limitations of the cited method used to determine D_q.

1cm depth	**20cm depth**
z_1 = 0.01 m	z_2 = 0.2 m
Maximum temperature: 29°C at 1:20pm Minimum temperature: 21°C at 5:10am $\hat{A}_1$ = (29-21) ^{o}C = 8°C	Maximum temperature: 23 ^{o}C at 7:00pm Minimum temperature: 22°C at 8:30am $\hat{A}_2$ =(23-22)^{o}C=1°C

In this example, τ is 1 day (86400 sec). The maximum has t_2=7:00pm and t_1=1:20pm whereas the minimum has t_2=8:30am and t_1=5:10am. Using Equation 3-8 gives:

$$\boldsymbol{D_q = (3.1416)(0.19)^2/(86400)\left[(2.303)\log\left(\frac{8}{1}\right)\right]^2 = 3\times10^{-7}\, m^2\,.\,s^{-1}}$$

Using $\boldsymbol{D_q = \frac{\tau(z_2-z_1)^2}{4\pi(t_2-t_1)^2}}$

Equation3-9Equation 3-9, the time lag for the:

(i) Maximum is $(t_1\text{-}t_2)_{max}$ =20400sec

$$\boldsymbol{D_q = 86\,400\,(0.19)^2/(4)(3.1416)(20400)^2 = 6\times10^{-7} m^2.s^{-1}}$$

(ii) Minimum is $(t_1\text{-}t_2)_{min}$ =12 000sec

$$\boldsymbol{D_q = 86\,400\,(0.19)^2/(4)(3.1416)(12000)^2 = 1.72\times10^{-6} m^2.s^{-1}}$$

The significant discrepancies shown by the three procedures highlight the fact that the soil is not completely uniform with invariable thermal properties throughout; and signals caution when using this approach to determine D_q (Taylor and Ashcroft, 1972). Results obtained in this study showed that Equation 3-9 using the maximum time lag gives the most realistic values for D_q. The latter was therefore used when calculating D_q. However, it must be pointed out that these values are rather used to determine qualitative trends in D_q, rather than precise values.

3.2.3 Thermal conductivity (K_q)

K_q ($J.s^{-1}.m^{-1}.{}^{o}C^{-1}$) is defined as the quantity of heat transferred through a unit area of soil in unit time under a unit temperature gradient (Hillel, 1980). K_q was calculated by multiplying C_v by D_q (Hanks and Ashcroft, 1980):

$$\boldsymbol{K_q = D_q C_v} \qquad \text{Equation2-4}$$