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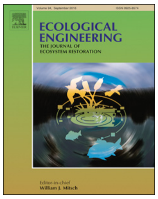

Thermal-cooling performance of subtropical green roof with deep substrate and woodland vegetation

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ABSTRACT

As building-integrated vegetation, green roofs can improve thermal performance of buildings and their ambience. Research efforts tended to focus on thermal behavior of extensive green roofs outside the tropics, with inadequate attention on intensive type and tropical region. Using detailed microclimatic monitoring, this study investigated the thermal behavior of a native-woodland intensive green roof in subtropical Hong Kong. Three summer weather days denoting sunny, cloudy and rainy were chosen from long-term monitoring data for comparison with a nearby bare control roof. Shading and evapotranspiration by the woodland canopy respectively reduced roof surface temperature and air temperature by latent-heat absorption. The most notable maximum surface and air cooling, respectively at 19.80 °C and 6.21 °C, was achieved in daytime sunny condition, with cooling effect extending into nighttime. Surface cooling was mainly governed by daily pattern of solar irradiance, whereas air cooling was more pronounced nearer ground surface except in nighttime period on rainy days. Slight near-surface air warming occurred in rainy nighttime. The woodland vegetation filtered 90% of the incoming short-wave radiation during most of the daytime, serving as an insolation filter which contributed to surface cooling. The substrate experienced net heat loss in cloudy and rainy weather, exporting its antecedent stored heat. At 0.5 m substrate depth, the temperature stayed at a stable level, suggesting restricted heat exchange in subsoil. With appropriate design and regular maintenance, an intensive green roof with dense woodland canopy and 1-m substrate could provide effective above-ground and soil cooling and buffer against outdoor-to-indoor heat ingress.

1. Introduction

Compact cities are susceptible to the double impacts of global climate change and urban heat island effect. Anthropogenic heat can degrade urban liveability in thermal terms. Growing urban expansion, densification and associated natural-to-urban land conversion have continued to intensify the thermal stress to affect the comfort and health of urban dwellers. Different measures have been adopted to bring relief. Vegetation and natural areas in cities can ameliorate the thermal load of cities. However, compact cities often lack ground-level space for green spaces. Green roofs provide a feasible alternative nature-based solution to mitigate the thermal plight and bring an array of associated benefits.

Green roof denotes building-integrated vegetation planted deliberately on the roof of a built structure (Grant, 2006). It is sometimes called roof garden and living roof in the literature. Green roofs can be classified according to key vegetative and substrate features (Grant, 2006; Dunnett and Kingsbury, 2008; Roehr and Fassman-Beck, 2015). Intensive green roof (IGR) has at least 0.15 m-deep substrate to support complex vegetation including herbs, shrubs and sometimes trees. In comparison, extensive green roof (EGR) has substrate shallower than 0.15 m to accommodate mainly herbaceous vegetation, incurring lower establishment cost and maintenance requirements. To reduce the gross load of IGR on building structure, light-weight materials such as pumice, zeolite and perlite have been used as substrate (Kotsiris et al., 2013). Existing research conducted in compact cities mostly focus on EGR (e.g. Jim, 2015a,b). With increasing installation of IGR, empirical research is needed to ascertain their design, management and benefits.

Green roofs bring multiple thermal benefits. Shading by vegetation canopy shields green roof soil surface from incoming solar radiation. Jim and Tsang (2011a) observed woodland vegetation on a Hong Kong green roof filtering 80% of solar irradiance. Reduced solar irradiance can bring surface cooling vis-a-vis conventional bare roof. Cooling performance depended on vegetation characteristics. The respective maximum ground surface cooling for green roof with turf, shrubs and trees reached approximately 18 °C, 26.5 °C and 23.5 °C (Wong et al.,

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2003a). The insulation effect of the landscape materials could dampen the temperature oscillation experienced by roof materials and lengthen their service life (Wong et al., 2003c; Teemusk and Mander, 2009). Besides the surface, green roof also cools the air above the ground surface. For instance, Speak et al. (2013) observed a nighttime median air cooling of 1.06 °C at 0.3 m height above the short vegetation canopy on a British IGR. For woodland IGR, the beneath-canopy air would affect the heat transfer into the building, which could mitigate the impact of urban heat island effect on indoor building users (Lee et al., 2014). More elaborate measurements of subcanopy air and surface cooling of IGR could improve understanding of relevant thermal functions.

Both outdoor and indoor thermal comfort could be enhanced by green roof. On a Singaporean shrub green roof, decrease in globe temperature and mean radiant temperature were respectively 4.05 °C and 4.5 °C against bare roof (Wong et al., 2003b). Green roof serves as additional insulation layer to reduce indoor-outdoor heat exchange. Below a Greek EGR in summer, the indoor air temperature was maintained below 30 °C most of the time versus exceeding 30 °C most of the time in the outdoor air (Niachou et al., 2001). A controlled experiment in India found an average indoor air cooling of 5.1 °C (Kumar and Kaushik, 2005). However, thermal comfort is influenced by local climate. The subtropical region lacks studies on the thermal behavior of IGR. Data harvested from field monitoring would be essential for a deeper understanding of the IGR-induced impact on thermal comfort.

The regulation of indoor temperature under hot weather condition is largely realized by suppressing heat ingress. The landscape materials of green roofs function as a thermal mass with a notable heat capacity to block, absorb and store heat which would otherwise enter and warm the indoor environment. Green roofs could trim heat ingress from 47% (Wong et al., 2003a) to 60% (Wong et al., 2007) according to Singaporean studies. The enhanced indoor thermal comfort could be translated into energy saving. Simulation of a Mediterranean IGR in Greece projected a 19%-reduction of annual cooling energy load (Karachaliou et al., 2016). Another Greek study showed green roof benefited non-insulated buildings with a 48% reduction in energy consumption for air-conditioning (Niachou et al., 2001). However, adding building insulation slashed the energy saving to 2%. Different figures were found in green roof studies in the tropical zone. A Singaporean study found annual energy saving from 0.6 to 14.5% depending on vegetation and soil depth (Wong et al., 2003a). These studies found a wide range of energy saving values due to differences in green roof design, local climate, and inherent roof-slab insulation efficacy (Jim, 2015b). There is a dearth of related studies in subtropical zone. Therefore, before computing the energy saving potential of IGR on buildings in subtropical compact cities, l the thermal behavior of subtropical IGR should be investigated through field monitoring.

The thickness of substrate has important bearing on heat transfer on green roofs. Jim and Tsang (2011b) found that for an IGR with 1 m deep substrate in combination with woodland vegetation, little heat could penetrate below 0.1 m even in summer. This finding indicated that 10 cm substrate would be sufficient to insulate against the heat penetration into the indoor space on condition that the substrate is well shielded by a dense tree cover. Other studies utilized deeper substrate. Darkwa et al. (2013) monitored a grass-and-shrub green roof with 0.4 m-deep substrate (Darkwa et al., 2013). Wong et al. (2003a) simulated 0.9 m-deep substrate with turf, shrub or trees. Further research could investigate the substrate thermal behavior of IGR featuring woodland vegetation with substrate depth up to 1 m.

Green roof thermal performance could vary considerably by climate zones. The thermodynamic processes of IGR have been studied in tropical (Wong et al., 2003b), Mediterranean (Fioretti et al., 2010) and oceanic (Speak et al., 2013) climates. Few studies have covered subtropical IGR (Jim and Tsang, 2011a). An IGR study (Darkwa et al., 2013) with 0.4 m-deep soil conducted in Ningbo, China, did not include a bare roof serving as control. Therefore, more in-depth subtropical IGR studies would enhance the understanding of the thermal behavior for comparison with other climatic regions.

In terms of design and structural differences, IGR differed profoundly from EGR. The considerable IGR-induced benefits of cooling, thermal comfort and energy saving are due to the synergistic thermal behavior of different material layers above and below the ground. Besides simple EGR with less cooling and other ecosystem services, it is desirable to establish complex green roofs, i.e. IGR, with deep substrate to support woodland vegetation. Accordingly, this study aimed to: (1) Investigate thermal behavior of an IGR in subtropical urban area under different weather scenarios in summer, and (2) Quantify the cooling performance with meteorological data harvested from precision sensors. Some research questions would be explored: (1) How would the cooling effectiveness of the IGR in this study compare with those reported in existing studies, and (2) What would be the roles played by vegetation in cooling the ground surface and air. The experimental design and instrumentation are elucidated in Section 2. The key findings are expounded in Section 3. The research questions are discussed in Section 4. Concluding remarks are given in Section 5.

2. Methodology

2.1. Study area

Hong Kong (22 °N, 114 °E), situated at south China's coast, experienced a monsoon-influenced humid subtropical climate (Köppen climate classification Cwa). The 30-year climate normals (Hong Kong Observatory, 2015) identified the highest monthly mean temperatures in summer months (June: 27.9 °C, July: 28.8 °C, August: 28.6 °C). Over half (52.7%, 1264.8 mm) of the annual rainfall (2399 mm) was received in summer. Hong Kong accommodated 7.39 million population and 2.53 million households (Census and Statistics Department, 2017). The ultra-compact development mode confined residents to 77 km^2 of residential land-use (Planning Department, 2017). With high built-up density, provision of urban green spaces was very limited, demanding innovative and alternative means to cool down the city.

The experimental plots of this study were situated on a power substation in Tseung Kwan O New Town, Hong Kong. The building is located beside a dual carriageway (Fig. 1). A green roof (GR) installed on the top of the four-story (14 m tall) building served as the experimental plot, and a nearby bare roof (BR) was chosen as the control plot. To provide adequate structural load-bearing capacity, the static and dynamic loads of the IGR were taken into consideration in the building design phase. The GR and BR were respectively 451 m^2 and 16 m^2 in area. The GR was the intensive type with native woodland vegetation comprising vertical stratification of herbs, shrubs and trees growing on 1 m-deep substrate composed of completely decomposed granite enriched with compost. No heat-generating equipment was placed on the GR and BR. Although they were only at approximately 19 m-distance from each other, the BR was located at an elevated platform to avoid convective-radiative interference between them.

2.2. Environmental monitoring, data selection and analysis

The in-situ microclimatic monitoring was conducted from 20160601 to 20160831 (yyyymmdd). A comprehensive range of variables were measured on the GR and BR plots, with the former including below-surface measurements. The experimental setup showing positions and orientations of the monitoring sensors is depicted in Fig. 2. The technical specifications of the precision sensors are summarized in Table 1. Both BR and GR featured parapet wall of the same height as shown in Fig. 1a and b. However, the surface temperature measurement point was positioned away from the parapet walls to minimize their thermal influence associated with daily sunshine and shade cycle due to sun path variation.

From the monitoring dataset, one representative day was selected for each of the summer weather scenarios, namely sunny, cloudy and