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Substrate moisture effect on water balance and thermal regime of a tropical extensive green roof

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ABSTRACT

Green-roof thermal and hydrological performance has been extensively studied, but the specific effect of substrate moisture has received little attention. This study investigates the substrate moisture effect on evapotranspiration (ET), water balance and subaerial and subsurface temperatures of an extensive tropical green roof. Firstly, three weather types (sunny, cloudy and rainy) in conjunction with three substrate moisture states (wet, moist and dry) generate nine permutations for a scenario analysis. Secondly, the correlation analysis explores the relationship between substrate moisture and thermal performance indicators. The major finding is that substrate moisture is effective in regulating substrate thermal behavior, but less so in enhancing ET and associated cooling. Substrate moisture can notably cool the soil, rockwool and concrete tile on sunny days, and warm them on cloudy and rainy days. In contrast, substrate moisture has limited effect on ET, which is largely dependent on solar radiation, relative humidity and wind speed. The dry substrate on sunny day demonstrates an aberrant behavior of high ET which contradicts with previous studies. This unusual phenomenon is explained by the limited substrate mass effect of the thin extensive green roof. The vegetation surface and air temperatures show little variations between different soil moisture states, and their correlations with substrate moisture are insignificant. The findings could provide an additional substrate moisture dimension to enhance the design and management of green roofs with reference to water and thermal behavior.

1. Introduction

Green roofs have been adapted increasingly as a sustainable urban design strategy to bring multiple environmental and social benefits. With the growing global concern about climate change and associated interest in low-carbon technologies, the thermal-energy effects of green roofs have received increasing attention. Many empirical and modeling studies have been conducted in different climatic zones and cities of different sizes and development modes. The findings demonstrate notable green-roof contribution to lowering peak roof surface and ambient air temperature, contracting temperature fluctuation, reducing transmission of solar heat through the roof slab into indoor space, and trimming building cooling load (Takakura et al., 2000; Papadakis et al., 2001; Bass and Baskaran, 2003; Wong et al., 2003; Sonne, 2006; Wong et al., 2007; Spala et al., 2008; Eumorfopoulou and Kontoleon, 2009; Teemusk and Mander, 2007; He and Jim, 2010; Jim and He, 2010).

Cooling is attributed to the combined effect of evapotranspiration from soil and plants, shading by vegetation canopy, and thermal insulation by the substrate-drainage layers of the green-roof system. In tropical Singapore, an intensive green roof could reduce surface and ambient air temperatures by 30 °C and 4.2 °C respectively (Wong et al., 2007). Studies in temperate Athens reported 2 °C depression in summer indoor and outdoor air temperature brought by intensive green roofs (Niachou et al., 2001; Santamouris et al., 2007). Field measurements in Japan found that a grass roof can lower peak surface temperature by 30 °C and cut cooling load by 50% (Onmura et al., 2001). In Florida, 22 °C reduction in daily maximum surface temperature and 18.3% reduction in heat flux were recorded in an intensive green roof (Sonne, 2006). In Ottawa, Liu and Baskaran (2003) found that daily surface temperature fluctuation of a green roof was limited to only 6 °C, contrasting with 45 °C on an adjacent bare roof. These studies have largely focused on single temperature parameters, with little investigation on the temperature-gradient in the vertical profile of green roofs.

Green-roof thermal performance denotes an expression of a key abiotic-cum-biotic ecosystem function. They reflect the joint effect of background weather conditions, vegetation, soil and moisture factors. Their investigation can throw light on green-roof science, technology and management. Most studies analyzed the influence of vegetation types and biomass to guide species choice and design (Takakura et al., 2000; Fang, 2008; Spolek, 2008; Köhler and Poll, 2010; Jim, 2012). Few studies explore the soil effect, although the green-roof thermal behavior in dry and moist conditions implies

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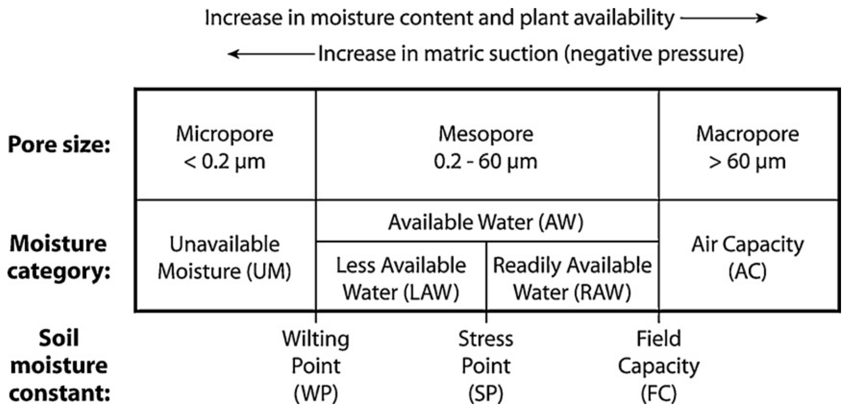

Fig. 1. The pertinent soil moisture concepts in relation to soil pore size, moisture category, and soil moisture constant.

possible substrate-moisture influence on evaporation. Wong et al. (2007) found that the surface temperature of extensive green roof with dry soil can be hotter than bare roof, but it is cooler by 18 °C when the soil is wet. Lazzarin et al. (2005) reported contrasting downward heat flux pattern induced by different soil moisture levels.

Soil thermal property is largely dependent on its water content. Water could enhance soil thermal conductivity and heat capacity, facilitating downward heat transmission, storing heat and suppressing soil temperature fluctuation. Soil moisture also determines the water availability for evapotranspiration (ET), hence the latent-heat cooling of surface and air temperature. Moreover, wetter soil with darker color generally has lower albedo than dry soil, thus increasing net solar radiation at the unshielded soil surface (Bonan, 1989). Study on soil moisture effects could inform sustainable irrigation and water management to enhance green-roof ecological functions.

Soil moisture characteristics and their interaction with meteorological conditions have been extensively studied at natural and semi-natural sites, such as forests, croplands and urban green spaces (Mintz and Walker, 1993; Gillies and Carlson, 1995). For constructed green roof ecosystems with more human inputs in terms of materials and management, similar researches are scanty. This study evaluates substrate moisture effects of an extensive tropical green roof with four objectives: (1) investigate the diurnal substrate water dynamics under nine scenarios defined by three weather types and three substrate moisture states; (2) identify the main factors that regulate substrate moisture status; (3) evaluate the effect of substrate moisture on ET; and (4) analyze the effects of soil moisture on vertical temperature profile and thermal performance.

2. Pertinent soil moisture concepts

Soil moisture is related to the green-roof hydrological cycle. A soil gains water from rainfall (RF) and irrigation (IG), and loses it through evapotranspiration (ET), surface runoff (RO) and drainage (DN). The green-roof water budget can be expressed as:

$$\Delta W = (\mathrm{RF} + \mathrm{IG}) - (\mathrm{ET} + \mathrm{RO} + \mathrm{DN}), \quad (1)$$

where ΔW is the change in substrate water storage. On rainy days, antecedent soil moisture reduces the infiltration rate, hence increases runoff quantity (Berndtsson, 2010). On successive sunny or cloudy days when DN and RO are negligible, Eq. (1) could be simplified as:

$$\Delta W = \mathrm{IG} - \mathrm{ET} \quad (2)$$

Soil moisture status is largely determined by porosity which is a key attribute of soil structure. The size or diameter of pores regulates the energy state at which moisture is held in soil and its availability to plants (Fig. 1). The negative pressure (suction) at which water is held by the soil matrix is inversely proportional to pore size. The micropores at <0.2 μm diameter hold water tightly at high suction, and it cannot be taken up by plants. Hence they are labeled as unavailable moisture (UM). The mesopores at 0.2–60 μm diameter hold water at medium suction, which can be overcome by roots to allow absorption by plants. Hence they denote available water (AW). The macropores at >60 μm diameter hold water loosely at low suction, and it is drained away easily by gravity to allow air entry and facilitate aeration. Hence they denote air capacity (AC).

In the context of the present green roof study, some *soil moisture constants* are important for soil water management and plant growth (Fig. 1). The *field capacity* (FC) marks the upper limit of AW. It is usually attained some hours after a saturating rain or irrigation event due to emptying of AC pores by gravitational drainage. The *wilting point* (WP) marks the lower limit of AW, below which most crop plants will wilt permanently. The amount of AW held by a soil is a determinant of plant growth. AW is often divided into two fractions. AW held in relatively larger pores is *readily available water* (RAW). AW held in relatively smaller pores is *less available water* (LAW). The interface between RAW and LAW is the *stress point* (SP), below which ET may be curtailed and root uptake will be relatively more difficult. Soil water management should aim at maintaining the water content above the SP, hence SP is also known as *refill point* (RP) in irrigation practice. If rainfall is not available or insufficient to fulfill this objective, irrigation is applied as a supplement.

3. Study area and material

Hong Kong is situated at the south coast of China, at latitude 22°N and longitude 114°E with a typical humid-subtropical climate influenced by the dominating Asian monsoon climatic system. The summer is hot and humid with frequent showers, thunderstorms and occasional typhoons. It extends from late April to September when daily maximum temperature can exceed 33 °C. The rainy season largely overlaps with summer with annual rainfall over 2000 mm. The long, hot and rainy summer acknowledges green roofs as a sustainable urban design especially for cooling and stormwater management.

An experimental extensive green roof was installed in July 2009 on the Tai Po railway station situated in a suburban new town in Hong Kong (Fig. 2). It covers 484 m^2, with a nearby control bare plot of 106 m^2 to provide baseline for comparison. The modern