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Biophysical properties and thermal performance of an intensive green roof

C.Y. Jim*, S.W. Tsang

Department of Geography, The University of Hong Kong, Pokfulam, Hong Kong

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ABSTRACT

Green roofs have been increasingly enlisted to alleviate urban environmental problems associated with urban heat island effect and stormwater quantity and quality. Most studies focus on extensive green roofs, with inadequate assessment of the complex intensive type, subtropical region, and thermal insulation effect. This study examines the physical properties, biological processes, and thermal insulation performance of an intensive green roof through four seasons. An experimental woodland installed on a Hong Kong building rooftop was equipped with environmental sensors to monitor microclimatic and soil parameters. The excellent thermal performance of the intensive green roof is verified. Even though our site has a 100 cm thick soil to support tree growth, we found that a thin soil layer of 10 cm is sufficient to reduce heat penetration into building. Seasonal weather variations notably control transpiration and associated cooling effect. The tree canopy reduces solar radiation reaching the soil surface, but the trapped air increases air temperature near the soil surface. The substrate operates an effective heat sink to dampen temperature fluctuations. In winter, the subtropical green roof triggers notable heat loss from the substrate into the ambient air, and draws heat upwards from warmer indoor air to increase energy consumption to warm indoor air. This finding deviates from temperate latitude studies. The results offer hints to optimize the design and thermal performance of intensive green roofs.

1. Introduction

The increasing rate and intensity of urbanization has led to pervasive covers of impermeable structures and surfaces and a corresponding decrease in open-green spaces in many cities. The replacement of natural habitats by artificial and harsh surfaces has increased solar radiation absorption and storage by the urban fabric, and reduced infiltration to raise stormwater runoff and flooding risk. With limited evapotranspiration surfaces, the average temperature of dense urban areas in both daytime and nighttime is generally higher than surrounding rural lands throughout the year to incur the urban heat island (UHI) effect [1]. Especially in compact cities, the elevated urban temperature has induced a significant increase in air-conditioning energy consumption to cool buildings. The electricity generation in turn incurs upstream air pollutant and greenhouse gas emission to exacerbate the warming and air quality problems.

Vegetated areas in cities, as surrogates of nature, can serve multiple and essential environmental-ecological functions. They alleviate the UHI effect by evapotranspiration cooling and shading, and remove gaseous and particulate air pollutants. With enlightened planning, some municipalities have installed an extensive green space system to enhance natural ingredients and benefit from their sustainable ecosystem services. Many compact cities, however, are beset by a serious shortage of street-level green spaces, thus depriving them of the natural cooling and cleaning functions. Their numerous rooftops, which are largely left bare and often unused, could be enlisted to enhance urban vegetation cover and associated values.

Besides cooling the ambient air, vegetated roofs can reduce solar radiation absorption, retention, and transmission through the roof slab. They reduce the thermal load of the rooms situated underneath in summer [2], and loss of indoor heat through the roof in winter. Local ambient temperature can also be reduced by the shade cast by living plants [3]. The biological functions of vegetation, such as photosynthesis, respiration and transpiration, can absorb a significant proportion of the solar energy and contribute to evaporative cooling. The thermal performance of green roofs can reduce the local air temperature near the canopy and suppress heat flux into the building [4–10]. The wide range of environmental and energy benefits of green roofs have been studied recently. Besides thermal performance, they include increasing stormwater retention and stormwater quality [10–18], extending the life span of waterproofing membrane [17,18], improving air quality [19], enhancing urban wildlife diversity [17], and life-cycle analysis of green roof systems [20–24].

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* Corresponding author. Tel.: +852 2859 7020; fax: +852 2559 8994.
E-mail address: hragjcy@hkucc.hku.hk (C.Y. Jim).

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Due to a hilly and rugged terrain, Hong Kong's population of seven-million residents is accommodated in about 20% of its land area of about 1000 km^2. The resulting residential density, attaining an average of 6460 persons/km^2 and the highest district density of 53,110 persons/km^2 in the mid-2009 [25], is one of the highest in the world. The customary urban design adopted since the city was founded in 1841 is to maximize the use of developed lands, resulting in minimal provision of open spaces in built-up areas. Urban areas are dominated by high-rise and tightly packed buildings and roads, with an inordinately constrained supply of public open spaces amounting to merely 3 m^2/person. As it is very difficult to increase green spaces in tightly packed developed areas, roof greening offers a feasible and promising alternative to introduce nature into the city [17].

In most cities, extensive green roofs outnumber the intensive type by a wide margin due to the latter's high load-bearing requirement, high installation cost and maintenance burden [17]. A survey of the literature yields few studies on the benefits of intensive green roofs. An intensive green roof, a native woodland, was established in Hong Kong [26] for a two-year experimental investigation of environment benefits, including evapotranspiration cooling, thermal insulation, heat flux, and energy conservation.

The objectives of this research are: (1) to collect detailed environmental monitoring data of the intensive green roof at three observation points to elucidate its key physical properties; (2) to establish an energy budget model by assessing the environmental benefits due to the living processes of the sky woodland; and (3) to evaluate the thermal performance of the woodland by measuring the heat flux penetration into the building.

2. Experimental design

In order to assess the potential environmental benefits of intensive green roofs, a dedicated experimental plot was set up on the roof of a new electricity substation building situated in the heart of a densely developed urban district in Hong Kong. A woodland composed of a dominant layer of closely planted native trees was installed on the one-storey (10 m tall) reinforced concrete structure with a usable roof area of 150 m^2. The construction of the building was completed in late 2007, and the sky woodland together with environmental sensors and data loggers were installed in spring 2008.

The sky woodland has adopted modern design and materials based on ecological principles [26]. The overarching design principle was to emulate the vertical stratification in the soil and vegetation biomass structure and the diversified species composition of natural native woodlands in humid-subtropical China. The system consists of 12 layers arranged in sequence from top to bottom: reinforced concrete slab, waterproofing membrane, screed, root barrier, plastic drainage, geotextile filter, rockwool water storage, subsoil, topsoil, ground cover herbs, short trees, and tall trees. A 100 cm thick layer of soil, composed of 80 cm subsoil and 20 cm topsoil enriched with mature compost, was laid to provide ample rooting room for the trees. Native tree species with a final height of 5–10 m that are attractive to local wildlife were chosen. All except one species are evergreen. A summary of the species and their tree height at the end of the experiment is given in Table 1. Semi-mature trees were sourced from nurseries planted closely to permit the crown interlocking and the formation of a continuous woodland canopy. The saturated weight of the green roof was estimated to be about 2150 kg/m^2. The concrete roof slab was designed with additional reinforced steel bars to support the extra loading of the intensive green roof.

Environmental sensors were installed at different heights, substrate layers and locations to monitor key microclimatic and soil attributes (Tables 2 and 3). Three monitoring stations holding the sensors were set up at the site core, periphery, and at a nearby bare concrete rooftop serving as the control (Table 2). Thermister type probes (S-TMB, Onset Hobo, USA) were used to measure air temperature at different levels, soil temperature at different depths, interior temperature of the water storage layer (rockwool), tile temperature (on the tile surface at the bottom of the green roof), and interior temperature of the roof concrete slab (embedded in the center). Due to safety and security concerns, temperature sensors in the indoor space below the green roof were not allowed. Soil moisture sensors (S-SMC, Onset Hobo, USA) were installed at three depths. Infrared radiometer type of sensors (SI-111, Apogee, Logan, UT, USA) were used to monitor the bare concrete surface of the control plot, and the soil surface and tree canopy temperature of the experimental plot situated at the site center. Additional sensors were installed to record solar radiation, wind speed and rainfall. Readings were programmed to be taken automatically at 15-min interval and stored in data loggers. Monitoring was conducted continuously from March 2008 to March 2010. The automatic sprinkler irrigation system was programmed to supply water, but it was turned off by a rainfall sensor upon reaching an accumulated antecedent rainfall of 10 mm.

3. Physical properties of intensive green roof

3.1. Air temperature at different heights

The seasonal air temperature ranges at 15 cm and 160 cm levels are respectively 13.6 °C and 12.7 °C in spring, 13.6 °C and 14.1 °C in summer, 22.8 °C and 20.9 °C in autumn, and 20.9 °C and 19.7 °C in winter. The amplitude is notably wider in the cool seasons (autumn and winter) than the warm ones (spring and summer). The seasonal microclimatic regime of the sky woodland is largely regulated by macroclimatic phenomena. The incident shortwave solar radiation is partly absorbed by the soil, and the absorbed energy is partly re-emitted as longwave radiation to the sky. The northeast monsoon in autumn and winter often brings cool-dry weather accompanied by clear sky to expedite radiative heat loss especially in nighttime. Thus the relatively cool nights can stretch the temperature range in the cool seasons. The southeast monsoon in spring and summer usually brings hot-humid weather. As water vapor has strong absorption band at infrared wavelengths, the atmospheric components emit infrared radiation in night-time to

Table 1
The tree species adopted for the creation of the sky woodland.

Species	Common name	Family	Seasonality	Average tree height (m)
Aquilaria sinensis	Incense Tree	Thymelaeaceae	Evergreen	5.5
Bridelia tomentosa	Pop-gun seed	Euphorbiaceae	Evergreen	4.0
Camellia honkongensis	Hong Kong Camellia	Theaceae	Evergreen	5.0
Camellia oleifera	Oiltea Camellia	Theaceae	Evergreen	4.0
Cerbera manghas	Sea Mango	Apocynaceae	Decdiduous	4.0
Cinnamomum burmanii	Cinnamon Tree	Lauraceae	Evergreen	6.0
Elaeocarpus chinensis	Chinese Elaeocarpus	Elaeocarpaceae	Evergreen	5.0
Ligustrum lucidum	Glossy Privet	Oleaceae	Evergreen	4.5
Litsea monopetala	Persimmon -leaf Litsea	Hamamelidaceae	Evergreen	4.0
Sterculia lanceolata	Scarlet Sterculia	Sterculiaceae	Evergreen	5.0
Ternstroemia gymnanthera	Naked Anther Ternstroemia	Theaceae	Evergreen	3.5