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Mitigation of heating of an urban building rooftop during hot summer by a hydroponic rice system

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ABSTRACT

The use of green roofs is an important method for mitigating heating of urban rooftop environments. Our study aimed to demonstrate the mitigation of thermal effects on a hot rooftop during summer by a hydroponic system in which rice was grown. The system was installed on the top of a commercial building in the large city of Osaka, Japan; the roof was divided into two areas, one bare, the other covered by the hydroponic system. In both areas, we measured thermal factors, such as air temperature, rooftop surface temperature, and conductive heat flux; from the data we calculated three thermal mitigation indices. We also propose normalized types of mitigation indices. Mitigation effects on the thermal environment by the hydroponic system could be well estimated from ambient air temperature and solar radiation; the effects were better explained by solar radiation than by ambient air temperature. The results indicate that during the hot season, the system's mitigation effects on the thermal environment can be predicted from solar radiation level, and the normalized mitigation index is an appropriate index for estimating the cooling effect. Our results suggest that the hydroponic system might affect the energy flow in two ways: the proportions of sensible heat flux and latent heat flux are mainly affected by evaporative cooling and the portion of conductive heat flux is mainly affected by radiation shielding.

1. Introduction

According to a 2014 report by the Intergovernmental Panel on Climate Change, human activities are almost certainly the cause of global warming [1]. City dwellers have become increasingly familiar with urban heat island (UHI) effects during summer months. Unusually high air temperatures were recorded in Japan during the summer of 2013. According to a 2013 report by the Japan Meteorological Agency [2], UHI in metropolitan areas such as Tokyo, Osaka, and Nagoya led to record high temperatures. In Osaka in 2013, the maximum temperature exceeded 30 °C on 54 days during July and August, and was above 35 °C for 17 consecutive days, from 7 to 23 August, a new high-temperature record. Increasingly elevated daily temperatures magnify cooling loads, as people seek to make their daytime and nighttime indoor environments more comfortable. This leads to a vicious cycle, as the thermal environment is worsened by waste heat exhausted from cooling devices, which increases the air temperature in urban climates, exacerbating the UHI phenomenon.

The causes of high temperatures in UHI areas have been researched from various perspectives. The increased impermeability of surfaces is one of the causes of UHI effects [3]; relative importance of the causes should be examined case by case [4]. The causes related to thermal balance are reductions in the amounts of green areas and water surfaces, which decrease latent heat flux, and increases in the extent of concrete and asphalt surfaces, which increase sensible heat flux. High temperatures due to UHI effects can be mitigated by improving the thermal balance of urban environments; various methods can be used to decrease both sensible heat flux and ground conductive heat flux. One method is to apply highly reflective paint on rooftops, to reduce net radiation [5–9].

Another effective method employs rooftop greening to increase latent heat flux. Plants on green rooftops improve thermal environments by evapotranspiration, thereby reducing heat storage in

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building structures. Such roofs have been installed on a number of buildings. Previous studies have shown that the surface temperature in a rooftop garden of turf can decrease by from 60 to 30 °C, compared with that of bare roofs [10], and that the local air temperature can be lowered in a tropical environment by 4.2 °C by the installation of a green rooftop consisting of turf and shrubs [11]. Furthermore, on a campus that was modeled as a tiny city, the temperature difference between green and bare areas was 4 °C [12]. In recent years, the climatic improvement from rooftop greening has been evaluated with experimental methods [13–17], modelling techniques [18–21], and more general discussions [22–25]. Several studies examined how the efficacy of rooftop greening is affected by the use of various plant species [26–31]. Plants used for green rooftops must tolerate the high temperatures and dry conditions prevalent in such environments. In previous studies, turf and sedum were planted on rooftops and changes in the water balance and heat balance were observed [32,33]. Yoshinaga [34] reported that sedum is often used with artificial lightweight soil to minimize increases in building loads, taking advantage of sedum's resistance to parching; however, the grass and sedum conventionally used for rooftop greening retains only modest amounts of water, which constrains cooling effects [35].

Our experiments were designed to clarify the mitigating effects of a hydroponic rice system (HRS) to ameliorate the thermal environment of a rooftop in summer. The results allow us to quantitatively clarify the system's effects on local air and surface temperatures, as well as on the conductive heat flux. We also discuss the major climatological factors that influence thermal mitigation.

2. Materials and methods

2.1. Experimental site

This study was conducted on the roof of the Osaka Gas building (height = 30 m, 34°41′18″N,135°30′01″E). The average summer conditions at the Osaka weather station from 1981 to 2010 were 27.4 °C in July and 28.8 °C in August, with precipitation of 157 mm in July and 91 mm in August. The analysis period in our study was the 62 days from 1 July through 31 August 2013.

2.2. HRS

The HRS used in our study comprised a circulatory system with three open pools (each 76 × 91 × 20 cm) and two tanks, all made from polyethylene (Fig. 1). Water in the system was pumped from the downstream tank to the upstream tank and then returned by gravity to the lower tank, flowing in series through the three pools in which the rice was growing. The downstream tank was equipped with a float switch so that fresh water was automatically supplied to the tank whenever the water level declined below a set point. Moreover, rain water was effectively used, since the downstream tank and the rice plant area were not covered. In a preliminary feasibility study (data not shown), we used non-circulating water, but found that algae grew excessively and stole the nutrients. For the growth of hydroponic rice on our rooftop, continuous water flow was necessary. Water circulation mixed materials and equalized thermal conditions, thereby avoiding thermal stagnation in specific parts of the water containers. The roof type was a flat concrete slab. We calculated the weight that the rooftop could safely support. As the main part of the weight of the HRS is water, we limited water depth in the pools to 10 cm. At this water depth, the total weight of the HRS was about 80 kg per m^2, which was safe in a region without a significant snow load. The advantages of the HRS compared with roof ponds are ease of construction and removal, and flexibility of layout depending on user needs.

We sowed the rice (*Oryza sativa* L.) seed in a seedling box on 28 April, and the seed started to germinate on 5 May. On 24 May the seedlings were transplanted from the seedling box to the HRS. The rice plants in the HRS were set at 19 cm intervals in synthetic sponge material (Urethane foam U0281, Fuji Gomu Co. Ltd., Shizuoka, Japan) immobilized in wire nets in the units. The plants were fertilized with liquid fertilizer solutions (Table 1). Before transplanting, the rice seedlings were fertilized with NL1 and NL2. After transplanting, a ammonium chloride-based fertilizer (NL3) was applied to the plants weekly. The rice plants started to flower on 12 August, 80 days after transplanting. The flowering period coincided with an especially hot period. We harvested the plants on 4 October, 53 days after flowering.

2.3. Thermal observations

We used a Campbell CR10X data logger (Campbell Scientific, Logan UT, USA) with an array of copper – constantan thermocouples for temperature measurements, and a heat flux plate PHF-01 (Prede, Tokyo, Japan) for conductive heat flux measurements. Heat flux plates generate a small output voltage that is proportional to the temperature difference between the upper and lower surfaces of the sensor. Heat that flows through the attached surface is calculated by multiplying the output voltage by the calibration constant of the sensor body. The installation locations of sensors and instruments are shown in Fig. 2. Thermocouples were located at 12 points to measure the air, water, and surface temperatures in the green and bare roof areas. In order to observe the air temperatures in the boundary layer formed by HRS and bare roof surface, the air temperatures were measured at 10 cm above the water

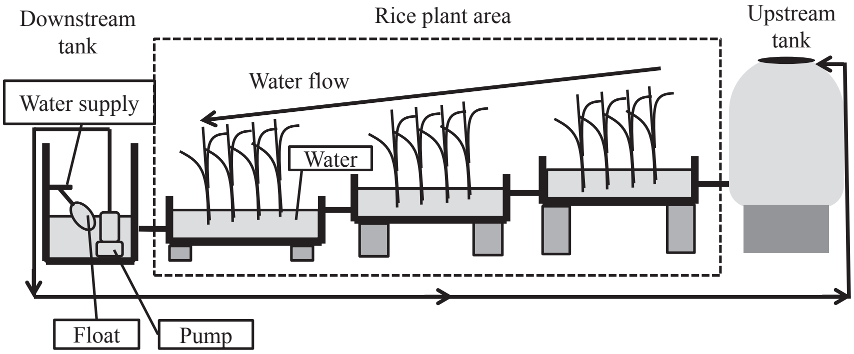

Fig. 1. The hydroponic rice system.