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Diurnal and partitioned heat-flux patterns of coupled green-building roof systems

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Coupled green-building roof system can assess bidirectional heat-flux with indoor space. Two high-rise residential blocks in humid-subtropical Hong Kong, with and without roof building thermal insulation (BTI), were monitored for thermal performance across seasons and weather conditions. Each block had three plots: Sedum and herbaceous Peanut green roofs, plus bare Control. Diurnal heat-flux data were partitioned into daytime and nighttime, and positive and negative fractions. On hot summer-sunny day, Control without BTI facilitates notable daytime influx and nighttime efflux of heat. Sedum augments thermal-mass effect pushing more heat indoor than Control. With balance between transpiration-cooling and heat-sink formation, Peanut registers intermediate heat gain. Adding BTI raises heat-gain and eliminates Control heat-loss, curtails Sedum heat-gain, and maintains Peanut heat-gain. BTI partnering with green roof offer synergistic thermal benefit by increasing thermal mass, thermal capacity and thermal resistance to furnish thermal buffering, thermal lag, and extending heat ingress to nighttime. Lower solar-radiation input on summer-cloudy day significantly trims heat gain at Control, with limited reduction at both green roofs. Summer-rainy day brings further drop in heat gain. For cloudy and rainy scenarios, heat-gain suppression is more notable with BTI. Interpretations for other season-weather conditions and implications of the findings are elaborated.

1. Introduction

Green space with vegetation and unsealed soil can provide cool island effect to counterbalance the intensifying urban heat island (UHI) effect [1–3]. Aggravated by the superposition of global warming, the UHI effect could be ameliorated by ample provision of urban green spaces (UGS) of the right kinds and at appropriate locations [4,5]. Some municipal authorities are earnestly seeking solutions to make cities climate-resilient or climate-proof [6,7]. Expanding UGS cover and increasing the greening rate of developed areas offer feasible and cost-effective ways to cool urban areas [8,9]. For new urban developments, UGS can be inserted generously preferably in a well-connected green matrix to maximize their environmental, landscape and amenity utilities [10–12]. For existing built-up areas and especially in compact cities, however, it is difficult to increase UGS at the ground level.

Three-dimensional urban greening can permit vegetation to literally scale the facades and rooftops of many buildings, which can be labeled as building envelope greening (BEG). The bare building envelopes offer novel habitats and solutions to spread greenery cover and attendant benefits in cities [13,14]. Densely-packed urban precincts and old city cores, which otherwise would be devoid of vegetation, could receive pleasant green liveries [15]. Recent advances in material science and technology, in conjunction with research, have provided the knowledge base, ingredients and impetus to embrace the urban-greening innovations to contribute to sustainable development [16]. The cooling effect under different combinations of intrinsic and extrinsic factors could be clarified by continued research [17]. Deeper understanding of the key factors and their interactions could help to further improve the design of green roofs, with a view to optimizing their ecosystem services and other amenity functions [18–20].

As a supplementary installation, green roof can be added to new buildings or retrofitted on existing ones to modify the thermal behavior and response of the building envelope [21]. The multiple abiotic and biotic layers of vegetated roofs confer thermal properties that deviate from conventional roofing materials [22]. The additional thermal-mass effect [23,24], enhanced by entry and exit of water, can alter the thermal regime at the building skin. With the joint operation of cooling mechanisms, including shading,

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insulation, evapotranspiration, higher albedo, and more longwave radiation, green roof can bring cooling to the ambient air above them and the indoor air below [25,26]. In particular, the thermal burden of bare-roof warming by solar radiation can be reversed to become green-roof cooling to reduce the cooling load of the affected building [27–29]. More of the renewable, sustainable, clean and free energy from the sun can be employed constructively to cool roofs and cities.

The efficacy of thermal benefits and attendant air-conditioning energy saving vary according a basket of building and green-roof design factors [30,31]. Green-roof studies tend to concentrate on the green-roof layers and give little or no attention to the building-roof layers. As the two contiguous layers jointly determine green-roof thermal-energy performance, they can be considered as a coupled green-building roof (GBR) system. It is composed of four compartments, two air sandwiching two solid, organized from the top downward:

(a) Ambient-air compartment
(b) Green-roof compartment
(c) Building-roof compartment
(c) Indoor-air compartment

The two solid compartments are made of multiple layers of materials laid in sequence. The material type, thickness and installation sequence tend to vary according to system design. Different green-roof types use plant species with varied growth rate, vigor, site coverage, leaf-area ratio, emissivity, albedo, and transpiration rate. Different species demand varied substrate in terms of composition, depth, texture, structure, bulk density, porosity, water-holding capacity, and water supply which may involve supplementation by irrigation. These green-roof design factors and materials have important bearing on thermal properties and behavior [32,33]. The inherent thermal insulation materials embedded in the building roof slab can influence heat transmission through it. Different efficacy of building thermal insulation (BTI) can influence the thermal performance of green roof. The amount of heat and the direction of the heat flux moving upward or downward through the GBR system is the ultimate indicator of its thermal-energy benefit.

A field study aiming at understanding how GBR systems with inherently different composition and property could influence thermal performance, could be denoted by the surrogate measure of heat flux through the roof. A real-world field experiment was developed to evaluate the heat flux regime with the following experimental treatments: (a) two sets of green-roof compartments, namely a simple extensive green roof and a more complex one, were compared with a bare-roof control plot; (b) two sets of building-roof compartments, namely with normal BTI, and without it to denote poor insulation. To assess comprehensively the thermal performance of intrinsically different GBR systems interplaying with different extrinsic conditions, the temperature and heat flux regimes were monitored on sampled days to provide representatives of different seasons each with different weather conditions.

2. Study area and methods

The study was conducted in urban Hong Kong situated at the south China coast at longitude 114°E and latitude 22°N, which lies in the humid-subtropical climatic zone strongly influenced by the Asian Monsoon system. The annual climatic pattern is characterized by contrasts between hot-humid summer and cool-dry winter, interspersed with mild-humid spring and mild-dry autumn. The frequent and heavy rainfalls in the wet season, running from May to September, account for most of the yearly 2400 mm precipitation. The potential evapotranspiration amounts to 1062 mm per annum [34]. In summer, the mean daily temperature is 30.2–31.4 °C, and in winter 16.3–17.9 °C. Typhoons (tropical cyclones) occasionally struck the city in the warm months to bring exceptionally strong winds and prolonged torrential rains.

Two recently-built high-rise (over 30 stories) residential blocks (Blocks 1 and 2) in a new town served as the study site. Tall buildings for domestic or commercial use are common in Hong Kong. The two blocks have the same building footprint, floor plan and orientation, and lie adjacent to each other. One wing of each block with the same southeast orientation was identified for the field study. Each wing contains three apartments (Flats A, B and C) of similar floor area. The total of six top-floor apartments (Block 1: 1A, 1B and 1C; Block 2: 2A, 2B and 2C) and the respective six roofs lying above were left unoccupied for a year to conduct the experiment. The windows and doors were kept closed in the course of the study which runs from November 2011 to December 2012.

All the main windows of the flats faced the same southeast direction. The small side windows of Flats B and C were small and situated in the indented part of the buildings sheltered from direct insolation. The relatively exposed windows of Flat A, situated at the end of the building wing, were shielded from floor to ceiling by double gypsum boards sandwiching a layer of thermal-insulation glass fiber to exclude the impact of direct solar radiation. The experimental treatments of the six plots were summarized in Table 1. In the course of construction, the thermal insulation layers in the roof slab of Block 1 were omitted. In Block 2, the normal thermal insulation layers adopted in Hong Kong were installed with the following layers listed from top downward: concrete tile (35 mm), cement-sand bedding (25 mm), polystyrene foam (40 mm), waterproof membrane (2 mm), cement-sand-aggregate screed (25 mm), and reinforced concrete roof slab (160 mm).

At each block, the three plots were devoted to different covers: (a) Plot A ("Control") used the original bare concrete-tile surface. On Plots B and C (experimental treatments), two kinds of extensive green roofs were established. They differ in terms of biomass structure with reference to vegetation growth form, foliage density and cover, and rate and mode of photosynthesis and transpiration. Plot B ("Sedum") was planted with Mexican Sedum (*Sedum mexicanum* Britton, Crassulaceae), a drought-tolerant succulent plant native to Mexico. Adopted for roof greening in the tropics with fast establishment rate from cuttings [35], its special Crassulacean acid metabolism (CAM) photosynthetic strategy can tackle soil-moisture deficit by temporary closure of stomata in daytime [36]. Daytime cooling could be suppressed by curtailed or stopped transpiration [37,38]. In nighttime, stomata can stay open to store carbon in leaf tissues to sustain photosynthesis in daytime when stomata are closed. With full cover, the Sedum plants form a single layer of tightly-packed succulent tissues resting on the substrate surface. Plot C ("Peanut") was planted with Perennial Peanut (*Arachis pintoi* Krapov. & W.C. Greg., Fabaceae). It is a tropical leguminous nitrogen-fixing groundcover herb which is unusually vigorous. Starting from stem cuttings, it can establish a full cover in one growing season, and has been proven to perform well on tropical rooftops [39,40]. Adopting the common C3 photosynthetic physiology, it can provide active transpiration cooling in daytime [41]. The plant can develop a three-dimension lattice of stems topped by dense layers of leaves that tend to be oriented horizontally to form a luxuriant and continuous green surface.

In the lower part of both green-roof plots, the same materials layers were used, including from the bottom the root barrier (1 mm), drainage sheet (25 mm dimple type), and geotextile filter (1 mm). A proprietary green-roof system (Nophadrain, Kirkrade, the Netherlands) that meets the stringent German standards [42] was employed. Their substrates differ to match species