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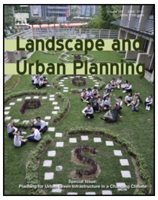

Research Paper

Assessing climate-adaptation effect of extensive tropical green roofs in cities

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HIGHLIGHTS

- Urban greenspaces can bring multiple benefits and climate adaptation to cities.
- Green roofs offer plausible solution to greenspace-deficient compact cities.
- Detailed field experiment allows in-depth assessment of greenroof thermal performance.
- Sedum roof stores some heat to warm near-ground air and indoor space to intensify UHI.
- Peanut roof cools near-ground air but creates heat-sink to induce indoor cooling load.

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ABSTRACT

Many cities have inadequate green infrastructures and cannot benefit from ecosystem services brought by greenspaces. Global warming and urban heat island (UHI) effect impose a dual warming impact on cities, especially compact ones. Green roofs offer a plausible solution for climate adaptation. In compact humid-tropical Hong Kong, two green-roof and a control bare-roof plots were installed on a high-rise building. Precision sensors were installed along a holistic vertical temperature profile extending from outdoor air to roof surface, green-roof material layers, and indoor ceiling and air. Three apartments under the plots were kept vacant to monitor air-conditioning energy consumption. The comprehensive-systematic data allowed in-depth analysis of thermal performance of vegetation (Sedum and Perennial Peanut) and weather (sunny, cloudy and rainy) in summer. Intense solar radiation at Control plot triggered significant material heating, which in turn warmed near-ground air to intensify UHI effect and indoor space to lift energy consumption. Sedum plot with incomplete plant cover, sluggish transpiration and limited substrate moisture storage had feeble evapotranspiration cooling. The warmed roof passed heat to near-ground air and subsurface layers to impose a small indoor cooling load. Peanut plot with high transpiration rate can significantly cool foliage surface and near-ground air to ameliorate UHI. Its high moisture-holding capacity, however, can generate an appreciable heat-sink to push heat downwards and increase indoor cooling load. Practical hints on green roof design and management were distilled from the findings for application in Hong Kong and beyond and to contribute to climate-resilient cities.

1. Introduction

Many cities in developed and especially developing countries have inadequate urban green infrastructure (UGI) to ameliorate the harsh impacts imposed by excessive gray infrastructure (Svendsen, Northridge, & Metcalf, 2012). With intensification of global warming superimposed on urban heat island (UHI) effect, cities are literally heating up, pleading for sustainable and cost-effective climate-adaptation solutions. Urban green spaces (UGS) with vegetation and unsealed soil can offer cool island effect to alleviate the UHI effect and reduce energy consumption (Akbari & Konopaci, 2005; Castleton, Stovin, Beck, & Davison, 2010). At the street level, roadside trees can provide a thermally comfortable environment to pedestrians in the real and perceived senses (Klemm, Heusinkveld, Lenzholzer, & Van Hove, 2015). To a certain extent, green cities with generous provision of UGS are pre-adapted to be climate-resilient (Getter & Rowe, 2006; Jones, Hole, & Zavaleta, 2012; Mathey, Rößler, Lehmann, & Bräuer, 2010). Municipal governments can probe and muster community support to enhance UGI to prepare cities for climate adaptation (Byrne, Lo, & Yang, 2015).

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Compact cities with few interstitial green covers, however, cannot benefit liberally from their natural ecosystem services of cooling, cleaning and ventilation. The prevalence of hard covers vis-à-vis green and blue surfaces can contribute notably to human discomfort with implications on human health especially in hot and dry cities (Mazhar, Brown, Kenny, & Lenzholzer, 2015). A common societal response to rising temperature is to increase the use of air-conditioning in an attempt to maintain the accustomed level of human comfort (Parsons, 2003). The consequential upstream-cum-downstream generation of sensible heat, greenhouse gas and air pollutants, creates a positive-feedback vicious circle. To be freed from the bondage and to contain the sprawling ecological footprint of cities, innovative approaches are called for.

The opportunities to increase UGS in new towns or new or renewal development of existing cities through spatial and climate-responsive planning should not be squandered (Brown, Vanos, Kenny, & Lenzholzer, 2015; Matthews, 2015). Nevertheless, the scope for UGS expansion is limited in established compact cities. Greenspace provision, however, does not need to be confined to the ground level. Numerous building rooftops, which tend to be left bare, offer potential sites for green roofs (Milburn, Fernández-González, Jones, Solano, & Martínez-Wong, 2013). The external vertical surfaces of building envelopes provide chances for green walls. Such elevated UGS can supplement the existing stock to reinforce provision of ecosystem services in built-up areas. Collectively, they constitute a valuable and substantial yet largely neglected if not wasted resource. They can help to ameliorate the local urban heat islands that suffer from overheating problems (Emmanuel, 2015). Their potential contribution to climate-proofing cities (Hall, Handley, & Ennos, 2012; Tzoulas et al., 2007) could be mobilized by a proactive greenery infilling policy above the ground level.

Green roofs can usher nature's clean and free evapotranspiration passive cooling (Jim & Tsang, 2011a; Tan, Wong, Chen, Ong, & Sia, 2003; Voyde, Fassman, Simcock, & Wells, 2010), driven by solar radiation, into the heart of the city and proximal to people (Jim, 2012; Köhler, 2004; Theodosiou, Aravantinos, & Tsikaloudaki, 2013). The cooling effect extends upwards to the ambience and downwards to the building fabric and indoor space (Del Barrio, 1998; Givoni, 2011; Teemusk & Mander, 2009; Wong, Tan, & Chen, 2007). Green roofs bring collateral benefits of accessible and safe amenity spaces, clean air, noise abatement, and associated contributions to physical and mental health. At the city scale, the UHI effect and smog formation which is catalyzed by high temperature can be alleviated (Bass, Krayenhoff, Martilli, Stull, & Auld, 2003; EPA, 2009; Susca, Gaffin, & Dell'Osso, 2011). They can reduce the quantity and improve the quality of urban stormwater discharge, with implications on flood prevention, quality improvement in receiving water bodies, and reduced capital and maintenance costs of stormwater drainage systems (Berghage et al., 2009; Carter & Jackson, 2007). Their benefits can be shared with wildlife which can use green roofs and walls as refuges or habitat islands for roosting and feeding, and as stepping stones to penetrate the city to enhance urban biodiversity (Brenneisen, 2006; English Nature, 2003).

Solar energy reception at the roof affects temperature in the air above the green roof, on the roof or vegetation surface, and in the green-roof material layers. In turn, the heat retained by the green roof system can transmit downwards to underlying indoor space. The heat that fluxes downwards from the roof could increase energy consumption by air-conditioners especially during summer. Understanding this relationship could throw light on environmental benefits of green roofs in compact urban milieu. The results could provide practical hints on the choice of plant species and green-roof design for cost-effective application of the innovative technology.

A control experiment was designed to evaluate the effect of two extensive green roofs with different vegetation and associated substrate design on air-conditioning electricity consumption in the underlying apartments. The study develops a new dimension to reinforce existing findings on the effect of green roofs on outdoor–indoor temperature and building energy performance especially in the warm season under different climates (e.g., Blanusa et al., 2012; Castleton et al., 2010; Getter, Rowe, Andresen, & Wichman, 2011; Jim, 2014; Niachou, Papakonstantinou, Santamouris, Tsangrassoulis, & Mihalakakou, 2001). The living quarters provide a real-world setting to assess the relationship between green-roof effect and energy use. Instead of employing assumptions to compute estimated energy use in previous studies, this research directly acquired electricity consumption data with precision energy loggers. As the literature lacks experimental data on actual electricity consumption for space air-conditioning in relation to green roofs, this study could fill the knowledge gap.

Using Hong Kong as a good compact-city example, this study assessed the key climate-adaptation functions of green roofs in the tropical weather zone. With the help of controlled field experiments, it aimed at three objectives: (1) evaluating the temperature moderation function of two types of green roofs in a holistic vertical profile extending from the outdoor ambience to roof surface and material layers, and to indoor ceiling and air; (2) assessing the air-conditioning energy consumption patterns and saving in relation to the green roofs; (3) distilling from the findings practical recommendations on design and management of green roof for buildings in tropical cities. The study focuses on three weather scenarios of the summer season to highlight thermal-energy performance under hot conditions.

2. Study area and methods

2.1. Study area

Hong Kong is situated at the northern edge of the tropical zone, close to the Tropic of Cancer at 22° N latitude and 114° E longitude, at the south coast of China, and on the east side of the Pearl River Estuary. The humid-subtropical climate is notably influenced by the region-wide Asian monsoon system. Summer is hot-humid with frequent showers, thunderstorms and occasional typhoons. The warm months, running from May to September with the hottest days exceeding 33 °C, coincide with the rainy season with annual precipitation of over 2300 mm. The rather short and mild winter has average temperature above 10 °C. With a long, hot and humid period, air-conditioning is used in most commercial, residential and institutional buildings.

Experimental green roof plots were established on the top of a high-rise residential block in Shin Ming Estate in Tseung Kwan O New Town in Hong Kong (Figs. 1 and 2). It is a public housing estate built by the government and occupied in 2011, catering to the low-income group. The rooftop of the 33-storey building was reserved for the experimental study. Below the three experimental plots, three domestic apartments were kept unoccupied in the study period for indoor monitoring.

2.2. Experimental plots and design

The subject roof was equipped with the full range of five material strata resting on the concrete roof slab, from the bottom upwards: 25 mm screed, 1 mm waterproof membrane, 40 mm polystyrene foam, 25 mm cement-sand bedding, and 35 mm precast concrete tile. Such construction details are commonly adopted in Hong Kong. The finished roof surface has a 2% gradient to shed water to drainage channels and drain pipes.