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Effects of green roofs' variations on the regional thermal environment using measurements and simulations in Chongqing, China

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ABSTRACT

In the present work, field measurement and simulation method were employed to investigate the effects of several green roofs variables on regional thermal environment in Chongqing (29°N, 106°E), China. Field experiments were conducted in two typical places. The real influence of green roofs on ambient environment was analyzed and compared with the simulation results. The software ENVI-met was employed to simulate 29 cases with different factors, including green roofs types, vegetation coverage, building height, arrangement position and regional layouts. With the aim to investigate the effect of the green roofs thoroughly, different design factors of green roofs were taken in consideration. From the aspect of cooling effect, it can be found that enclosing layout has the maximum air temperature drop, which is up to 0.5 °C. From the perspective of the uniformity of regional environmental temperature distribution, the regional thermal environment of scattered layout is better than enclosing and array layout as a whole. In addition, with the same vegetation coverage, the effectiveness of air temperature dropping of the whole region differed according to the arrangement position. Centrally arranging the green roofs upwind can effectively reduce the air temperature of the whole region. These findings can be used to improve the regional thermal environment by designing the green roofs reasonably.

1. Introduction

With the continued urban sprawl, an increasing number of buildings are constructed, as a result, urban ecological environment is increasingly deteriorated and the urban heat island effect is intensified (Saadatian et al., 2013). Green roof strategy is a sustainable design of roof, which can bring cooling effect and add ecological benefit and landscape value to the community (Francis and Lorimer, 2011; Saadatian et al., 2013; Xiao et al., 2014). Given their commonly recognized benefits, in 2014, China adopted the green roof as a part of the Assessment Standard for Green Building, which guides Chinese construction industry (China, 2014).

In recent decades, with the rapid development of the green roofs, the benefits of green roof are in-depth investigated in the aspects of plant species (Heim and Lundholm, 2014; Lundholm et al., 2010), growing media (Graceson et al., 2014; Lu et al., 2015; Rowe et al., 2012), seasonal performance(Getter et al., 2011; Lin et al., 2013) and so on. According to the study that analyzed the effectiveness of green roofs in the warm and humid climate of Hong Kong, the results showed that the plant form, type and biomass structure play a notable role in cooling potential (Jim and Tsang, 2011). And Zeng utilized the simulation for determination of the optimal parameter settings for green roofs in different climate zones, China, and demonstrated that in cooling-dominated areas, such as Chongqing, the leaf area index (LAI) is the most significant factor that influence the energy consumption (Zeng et al., 2017). Moreover, the research of green roofs achieved fruitful results, especially in the aspect of individual buildings. As we all know, green roofs can effectively lower the outer surface temperature of a roof. A study (Rosenzweig et al., 2006) carried out in New York City compared the impact of each of the mitigation strategies on surface and near-surface air temperature. The conclusion was that vegetation cools surfaces more effectively than increases in albedo, and living roofs offer greater cooling per unit area than light surface. Numerous studies have performed the cooling effects of green roofs (Sun et al., 2012; Sun et al., 2013). The relevant studies were reviewed by Feng Chi, and made a conclusion that green roofs can bring the maximum temperature drop up to 30 °C, and the decreasing magnitude of indoor air temperature was approximately 2–3 °C (Chi et al., 2010; Feng et al., 2010). Green roofs also reduce annual energy use within the building (D'Orazio et al., 2012; Virk et al., 2015). Besides, green roof characteristics were linked

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Table 1
Classification of green roofs and their main attributes.

Main attributes	Extensive	Intensive
Thickness of growing media	Below 200 mm	Above 200 mm
Accessibility	Inaccessible (fragile roots)	Accessible (usable for recreation purpose)
Weight	60–150 kg/m^2	Above 300 kg/m^2 (may require a reinforced structure)
Diversity of plants	Low (moss, herb and grass)	High (lawn or perennials, shrub and tree)
Construction	Moderately easy	Technically complex
Irrigation	Often not necessary	Necessity of drainage and irrigation systems
Maintenance	Simple	Complicated
Cost	Low	High

with respective traditional insulation layers (Jim, 2014, 2015; Kokogiannakis and Darkwa, 2014). In summary, it was commonly demonstrated that green roofs can bring cooling effect and energy saving benefits.

Recently, the effects of green roofs on regional thermal environment have gradually become the focus of research, which followed by the study of urban heat island. The effects of vegetation on microclimate depend on climates and urban canyon geometries, as demonstrated by (Alexandri and Jones, 2008); the conclusion was that the hotter and drier a climate is, the greater the effect of vegetation on urban temperatures. In addition, the wider a canyon is, the weaker the effect green roofs have on temperature decreases. Height of buildings in a city area influences potential temperature, and mean radiant temperature (Perini and Magliocco, 2014). Meanwhile, ground level greening is a lot more useful than rooftop greening given the tall building. But for ground level greening, the cooling benefits of greening when building heights are lower (at 20 m) are higher than the cooling benefits when buildings are taller (at 40 m and 60 m). And taller buildings temperatures are lower due to their shading effect (Ng et al., 2012). The aspect ratio (or height-to-width ratio) of building height to street width also had an important role on the cooling effect of green roof influencing street canyon, which directly influence the design choices in relation to street usage (Ali-Toudert and Mayer, 2007b). Meanwhile, Ng (Ng et al., 2012) analyzed the effect of building-height-to-street-width (H/W) ratio on cooling effect of green roof, and demonstrated that the benefit of the cooling effects at grade is low when the H/W ratio exceeds 1. (Ouldboukhitine et al., 2014) presented that vegetation could reduce the outside air temperature of the street canyon by 0.8 °C. Besides, several studies illustrated the effect of building layout on the microclimate. The main building layouts in the studies can be categorized into enclosing layout (Berardi, 2016; Berkovic et al., 2012; Taleghani et al., 2014), array layout(Paramita and Fukuda, 2013; Perini and Magliocco, 2014) and scattered layout(Dimoudi and Nikolopoulou, 2003; Lei et al., 2016; Souza, 2013). Especially, the enclosing layout can promote the microclimatic conditions (Meir et al., 1995). Peng demonstrated that the cool enclaves depends on building density and the layout pattern and geometry of buildings in conjunction with roads (Peng and Jim, 2013). According to Berardi, who compared the benefits before and post green roof retrofits, the results showed that the cooling effect on the urban microclimate with green roof retrofits increased with the increase of the LAI (Berardi, 2016).

From the previous works, in view of the complexity of the formation of regional environment, current regional environmental studies rely heavily on simulation tools without field measurements, and most studies only analyze the effect of single or individual factor, such as green roof types, soil depth, vegetation coverage, etc. of green roofs on building scale or microclimate scale. And those lack systematic

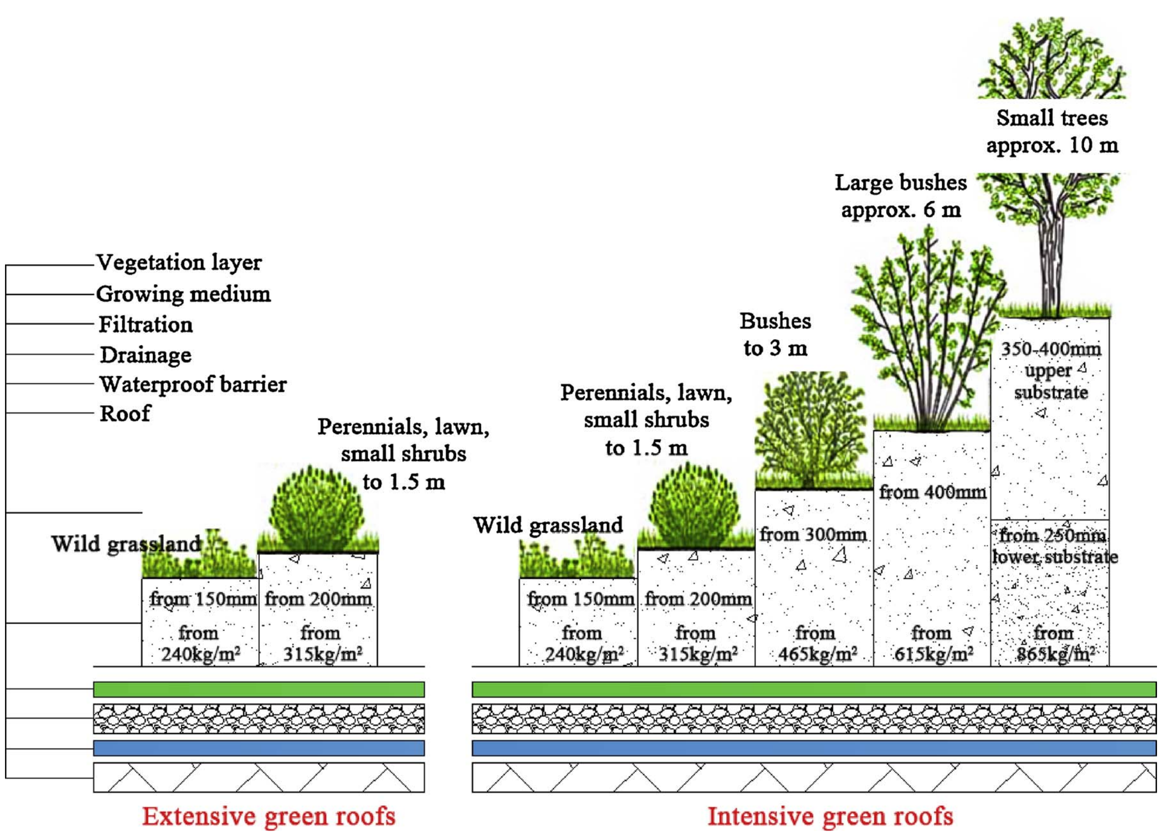

Fig. 1. The configuration of intensive green roofs and extensive green roofs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)