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RESEARCH PAPER

The Role of Green Roofs on Microclimate Mitigation Effect to Local Climates in Summer

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Abstract

Although there is a large body of previous studies on the cooling effect of green roofs on urban heat islands (UHIs), more empirical studies with an experimental setting measuring the role of green roof on mitigating urban heat should be considered. The purpose of this research is to determine the air temperature difference between green and bare roofs located on two buildings in the same local climate zone, and calculate the expected cooling effect extended from the green roof to the local climate. The study site consisted of an extensive green roof and a bare roof which were close to each other and were located in a highly built-up same area. During the three and a half clean days of testing in the middle of summer, air temperature data were collected from each roof using an air temperature logger and a local automatic weather station close to both roofs; these data were then converted to hourly data. The data were analyzed by the *t* test, ANOVA test, and a regression analysis to determine the heat mitigation effect of green roofs. As a result, the green roof's air temperature showed much lower than the bare roof's and followed the local station's air temperature change during the day. At night the air temperature difference between the two roofs was only slight and the green roof's air temperature kept lower than the local station's. Thus, even extensive green roofs can reduce air temperature through their cooling effects from their vegetation and substrates against solar radiation. The established models reported that the green roof contributed to lowering air temperatures in a local climate zone, while the bare roof made such zones more heated. The findings of this study contribute to the existing literature by proving that green roofs can be expected to help cool down not only at the small scale with building units, but also at the broader scale of urban district area. The study also gives field-experimented values to be used as updated variables to local climate simulation models.

Keywords UHI · Rooftop garden · Local climate zone · Urban area · Albedo

Introduction

Urban heat islands (UHIs) have created a need for many heat-fighting countermeasures in urbanized areas. In cities, excessive heat in the air causes buildings to consume additional energy to keep their interiors cool and comfortable for residents (Zinzi and Agnoli 2012; Coutts et al. 2013; Jim 2014c). Meanwhile, waste heat originating from cooling machines and facilities including air-conditioning units increases the air temperature and subjects people

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outside of buildings to an increased risk of heat stress (Köhler et al. 2003; Harlan et al. 2006; Memon et al. 2008; Tan et al. 2010; Costanzo et al. 2016; Sun et al. 2016).

The modification of impervious urban areas into green spaces such as open spaces with trees, greenways, and parks has led to a reduction in UHIs, and the resulting cooling effects have been well documented (Loughner et al. 2012; Doick and Hutchings 2013; Kim et al. 2016; Park et al. 2017). Urban green spaces keep the air temperature cooler than in the surrounding areas, due to increased latent heat and shade (Kjelgren and Clark 1992; Akbari 2002; McPherson and Muchnick 2005; Napoli et al. 2016). Previous studies have shown that cities have reduced their UHIs by replacing impervious land cover with green spaces ranging in size from single patches of trees to entire neighborhoods (Kjelgren and Clark 1992; Saaroni et al. 2000; Shashua-Bar et al. 2011; Loughner et al. 2012).

Experimental UHI mitigation studies have primarily focused on urban green spaces on a street or at a ground level (Spronken-Smith and Oke 1998; Petralli et al. 2009; Hamada and Ohta 2010; Ren et al. 2013; Lehmann et al. 2014; Park et al. 2017). Meanwhile, existing research on green roofs' UHI reduction has experimented on the building scale; only a few simulation studies have considered the thermal benefits of green roofs on citywide or regional scales. Much work has used experiments to measure a green roof's cooling effect on the inside of a building (Hamdi and Schayes 2008; Coutts et al. 2013; Jim 2014a, b; Karachaliou et al. 2016), as well as green roofs' economic and visual benefits (Köhler et al. 2003; Yuen and Nyuk Hien 2005; Clark et al. 2008; Chen 2013; Jim 2014a; Santamouris 2014). Some previous studies have attempted to calculate green roofs' cooling effects on UHIs throughout large and wide urban areas using computer-based simulation models (Köhler et al. 2003; Kumar and Kaushik 2005; Lazzarin et al. 2005; Rosenzweig et al. 2006; Castletona et al. 2010; Scherba et al. 2011; Zinzi and Agnoli 2012). However, even though some previous experimental studies on green roofs' cooling influences on a local level has reported, most of the existing body of research has led to green roofs being considered for temperature countermeasures only when cooling on a building level; the result is that many Asian, North American, and European cities have limited green roof support programs (Blackhurst et al. 2010; Chen 2013; Doug et al. 2005; Dvorak and Volder 2010; Gaffin et al. 2009; Kleerekoper et al. 2012; Li et al. 2014; Middel et al. 2015; Mullen et al. 2013; Solecki et al. 2005; Vijayaraghavan 2016; Williams et al. 2010; Wong and Lau 2013).

Thus, the knowledge gap of those experimental studies on green roofs' UHI reduction lies on the facts that many field experiments have been limited to the building level and many simulation studies have taken unrealistic thermal conditions. Moreover, simulation studies can only offer a rough approximation of green roofs' thermal performance in large modeled urban areas; field experiment studies on buildings have shown green roofs' precise level of cooling performance, but the results from those studies have been restricted to the building scale. To experimentally evaluate green roofs' cooling effects in a broader area, related studies should receive local UHI mitigation concepts such as the local climate zone, which is a theoretical climatic model to indicate identical urban settings that have similar boundary layer climates (Oke 1987; Stewart et al. 2014). In a same local climate zone, building roofs show the same microclimate when they share identical micro-climatic conditions, such as the same land use pattern, the same geographical location, and the same height of roofs (Stewart and Oke 2012; Stewart et al. 2014; Park et al. 2017). Thus, to compare cooling effects of bare roofs with those of green roofs having identical urban settings and field experimental methods in the same local climate zone lies on filling the knowledge gap.

Therefore, this study conducted the stationary survey on green and bare roofs, respectively, with identical settings and compared air temperature data from two roofs and weather stations. The purpose of this study was to determine air temperature difference among green and bare roofs and the weather station under the same local climate zone, find how large green roof's cooling effects on a building and local level, and understand if the green roof's cooling effect extended to the district within which the green roof was located.

Method

Study Site

The study site was in Gangnam-gu, Seoul, South Korea (37°31′2.68″N, 127°2′39.49″E). The site consisted of a green and a bare roof, and was located in the same highly built-up urban block within large areas of low-rise single houses and small high-rise residences (see Fig. 1). Two automatic weather stations are located nearby the project site (see Fig. 1). Except for the vegetation in the green roof, the two roofs had identical microclimate condition; the same roof height (20 m), the same geographical location (in a 48.2 m Euclidean distance away from each other) (see Fig. 1). The green roof was flat and bounded by parapet walls with their height of 1.2 m (see Fig. 1). The two roofs had tall residence buildings (60 m) on their west and south side. The size of the green roof was 2630.09 m^2 and the roof consisted of an outdoor facilities area (829.36 m^2, 31.5%), lawn space (1040.79 m^2, 39.6%), and an

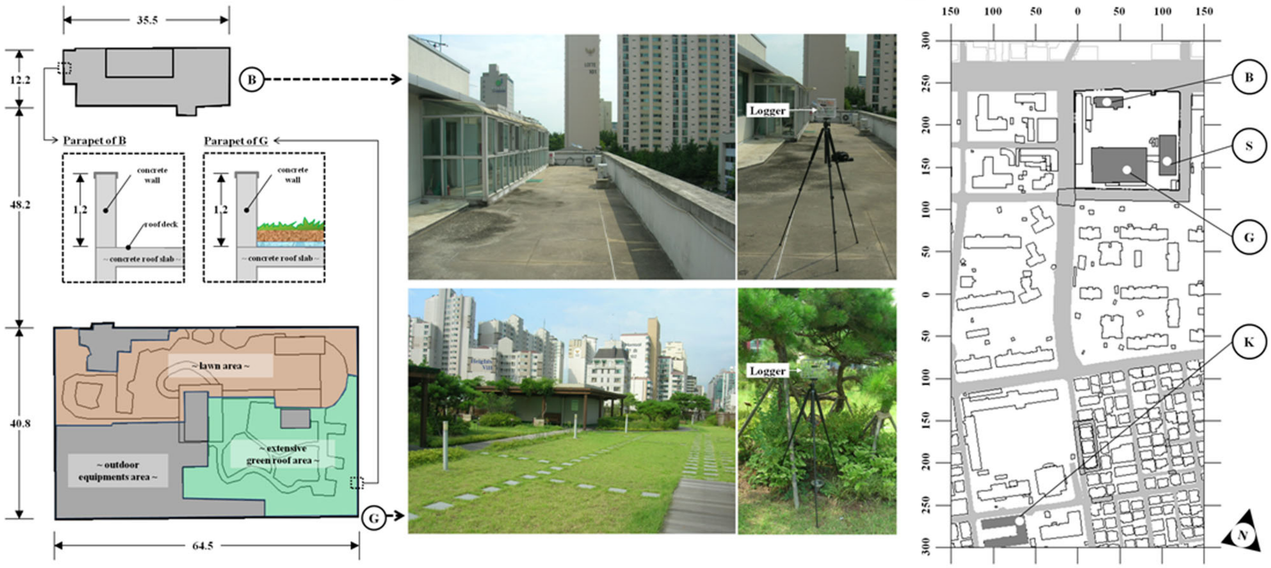

Fig. 1 Study site illustration and air temperature measurement points. B: the stationary measurement point in the bare roof; G: the stationary measurement point in the green roof; S: Station S; K: Station K

extensive green roof (759.92 m^2, 28.9%). The extensive green roof was comprised by vegetation areas, a narrow pathway and several resting places. The vegetation areas were covered with herbs, sedums, shrubs, and arbors above shallow substrates (20 cm in depth) (Getter et al. 2009; Jim and Peng 2012; Xiao et al. 2014). The bare roof (392.30 m^2) had a light gray concrete coating on its surface bounded by parapet walls with the height of 1.2 m (see Fig. 1).

Two automatic weather stations represented the local climate zone surrounding the two roofs. One station (Station S), owned by the Seoul Metropolitan Government, was very close to both roofs selected (54 m from the bare roof and 30 m from the green roof); it only collected mean daily weather data with four-wire PT1000s (accuracy ± 0.3 °C and − 40 to + 60 °C). The other station (Station K), owned by the Korea Meteorological Administration, collected mean weather data every hour with four wire PT1000s (accuracy ± 0.3 °C and − 40 to + 60 °C). Station K was 464 m away from the two roofs (see Fig. 1).

Data Collection and Analysis

The air temperature measurements for the two roofs were obtained via a stationary survey with a Testo 174H (Testo, Germany). This device collected air temperature data with a thermistor and was mounted on a white shield to prevent self-heating (Erell et al. 2003; Oke 2004; Park et al. 2017). One of the measurement sets was obtained in the middle of the extensive green roof area on the green roof, and the other was in the middle of the bare roof (see Fig. 1). Both sets were 1.5 m above each roof's ground surface to gather the air temperature data (Oke 2004) (see Fig. 1). The accuracy of the Testo 174H was ± 0.5 °C, and its measuring range was from − 20 to + 70 °C. Air temperatures were continuously recorded every minute from August 7 to August 11, 2012. During the measurement period, the weather in Gangnam-gu was clear, except for on August 10 when it rained in the daytime. The mean ambient temperature was 29.3 °C (min. 24.6 °C and max. 36.4 °C), and the mean relative humidity was 65.2% (min. 57.1% and max. 73.2%). The mean wind velocity was 1.12 m/s (max. 4.6 m/s) and the mean wind direction was northwesterly (degree direction 318). Moreover, during the daytime of the measurement days, the bare roof had received solar radiation avoiding shadows from surrounded taller buildings because the bare roof was too far away from those buildings and the lengths of shadows were not long enough to reach the roof. As for the green roof, surrounded tall buildings were on the west and south side of it in a ranged Euclidean distance away (52.6–81.1 m) (see Fig. 1). The shadows by those buildings met the green roof during sunrise (6–8 h) and sunset (17–19 h) when the air temperature was decreased. However, these shadows avoided completely the green roof during the hottest hours of the day (9–16 h).

For 3 days and 12 h, 10,080 data points were collected from the each roof, respectively; these were comprised of 5040 air temperature data points and 5040 relative humidity data points, which were measured every minute. All of the air temperature data were converted from 5040 data points to 84 data points, to imply hourly data.

With regards to the air temperature of the local climate, we used the hourly air temperature data collected by Station K (T_K) because its data amount matched the amount of each roof's data. At the first glance, the Station S seemed to represent the local climate regarding the distance from each roof. (30 m from the green roof and 54 m from the bare roof) than Station K did (464 m away). However, the air temperature data from Station S (T_S) included only four data during the whole measurement days (April 7, 8, 9, and 11) because the Station S produced one daily mean data per day. The number of data from Station S ($N = 4$) was not enough to make an accurate comparison with the data collected from the two roofs ($N = 84$ each). Station K offered hourly data, which matched the amount collected from each roof ($N = 84$). To verify the reliability in using the data from Station K as our reference data representing the local climate for our study area, an independent samples t test was conducted on both stations' daily data through SPSS (99% confidence interval of the difference) after converting Station K's hourly data to daily data. The result showed that the mean T_S and mean T_K were not significantly different ($t = -0.467 < 2.58$ and $p = 0.657 > 0.01$). Consequently, T_K could be compared to the two roofs' data.

Then, a paired samples t test through SPSS was conducted to compare the mean air temperature data of the bare roof (T_B) to that of the green roof (T_G). This test showed the difference between T_B and T_G (ΔT_{B-G}) both during the day and at night. An independent samples through SPSS t test was conducted to find the difference between diurnal T_G and nocturnal T_G, as well as the difference between diurnal T_B and nocturnal T_B. After T_K was statistically approved, an one-way analysis of variance (ANOVA) was performed to determine the differences among T_K, T_G, and T_B through SPSS. Six regression models using SPSS were created to identify the relationships between T_G and T_K, and T_B and T_K.

Results

Air Temperature Difference Between T_G and T_B

During the day and night when the measurements were made, T_G was 6.1 °C lower than T_B (see Table 1). The difference between T_B and T_G (ΔT_{B-G}) was greater during the daytime than at night. During the day, ΔT_{B-G} ranged from 22.6 to 4.1 °C, and the mean value was 10.8 °C. The maximum T_G value was 42.1 °C during the daytime and 33.3 °C at night, while the minimum T_G value was 27.3 °C during the daytime and 23.7 °C at night (see Fig. 2). The maximum T_B value was 64.7 °C during the daytime and 35.2 °C at night, while the minimum T_B value was 31.4 °C during the daytime and 24.5 °C at night (see Fig. 2). Throughout the day and night, T_G fluctuated less (7.97 °C) than did T_B (17.78 °C). The mean ΔT_{B-G} was 10.8 °C during the daytime and 1.0 °C at night (see Table 1).

Differences Among T_K, T_G, and T_B

From the results of the ANOVA test, it was determined that throughout the test period, T_K, T_G, and T_B were significantly different; the value for ΔT_{B-K} was 7.97 °C and for ΔT_{G-K} was 1.89 °C (see Table 1). Specifically, the diurnal ΔT_{B-K} was 15.6 °C, and the diurnal ΔT_{G-K} was 4.8 °C, while the nocturnal ΔT_{B-K} was − 0.1 °C, and the nocturnal ΔT_{G-K} was − 1.12 °C (see Table 1). Overall of the results from the three groups, T_B had the highest value, followed

Table 1 Results of the T test on T_G and T_B and ANOVA test of T_K, T_G, and T_B

Pair or group		Mean difference ($I - J$)	Std. error	t	F	df	Stat. anal.
I	J						
T_G	T_B	− 6.051***	0.734	− 8.247		83	Paired
D T_G	D T_B	− 10.839***	0.977	− 11.100		42	Paired
N T_G	N T_B	− 1.029***	0.085	− 12.178		40	Paired
D T_G	N T_G	7.966***	0.705	11.291		82	Indep.
D T_B	N T_B	17.776***	1.494	11.902		82	Indep.
T_K	T_G	− 1.892**	0.630		27.195***	2	ANOVA
	T_B	− 7.944**	1.259				
D T_K	D T_G	− 4.770**	0.714		77.039***	2	ANOVA
	D T_B	− 15.609**	1.464				
N T_K	N T_G	1.124	0.511		2.777*	2	ANOVA
	N T_B	0.095	0.528				

D diurnal, *N* nocturnal; Paired: paired samples t test; Indep.: independent samples t test

$*p < 0.1$, $**p < 0.05$, $***p < 0.01$

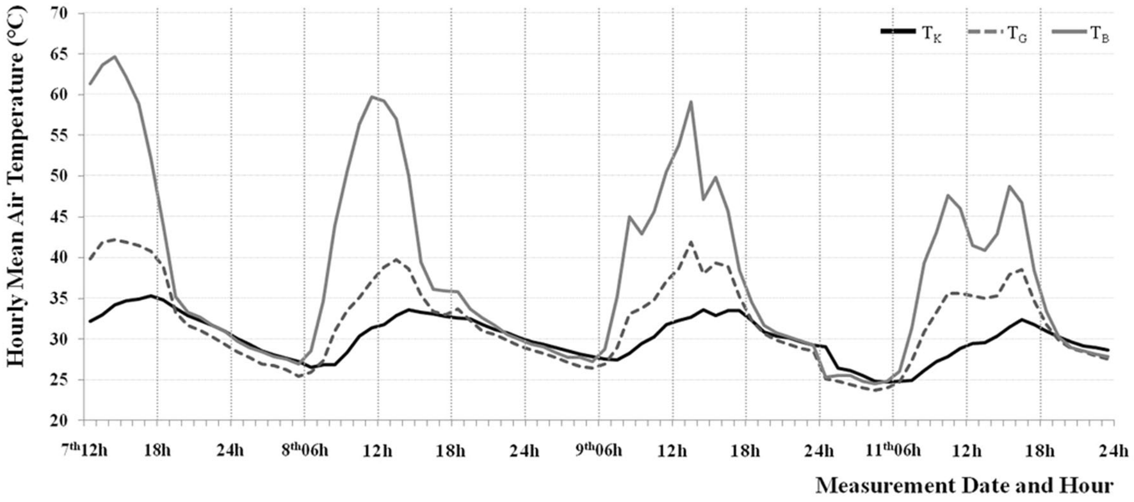

Fig. 2 Hourly changes in T_K, T_G, and T_B during the measurement period

by T_G and T_K. The drop in $\Delta T_{B\text{–}K}$ was far larger than in $\Delta T_{G\text{–}K}$. This consequence matched Duncan's homogeneous subsets, resulting in T_K and T_G belonging to one subset and T_B belonging to another.

Mitigation Effect of Green Roofs on UHIs in a Local Climate Zone

As a result of the regression analysis, six logarithmic functions were finalized (see Table 2). Through all of the functions, as T_K increased, either T_G or T_B increased along a positive logarithmic line. However, the models had different R^2 values to indicate the models' goodness of fit. The two nocturnal models (E3 and E4) were the most fitted to the regression line, more so than the overall or diurnal models. Furthermore, at night the cooling of the green and bare roofs showed little difference from one another. During the daytime, the fitness of the regression lines decreased, but E1 was far more fitted than E2. E1 in the diurnal models had similar R^2 value to that of E5 in the overall models. Moreover, as diurnal T_K increased, diurnal T_G increased smaller than diurnal T_B. Likewise, as overall T_K increased, overall T_G increased much smaller than overall T_B. From E1 and E2 to E5 and E6 the difference of the slopes between E1 and E5 was small but the difference between E2 and E6 was large. Thus, diurnal air temperature fluctuation of each roof mainly influenced each overall air temperature fluctuation because both nocturnal models were not different. Throughout the day T_G reacted smaller to T_K than T_B did.

Discussion and Conclusions

The diurnal difference between T_G and T_B was due to several cooling characteristics of each roof. As for the green roof, tree crowns and leaves of herbs blocked the direct solar radiation falling to the ground making shadows as well as avoiding much heat storage during the day (Akbari 2002; Gago et al. 2013; Getter et al. 2009; Kleerekoper et al. 2012). In addition, this green roof produced humidity evaporated from leaves of trees, grass, and herbs (Niachou et al. 2001; Getter and Rowe 2006; Susca et al. 2011) even though it had a shallow substrate (under 20 cm) which stored less heat than a deeper substrate did in the intensive green roof system (Castletona et al.

Table 2 Six regression models for T_K, T_G, and T_B during the day, night, and overall

Model type	Regression model		F	$df1$	$df2$	R^2
Diurnal models	$Y_1 = 34.628\ \ln(X_1) - 83.039$	E1	65.332	1	41	0.614**
	$Y_2 = 46.270\ \ln(X_1) - 112.218$	E2	9.745	1	41	0.192*
Nocturnal models	$Y_3 = 29.638\ \ln(X_2) - 71.842$	E3	437.910	1	39	0.918**
	$Y_4 = 30.485\ \ln(X_2) - 73.664$	E4	241.265	1	39	0.861**
Overall models	$Y_5 = 44.962\ \ln(X_3) - 120.957$	E5	127.298	1	82	0.608**
	$Y_6 = 72.193\ \ln(X_3) - 207.615$	E6	39.973	1	82	0.328**

X_1 diurnal T_K, Y_1 diurnal T_G, Y_2 diurnal T_B, X_2 nocturnal T_K, Y_3 nocturnal T_G, Y_4 nocturnal T_B, X_3 overall T_K, Y_5 overall T_G, Y_6 overall T_B

$^*p < 0.01$, $^{**}p < 0.001$

2010; Tsang and Jim 2011). Meanwhile, the bare roof gained, reflected, and accumulated direct solar radiation and showed very hot air temperatures during the day (Grant 2006; Speak et al. 2013; Ouldboukhitine et al. 2014). Thus, green roofs, even of an extensive type, were more effective in micro-UHI reduction than bare roofs.

Both values of nocturnal T_G and T_B reduced due to no additional solar radiation and little heat storage at night. But the significant differences between the nocturnal T_G and the nocturnal T_B prove that the extensive green roof was more effective to cool down due to its less emission of heat stored during the day (Gaffin et al. 2008; Giridharan et al. 2008; Smith and Levermore 2008).

In comparison among T_K, T_G, and T_B, the green roof followed the graph of T_K gently while T_B drew steeper curves in the daytime. The $\mathrm{T_G}$ increased more than the $\mathrm{T_K}$ did (see Fig. 2) and it is due to the difference of the data collection height between two stations. The T_G was resulted from near heated air on the roof while the T_K was too far away from the roof to integrate the thermal consequences generated by the factors of heating such as solar radiated spaces and cooling facilities producing waste heat and cooling factors such as wind, green spaces, parks, and shaded spaces by buildings (Oke 1987; Stewart and Oke 2012; Stewart et al. 2014; Park et al. 2017). At night, the green roof's less heat emission resulted in the lower air temperature than the T_K (see Fig. 2), while other bare roofs and impervious covers emitted heat which was stored during the daytime and kept the local area warm (Wong et al. 2003; Jim 2014c; Tan et al. 2014). This result supports previous studies reporting that even an extensive green roof can be a cooling factor in cities experiencing a tropical night (Castletona et al. 2010; Tsang and Jim 2011).

Referring to E1 and E2 or E5 and E6, we can expect how a local urban area would experience its UHI reduction if its concrete covered bare roof is transformed to an extensive green roof (Sailor 2008; Zinzi and Agnoli 2012; Coma et al. 2016). Because the ambient air temperature of Station K contained various heat sources from the entire local climate zone, the green roof's cooling on the local climate was hidden (Oke 2004; Stewart et al. 2014). However, according to these linear models, the more a local climate gets transformed green roofs, the more it gets the UHI reduction (Santamouris 2014).

Our results based on field experiments contribute to produce evidenced input values for a UHI simulation model which analyzes and expects a local climate reduction through green roofs' provision in summer (Ouldboukhitine et al. 2011; Chan and Chow 2013). Our findings also expect that if bare urban roofs in a hot local climate are transformed into green roofs, the local climate will be enhanced in upper parts of the boundary layer climate (Oke 1987). This study will be useful to urban planners and designers, policy makers, and researchers seeking to establish thermal mitigation strategies and identify the usefulness of small green spaces in UHIs. In identical local climate zones, especially in highly built-up locations, small green spaces such as green roofs can play an important role in mitigating UHIs (Park et al. 2017).

Although the contributions of this study are significant, there are some limitations. The number of study sites was not sufficient, but accurately representing regional cooling effects. The locations were carefully and logically selected to study the effect of a particular local climate zone while they did not fully avoid side shading effects by close tall buildings. The area of the green roof was larger than that of the bare roof; however, other than in this respect, the two roofs offered identical conditions for analyzing micro-climatic differences via the concept of the local climate zone. The duration of measurement was not sufficient to determine the green roof's UHI mitigation effect for the entire summer, because it included temperature gradients for just three and a half days although since these were the hottest days of the year, they could be considered representative of that year's summer.

Our results highlight the differences in thermal mitigation between the two roof types, and thus should aid in mitigating heat in the upper boundary climate layer. Bare roofs in highly developed urban blocks require thermal mitigation strategies such as small, multilateral green spaces on the ground, roofs, and walls of buildings. The findings of our study also suggest that the use of green roofs is an effective strategy in mitigating UHIs at the district level. Through this study, UHI mitigation policy can adopt a wider spatial range of maintenance. Roofs with no green spaces are one of the main causes of UHI intensification in local climate zones, due to heat emissions from their surrounding area.

The endeavor to fill the knowledge gap regarding local climate zones and their implications for local cooling should continue; eventually, it will lead to actual UHI mitigation in urban blocks through the provision of green roofs. In service of that effort, more data from multiple measurement points will offer clearer indications of green roofs' contribution to UHI mitigation. In future research, the selected local climate zones should be composed of green and bare roofs residing in similar thermal conditions such as their height from the ground, roof area, and so on. Also, it is necessary to study which types of green roofs will be most effective in reducing UHIs in local climate zones. The result will be economic value stemming from the knowledge of which local climate zones enjoy lower temperatures when green roofs are established.

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