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Ecological energetics of tropical intensive green roof

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ABSTRACT

Few green roof studies cover intensive and tropical types and specific canopy microclimate. We examined the ecological energetics of a sky woodland in humid-tropical Hong Kong. Environmental sensors monitored the microclimatic and soil parameters for 14 months. Key biophysical variables of transpiration, wind, light, and through-canopy energy flux are modeled to investigate seasonal and weather effects. The woodland forms a cloistered subcanopy environment with rather stable microclimate. Transpiration and latent heat loss are enhanced by solar radiation and low relative humidity, but less by wind. On sunny days, about 20% of incident solar radiation can reach the soil surface. The canopy reflected more near-infrared radiation (NIR) than photosynthetically active radiation (PAR), highlighting a hitherto neglected passive-cooling mechanism. The highest transpiration rate occurs in autumn rather than summer due to dry-mild weather. The woodland canopy could reduce 300 W m^{-2} energy flux into the substrate. The canopy warmed by solar energy transmits heat to subcanopy air. Latent and sensible heat loss in the subcanopy domain is suppressed, thus dampening the passive-cooling effect. The capability of the tropical intensive green roof to reduce temperature is relatively inefficient comparing with temperate region counterparts. The findings could inform design and choice of green roofs.

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1. Introduction

Green roofs are increasingly recognized as a modern and eco-friendly technology to cope with climate change and some common urban environmental problems. They could prevent solar energy penetration into buildings, trim the cooling load, and reduce the electricity consumption for air-conditioning systems [1–3]. The benefits of green roof include cooling ambient, surface and indoor temperature and alleviating the urban heat island effect [4,5], reducing rainwater runoff and flood risk, and improving stormwater quality [6–8], creating green amenity spaces especially in compact urban areas [9], increasing lifespan of roofing materials [10,11], and providing habitats and stepping stones for wildlife and enhancing urban biodiversity [9]. In addition, life cycle assessment and valuation analysis indicate a positive economic benefit from vegetated roofs [12–15].

Modern green roofs can be classified as intensive and extensive systems depending on the plant species, construction materials, management and use. Intensive green roof involves planting trees and shrubs that require a deeper substrate of >20 cm and more horticultural maintenance. In contrast, a shallow soil substrate of <20 cm can sustain the grass, herb or drought-tolerant sedum vegetation of extensive green roofs which only need minimal maintenance. Both intensive and extensive types employ similar materials and structure from bottom upwards: root barrier, drainage, filter, water storage (rockwool), substrate, and vegetation [5].

The merits of intensive green roofs outweigh the extensive type in terms of biomass quality and complexity, biodiversity, microclimatic effect, and landscape and aesthetic value. Intensive green roofs can provide more amenable habitats for birds and insects. The thick soil allows planting of large and woody plants such as trees and shrubs. Accessible green roofs could improve the quality of life in densely built-up urban areas by providing otherwise deficient green spaces. However, intensive green roofs are uncommonly installed due to high roof-loading requirement and installation and maintenance costs [16,17].

Deep understanding of the multiple environmental and economic benefits of green roofs could facilitate the dissemination of the technological innovation. Whereas extensive green roofs have been studied assiduously by researchers and practitioners, less interest has been shown towards intensive ones. The energy and thermal performance of tropical green roofs also deserves more attention. This paper examines the ecological energetics of an intensive green roof, a sky woodland, in Hong Kong in the context of the humid-subtropical climatic zone. We evaluated the microclimatic and biophysical properties of an intensive green roof under different weather and seasonal conditions, and explored its heat

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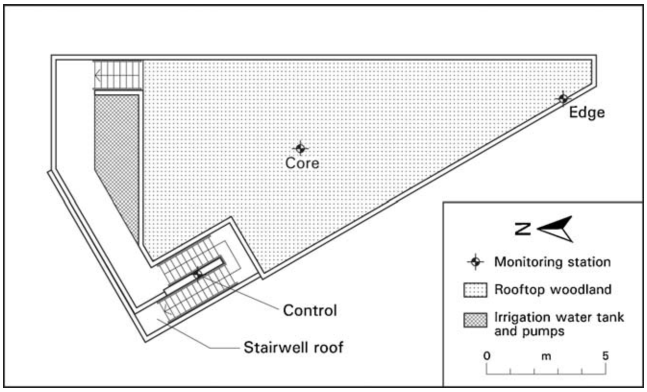

Fig. 1. The rooftop woodland site showing the locations of the three environmental monitoring stations. The sensors installed at each station are listed in Table 1.

flux patterns and thermal benefits. The findings could inform future design of intensive green roofs and promote its adoption.

2. Experimental design

An intensive green roof was designed for the experimental study on the rooftop of a newly constructed electricity substation building situated in the heavily built-up core of urban Hong Kong. The one-story building is 10 m tall with a roof area of 120 m^2. The surrounding buildings, separated by wide roads, are mainly high-rise residential blocks up to 30 storeys in height. The site is characterized by a low building coverage of about 50%, and it well exposed to sunshine with a high sky view factor. The high live-load requirements of the intensive roof equipped with a 1 m thick soil layer amounts to static load of 21 kPa at saturation. As the green roof design started before construction, it was possible to strengthen the reinforced concrete roof slab with additional pre-stressed steel bars. A native woodland was installed on the top with heavy standard planting materials (2–3 m tall saplings) of indigenous tree species with a final height of 5–10 m. Evergreen species were chosen to reduce the seasonal variations in canopy cover and biomass density. Twenty trees were planted closely together to form the interlocking woodland canopy that can generate its own internal microclimate. The construction was completed in late 2007, and the sky woodland was installed in spring 2008.

The sky woodland adopted contemporary green roof design and materials based on ecological principles [16]. The schematic drawing of the experimental setup is presented in Fig. 1. Scientific instruments were installed at three monitoring stations, namely at the core and edge of the vegetated site and an adjacent bare-roof control plot, to monitor key microclimatic and soil attributes (Table 1). They include direct solar radiation, photosynthetically active radiation (PAR), air temperature, dew point temperature, relative humidity, substrate moisture, wind speed, and temperatures at different heights or depths: air at 15 and 160 cm, soil and vegetation surface, soil interior at 10, 50 and 90 cm depth, water storage (rockwool), tile surface (at the bottom below the root barrier), and concrete slab interior (embedded in the concrete) temperatures. Readings were taken automatically at 15-min interval and stored in data loggers. The sky woodland was programmed to irrigate on a daily basis, and watering was turned off when a rainfall sensor has received an accumulated antecedent rainfall of 10 mm. The study period ran from January 2009 to March 2010 to cover a wide range of seasonal and weather conditions. Our study examined some key biophysical quantities computed from the monitoring data, including plant energy budgets, plant transpiration, light environment of canopy layer, and heat flux penetration.

This study presents the biophysical dynamics of an intensive green roof that can be used to evaluate its performance under different weather conditions. Some typical days are chosen to evaluate the weather effects over four seasons: 30 March 2009 (Spring sunny), 25 March 2009 (Spring rainy), 2 August 2009 (Summer sunny), 5 August 2009 (Summer rainy), 26 September 2009 (Autumn sunny), 28 September 2009 (Autumn rainy), 4 January 2009 (Winter sunny), and 29 December 2009 (Winter rainy). The selection criteria for these representative days are:

(1) Autumn and winter rainy days: >10 mm cumulative daily rainfall;
(2) Spring and summer rainy days: >40 mm cumulative daily rainfall;
(3) Autumn and winter sunny days: >500 W m^{-2} of average solar radiation; and
(4) Spring and summer sunny days: >700 W m^{-2} of average solar radiation.

3. Biophysical dynamics

The plant leaf temperature depends on the changing environmental conditions. Most plant leaves have small masses and contain a limited amount of water. Leaves experience wide temperature fluctuations because of the relatively low heat capacity. Plant leaves must respond to external environmental influences, such as solar radiation, wind, relative humidity, and air temperature, to counteract stresses and remain functional.

Table 1
The environmental sensors at three monitoring stations established on the rooftop woodland experimental site.

Sensor			Monitoring station[a]		
Environmental attribute	Model & brand	Measurement parameter and position	Core	Edge	Control
Soil moisture sensor	S-SMC, Onset Hobo, USA	Soil moisture at 10 cm, 50 cm and 90 cm depth	✓		
		Rockwool moisture	✓		
Air temperature sensor	S-TMB, Onset Hobo, USA	Air temperature at 15 cm and 160 cm height	✓	✓	✓
Soil temperature sensor	S-TMB, Onset Hobo, USA	Soil temperature at 10 cm, 50 cm and 90 cm depth	✓		
		Tile temperature (green roof bottom under root barrier)	✓		
Concrete temperature sensor	8160.TF, Lufft, Germany	Concrete roof slab internal temperature	✓	✓	
Infrared temperature sensor	SI-111, Apogee, USA	Surface temperature of soil with groundcover vegetation	✓	✓	
		Surface temperature of tree canopy	✓	✓	
		Surface temperature of bare concrete roof			✓
Relative humidity sensor	S-THB, Onset Hobo, USA	Relative humidity at 15 cm and 160 cm height	✓	✓	✓
Dew point sensor	S-THB, Onset Hobo, USA	Dew point temperature at 15 cm and 160 cm height	✓	✓	✓
Pyranometer	S-LIB, Onset Hobo, USA	Intensity and duration of solar radiation			✓
Anemometer	S-WCA, Onset Hobo, USA	Wind speed and wind direction			✓

[a] The core monitoring station is situated at the center of the rooftop woodland, and the edge at its perimeter wall; the control is set up on the bare concrete rooftop of an adjacent stairwell. The positions of the three stations are shown in Fig. 1

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