Urban Forestry & Urban Greening 24 (2017) 92–100

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Thermal mitigation of hydroponic green roof based on heat balance

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ARTICLE INFO

Keywords:
Green rooftop
Heat balance components
Latent heat flux
Thermal mitigation
Urban greening
Urban heat island

ABSTRACT

The creation of green rooftops is an important method for mitigating heat build-up in urban rooftop environments because they lower the sensible heat flux over the rooftop and conductive heat flux into the building. We propose a model for assessing thermal mitigation effects through a hydroponic urban greening system based on heat balance. We conducted an experiment with two different rooftops at two study sites, which were monitored for two months in two different years. Each rooftop was divided into two areas: one bare, the other covered by the hydroponic urban greening system. Parameters measured in both areas were air temperature, surface temperature, and conductive heat flux. The data were analyzed using three thermal mitigation indices. However, it was difficult to show a uniform relationship between the latent heat flux and mitigation indices during the period of analysis. This suggests it would be necessary to include factors such as latent heat flux, conductive heat flux, and water heat storage flux to assess the thermal mitigation effect. Our research indicated that the composition of heat balance terms could estimate thermal mitigation effects in the green roof area independent of the year. The results suggest a principle for assessing the mitigation effects of urban greening on the thermal environment.

1. Introduction

Human activities lead to various problems on the earth. City inhabitants have become increasingly familiar with urban heat island (UHI) effects during summer. Unusually high air temperatures were recorded in Japan during the summer of 2013. A report by the Japan Meteorological Agency (2013) showed that the UHI effect in metropolitan areas such as Tokyo, Osaka, and Nagoya led to the highest temperatures recorded. In Osaka in 2013, air temperature reached a new recorded high temperature, emphasizing the importance of mitigation in urban areas.

The phenomenon of high temperature in urban areas is partly due to decreasing green area and increasing area of asphalt pavement. Vailshery et al. (2013) indicated that ambient air temperature, road surface temperature, humidity, and air pollution were lower in a road segment with tree cover. The increase in impermeable surfaces is one of the causes of UHI effects (Oke, 1982), although the relative importance of the causes should be examined case by case (Zhao et al., 2014). One familiar method is to install cool roofs and green roofs on urban buildings. Generally, the increase in rooftop albedo plays an important role in decreasing the impact of rooftops on microclimate change and human health (Susca, 2012). Ambient air temperature on cool roofs and green roofs varies depending on the roof albedo (Santamouris, 2014). Perini and Magliocco (2014) showed that vegetation on the ground and roofs mitigated summer temperatures, decreased the indoor cooling load demand, and improved outdoor comfort. Middel et al. (2015) suggested that a linear relationship exists between percentage canopy cover and air temperature reduction. Although there are limitations to large-scale implementation, vertical greenery systems offer solutions for the key associated consequences of UHIs and have positive effects on human health (Price et al., 2015). In urban areas, the thermal mitigation effect of green roofs has attracted attention.

Recently, climatic improvement from rooftop greening has been evaluated using experimental methods (Onmura et al., 2001; Jo et al., 2010). The soil substrate layer of the intensive green roof can be considered a large heat sink on the rooftop that reduces temperature fluctuation (Jim and Tsang, 2011). The use of green roofs has provided opportunities to improve the heating performance of buildings in many regions of the world (Susca et al., 2011; Zinzi and Agnoli, 2012; Razzaghmanesh et al., 2016). Furthermore, Huang et al. (2016) reported that surface temperature on a hydroponic green roof reduced by 3–5 °C compared with a roof without vegetation.

In studies involving evaluation models, the changes in temperature were found to be a linear function of albedo fluctuation using a climate model (Smith and Roebber, 2011; Akbari and Matthews, 2012). Ouldboukhitine et al. (2014) evaluated the reduction of surface

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http://dx.doi.org/10.1016/j.ufug.2017.03.022
Received 15 September 2016; Received in revised form 21 March 2017; Accepted 23 March 2017

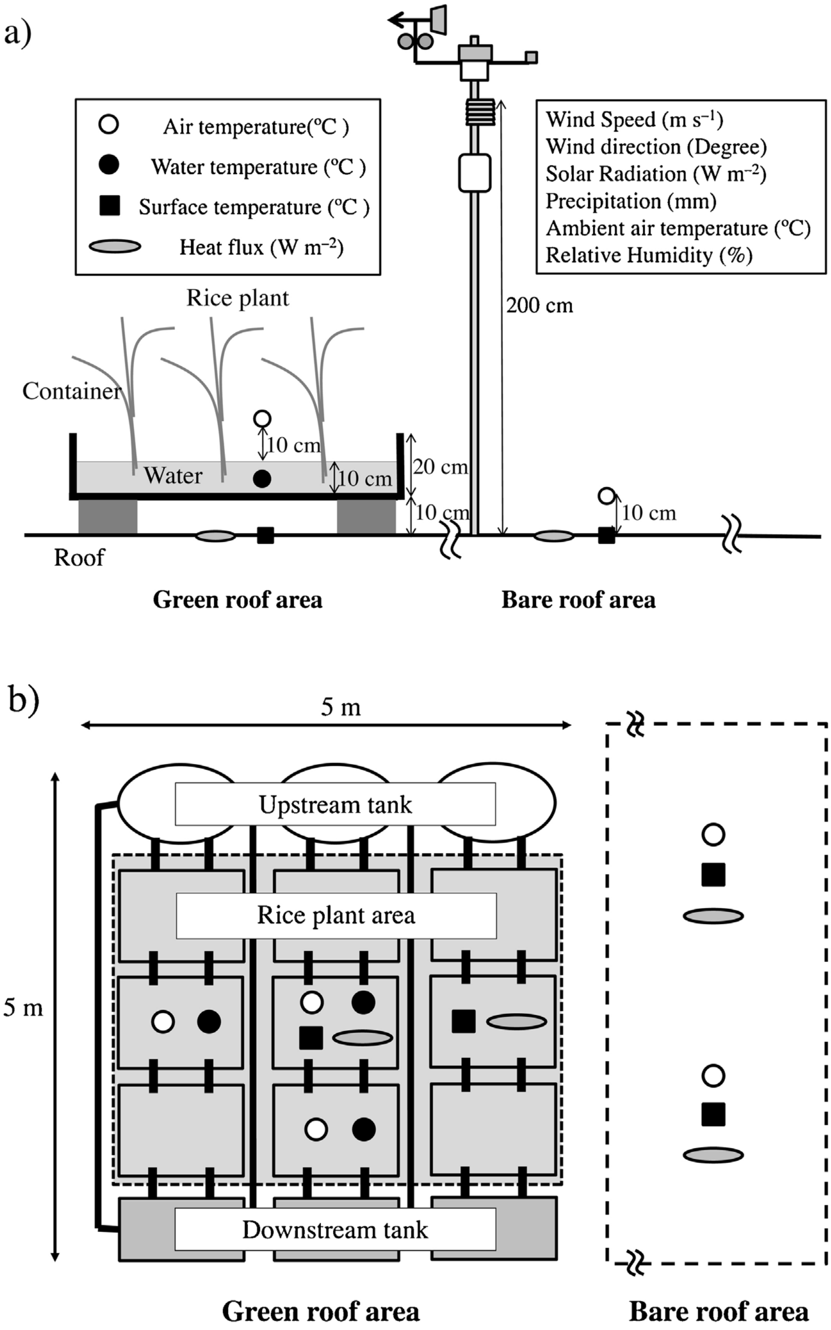

Fig. 1. Installation locations of sensors and instruments: (a) Vertical arrangement and (b) spatial layout.

temperature of a green roof on the energy performance of a building by simulating heat transfer. In a study using the Energy Plus model, green roofs contributed to improving the urban environment in terms of UHI under different climate conditions (Chan and Chow, 2013; Kolokotsa et al., 2013). In a study using a vertically resolved model, Sun et al. (2013) and Sun et al. (2014) revealed that solar radiation and medium-layer moisture were major determinants of thermal insulation effect by a green roof based on an analysis using a vertically resolved hygro-thermal model. Wang and Zacharias (2015) found that air temperature could be reduced by as much as 0.5 °C, using the ENVI-met micro-climate model to measure the impact of greening landscapes. Wang et al. (2016) found that the cooling effect of tree-shading was more significant than that by evapotranspiration from lawns, leading to a considerable reduction in cooling load. Moreover, Sung (2013) and Kong et al. (2014) explained that urban green spaces provided cooler microclimates and showed the effect of mitigating thermal environment using satellite images. Thus, the thermal mitigation effects of green rooftops in urbanized areas have been confirmed by empirical studies and evaluation models.

It is also important to consider heat balance in terms of the effects of microclimate and building efficiency in cities. In a study focusing on observations of the heat balance over the green roof, Takebayashi and Moriyama (2007) noted that the sensible heat flux of the green roof was small because most of the absorbed heat was used in evaporation. In terms of heat transfer from the atmosphere to the buildings, green roofs needed constant irrigation and high-transpiring vegetation (Coutts et al., 2013). Several studies estimated the heat balance on a green roof and assessed heat transfer by evaluation models (Feng et al., 2010; Scherba et al., 2011; Tabares-Velasco and Srebric, 2012; Yaghoobian and Srebric, 2015).

In this way, previous studies have reported the heat flow of rooftops, but few studies have assessed the relationships between