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Do green roofs cool the air?

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ABSTRACT

Rapid urbanization and an increasing number and duration of heat waves poses a need to mitigate extremely high temperatures. One of the repeatedly suggested measures to moderate the so called urban heat island are green roofs. This study investigates several extensive sedum-covered green roofs in Utrecht (NL) and their effect on air temperature right above the roof surface. The air temperature was measured 15 and 30 cm above the roof surface and also in the substrate. We showed that under well-watered conditions, the air above the green roof, compared to the white gravel roof, was colder at night and warmer during the day. This suggests that extensive sedum-covered green roofs might help decrease air temperatures at night, when the urban heat island is strongest, but possibly contribute to high daytime temperatures. The average 24 h effect of sedum-covered green roof was a 0.2 °C increase of air temperature 15 cm above the ground. During a dry year the examined green roof exhibited behavior similar to conventional white gravel roof even exhibited slight cooling effect in late afternoon. Interestingly, the pattern of soil temperature remained almost the same for both dry and well-prospering green roofs, colder during the day and warmer at night.

1. Introduction

Heat strokes, decreased quality of sleep, and higher mortality rates, a decrease in labor productivity, and a substantial increase in power consumption for air conditioning are just some examples of negative influences of high temperatures [1,2]. Such negative impacts of extreme heat particularly occur in urban areas, as temperatures there are higher than in the surrounding rural areas. This urban heat island (UHI) phenomenon was already described in London 200 years ago [3]. Climate change, urbanization and urban densification will lead to an increase in frequency and intensity of heat waves [4]. Given all the negative impacts of extreme heat, there is a real need to work towards reducing outdoor temperatures in urban areas.

Increasing the vegetated fraction in a city has shown to be an effective way to decrease urban temperatures [5,6]. Green roofs are suggested as one of the possible ways to achieve this [7–9]. Implementing green roofs is popular due to their versatile effects and functions, such as roof gardens [10], isolation [11], or runoff peak delay [12]. The thermal effects of green roofs on the urban environment are another widely used argument to promote their implementation [13].

Literature focused on temperature measurements of green roofs generally covers two topics: (1) Cooling effect of green roofs on indoor environment and its use as insulation layer and (2) Effect on roof surface temperature. Many studies showed potential benefits of green roofs for the indoor environment of the building, such as energy savings [14] or reduction of indoor temperatures by several degrees [15]. This is closely connected to green roofs' ability to work as insulator and temperature buffer and decrease high surface temperatures [16], as well as low winter temperatures [17].

When it comes to the effect of green roofs on outdoor temperature, most modeling studies agree that green roofs have the potential to decrease UHI [13,18,19]. Those results are supported by several measurement studies [20–23]. Additionally, Peng and Jim (2015) [21] also showed a slight warming effect of green roofs during winter months.

However, measurement studies focusing primarily on effects of

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green roofs on outdoor temperature are relatively scarce. Berardi et al. [24] summarized the literature about green roofs. From the large number of articles presented in that review, only three dealt with outdoor air temperature measurements [5,25,26]. Another highly cited review article [27] discusses the ecosystem services of green roofs. From 61 references only one [28] focused on urban heat island mitigation.

Some studies discuss possible negative effects of green roofs. Jim (2015) [29] showed that sedum covered green roofs might under tropical conditions increase the air-conditioning energy consumption in apartments below. Contrary to that, MacIvor et al. (2016) [23] promote sedum for its cooling properties as a good choice for temperate continental climates. Previous studies also suggested that green roofs need a certain level of maintenance, because vegetation damage can reduce the desired cooling effects [25], and the temperature of the bare substrate can easily run higher than surface temperature of a bare roof [16].

Research presented in this paper is based on monitoring results from an extensive, sedum-covered green roof in Utrecht and provides an analysis of these observations. We aim to provide additional insight in thermal behavior of sedum-covered green roofs in a temperate climate, and to contribute to understanding of the role of soil moisture in the cooling effect of green roofs. We also aim to clarify how thermal behavior of a green roof changes under extreme conditions, and compare the effects of a dry green roof to a well prospering green roof, and white gravel roof.

2. Methods

2.1. Monitoring site

The study site is located in Utrecht, The Netherlands (52°5′ N, 5°7′ E). The climate is a moderate sea climate with summer starting in June and ending mid-late September.

We examined seven green roofs installed on a rooftop of a one-story school building two of which were examined in depth (GR4 and GR7); they are considered, and proved by comparison, to be representative of the other ones (Fig. 1). Additionally, those two roofs had preinstalled soil moisture sensors, and therefore provided more information for the analysis. All roofs were installed in 2010 and did not receive routine maintenance. All green roofs were 7 m long and 3.5 m wide, with exception of GR2 which had dimensions 7 × 7.5 m. Part of the installation was also a conventional white gravel (WG) roof which was used as a baseline for comparison (8.5 × 8 m).

The construction of each green roof was as follows. A membrane separated the rooftop from the green roof, above which lied a drainage layer (ca. 2 cm) and a cloth layer (0.3 cm). On top was a substrate layer with vegetation. The combined depth of root zone and substrate layer was approx. 3.5 cm. The vegetation on all the green roofs was a mixture of six sedum species (*S. floriferum ”Weihenstephaner gold”, S. album ”Coral carpet”, S. reflexum, S. spurium ”Fuldaglut”, S. sexangulare, S. album superbum*) and was considered stabilized. As visible from Fig. 1a), the percentual representation of the sedum species was different for each roof.

During the monitoring period (2010–2015), a small meteorological station was installed on the roof including an air temperature sensor 2 m above rooftop level, solar radiation, wind speed, and rainfall. Each roof had two additional temperature sensors positioned 15 cm (T15) and 30 cm (T30) above the ground in the center of each green roof, and one temperature sensor positioned 2 cm under the surface inside the substrate layer or gravel layer (Ts). Runoff was measured from each roof separately [30]. Soil moisture sensors were placed in GR4 and GR7 2.5 cm under the substrate surface. All data were recorded at 5 min intervals. The accuracy of the sensors, as well as the manufacturer and sensor type, can be found in Table 1 Calibration of the sensors was done before installation and the green roofs, as well as the devices, were regularly checked.

2.2. Influence of soil moisture

Influence of initial soil moisture on the thermal performance of green roofs was studied using the 2014 dataset. Two six-day periods in July were chosen for the analysis, further referred to as ”cloudy” and ”clear sky”. First period, 12–17 July was considered as

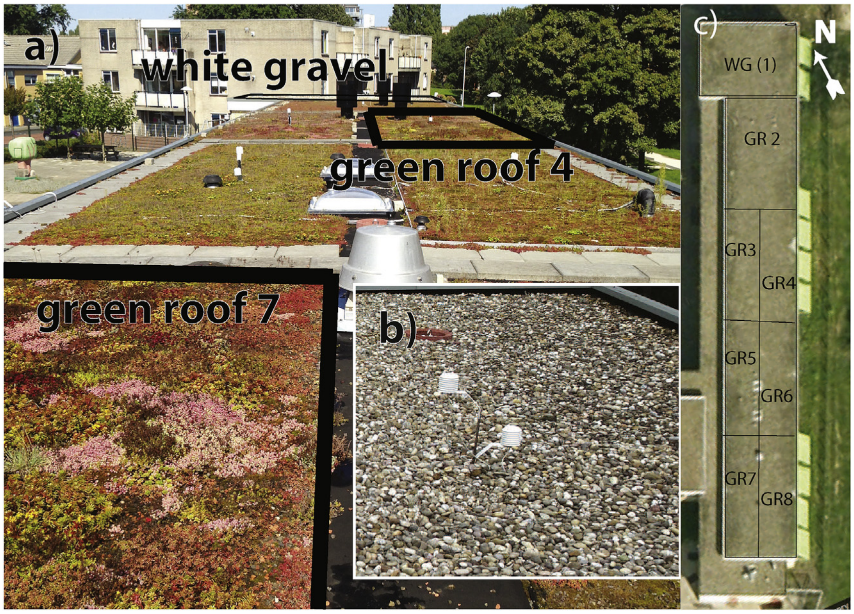

Fig. 1. Green roofs in Utrecht on 03-09-2014. a) plant cover and positioning of GR4, GR7, and WG with respect to each other, and position of temperature sensors b) white gravel roof with temperature sensors, and c) layout of the fields on the roof.

Table 1
Sensors' specifications.

Variable	Sensor manufacturer and type	Accuracy
Air temperature	EKOPOWER thermometer TS 21	<0.1 °C
Soil temperature	EKOPOWER thermometer TS 21	<0.1 °C
Soil moisture	*ECH$_2$O* EC-20	<0.04 m^3m^{-3}
Rainfall	EKOPOWER rain collector 7852 M	<0.2 mm
Runoff	STS pressure transmitter ATM/N	<0.5%
Wind speed	EKOPOWER anemometer MAX40	<0.1 ms^{-1}
Solar radiation	EKOPOWER solar radiation sensor 6450	<3% (0° to ±70° incident angle) ±10% (±85° incident angle)

a cloudy period with average daytime solar radiation of 212.5 Wm^{-2}. 15 July was an exception and was relatively sunny (average radiation 351.5Wm^{-2}). Second period, 22–27 July, was considered relatively sunny with average solar radiation of 328.8 Wm^{-2}. It should be noted that the incoming long-wave radiation was not measured. The cloudy and the clear sky periods were only based on the day time measurements of the short wave radiation and therefore nights may or may not be cloudy.

Weather conditions during the examined periods is shown in Fig. 2. A rainy week before 12 July caused a relatively high soil moisture level (0.18 m^3m^{-3} in GR7) at the beginning of the examined period. Soil moisture then decreased continuously until it reached zero value on 19 July. After a heavy rain on 21 July the soil moisture increased again to 0.21 m^3m^{-3}. The highest value of soil moisture measured in July reached 0.22 m^3m^{-3} (GR7). Two short rain events (14 and 26 July) with precipitation around 0.2 mm did not cause any change in soil moisture, probably because all the water was intercepted by the vegetation. Effects of the differences in soil moisture conditions on observed temperature are discussed in section 3.1.

2.3. Prospering vs. dry green roof

In August 2012 several of the green roofs dried out. This was due to relatively dry and warm spring and summer with higher than average temperatures. Already in the end of April, temperature occasionally reached 30 °C. In order to stimulate the growth, the roofs were fertilized and irrigated in early autumn 2012. No additional plants were added, so we can assume that the mixture of the sedum species was similar for both years (2012 and 2013). With the exception of this singular intervention, all green roofs were not fertilized or irrigated again during the study period. Fig. 3 shows the difference in appearance between a dry and a well prospering green roof.

To evaluate the thermal behavior of a wilted and a dried out green roof, a comparison was made between 15 and 31 August 2012 and 15–31 August 2013. Those two periods were chosen because of their similar weather patterns. They were both relatively sunny/warm months with small amounts of rainfall and few rainstorms. Average 2 m temperature was 1 °C higher in 2012 than in 2013 (19.0 vs. 20.1 °C). Correspondingly, the surface temperature of the gravel was also 1 °C warmer in 2012. Soil moisture showed higher variability during the dry year (values between 0 and 0.28 m^3m^{-3}) than during the well prospering year (values between 0 and 0.18 m^3m^{-3}).

Although both selected seasons had similar weather patterns, a day-to-day variability was still visible. We dealt with this variability in weather conditions in three ways: (1) we chose the same 15 days of the two years to minimize the influence of different sunrise and sunset times. (2) we only looked at the differences between the green roof and the white gravel roof temperature. No analysis was done with absolute values of the temperature measurements. The assumption was that even though the instantaneous temperature varied in time, the difference in the instantaneous temperature

Fig. 3. Well prospering (top) and dry (bottom) green roof.

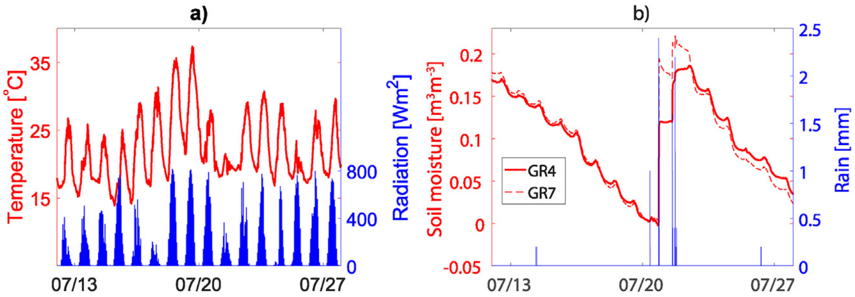

Fig. 2. a) Air temperature 2 m above the roof and incoming shortwave radiation, and b) soil moisture and rain during the study period.

measured above two spots, within proximity as not to experience different weather conditions, was dependent on the differences in the local conditions, such as albedo, exposure to radiation, proximity to source of evaporation, etc. Lastly (3), we averaged the differences for each hour of the day over the whole 15 day period for both 2012 and 2013. This way, we were able to analyze the diurnal pattern with smaller influences of a day-to-day or minute-to-minute variability.

The performance of a dry and a well prospering green roofs compared to a conventional white gravel roof was analyzed using data from the same two green roofs (GR4 and GR7) used to analyze influence of soil moisture (sections 2.1 and 3.1).

3. Results

3.1. Influence of soil moisture

In general, some similarities were found in the behavior of the soil and the air temperature in and above the green roofs and the white gravel roof independently on the initial soil moisture. Clearly, all the day time temperatures were higher than the night time temperatures. Further, all roofs indicated a vertical pattern of $Ts_{\max} > T15_{\max} > T30_{\max}$ in terms of daily maximum temperature despite the difference in a soil moisture content. Soil temperature of the white gravel roof was always the lowest measured temperature at night and the highest during the day. Measured for Ts and T15 for white gravel and GR4 are shown in Fig. 4.

Despite the similarities, the studied green roofs showed differences in their thermal performance depending on the soil moisture and the incoming solar radiation. Differences between green roofs and the white gravel roof ($T_{dif} = T_{GR} - T_{WG}$) were calculated for all the time steps between 00:00 and 06:00 for the night, and 7:30 and 21:30 for the day. These differences were then summed up to one number that represents the cooling power of the green roof during the whole day/night (Fig. 5). If divided by the number of measurements (72 for night and 168 for day for the 5 min time-step) we would get the mean cooling effect. Graphs showing mean values and standard deviations of the differences can be found in the additional material (Fig. 10).

Sum of the differences between soil temperature of the green roofs and the white gravel roof is shown in Fig. 5a) and b). To analyze the thermal behavior of the green roof, the data points can be separated into periods with relatively high soil moisture (HSM), and with relatively low soil moisture (LSM), with a tipping point around 0.12 m^3m^{-3}.

Differences in soil temperatures (Ts_{dif}) showed opposite behavior for the clear sky and the cloudy scenarios. At night, low soil moisture showed to be beneficial under clear sky conditions, while under cloudy conditions green roofs exhibited relatively high differences between green roofs and the white gravel. Interestingly, the same situation was found for high soil moisture. Average soil moisture, with values around 0.12 m^3m^{-3}, resulted in relatively low values of Ts_{dif} under cloudy conditions and vice versa.

Differences in air temperatures 15 cm above the roof ($T15_{dif}$, Fig. 5c) and d)) were generally negative at night and positive during the day, unlike Ts_{dif}. During clear sky nights, $T15_{dif}$ mirrored the concave behavior of Ts_{dif} for the same period. At 15 cm above the ground, the green roofs showed strongest cooling for the medium levels of the soil moisture. Both HSM and LSM, on the other hand, resulted in near zero cooling. High soil moisture levels were similarly non-beneficial during cloudy nights. $T15_{dif}$ showed average cooling lower than 0.2 °C for all three HSM days. For cloudy conditions, the cooling effect for 15 cm measurements got stronger with dropping soil moisture. The lowest soil moisture level analyzed during a cloudy night reached only 0.07 m^3m^{-3}. Due to the lack of lower soil moisture measurements we can not be sure that the overall dynamics were not the same as for the clear sky, but then just shifted.

During a daytime, $T15_{dif}$ showed opposite behavior under cloudy and clear sky conditions. During sunny days, HSM resulted in larger positive differences between green roof and white gravel than LSM. For cloudy days the differences reached only up to 0.7 °C on average. For LSM, the air above the green roofs was during cloudy days warmer than above white gravel. On the other hand, $T15_{dif}$ showed values close to zero on sunny days. Interestingly, the thermal behavior changed abruptly around the values of 0.12 m^3m^{-3} for both cloudy and clear sky conditions, as if a wilting point was reached.

$T30_{dif}$ showed a similar pattern as $T30_{dif}$, however, the sums reached ca. three times lower values (results not shown). During a day, the sum of the differences stayed positive for all examined days. At night, $T30_{dif}$ showed average values between −0.2 and 0.2 °C with highest positive values during cloudy nights with LSM and strongest cooling for average moisture and clear sky.

Net effect can be calculated by summing up the day time and night time temperature differences. For $T15_{dif}$ the total sum reached

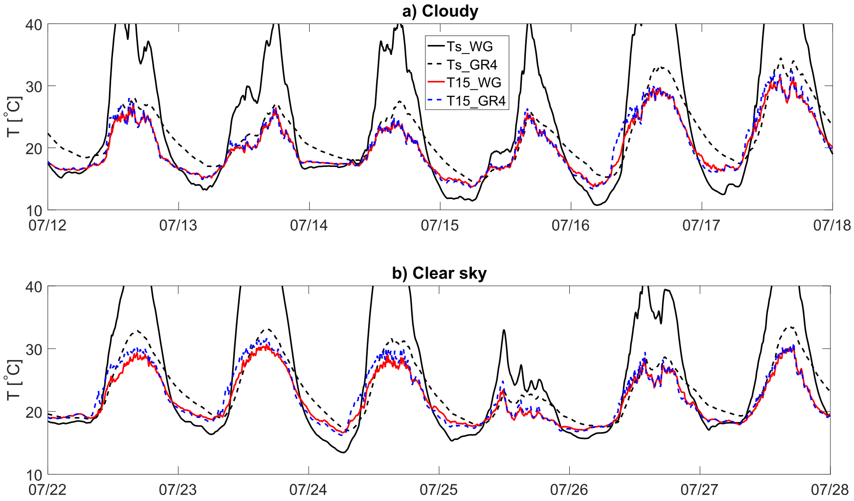

Fig. 4. Measured values of soil temperature (Ts) and temperature 15 cm above the roof (T15) for green roof (GR4) and white gravel roof (WG) for the two examined periods. Maximum values of Ts_WG reached 56 °C (17 July) and are not shown in the figure.

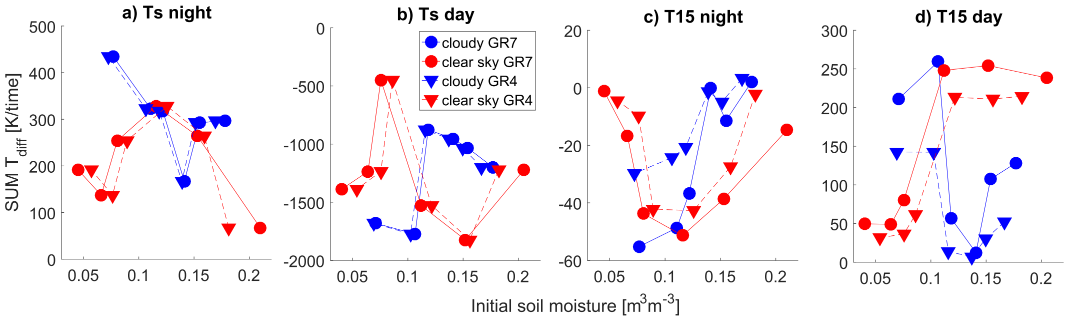

Fig. 5. Influence of the initial soil moisture on the temperature change. Each point represents the sum of the temperature differences ($T_{dif} = T_{GR} - T_{WG}$) for the whole night/day with respect to initial soil moisture. Please note, the vertical scale is different for each figure.).

values between 0 and 120 °C/24 h. This shows that the net effect of this sedum covered green roof was warming the outdoor environment. Net temperature of the soil was colder than of the white gravel, despite higher temperatures at night.

3.2. *Prospering vs. dry green roof*

Results from 2012 showed effects of the unmaintained green roof that, due to unfavorable weather conditions, wilted and died. We compared observed temperature differences ($T_{dif} = T_{GR} - T_{WG}$) from August 2012 to August 2013. Fig. 6 shows averages of temperature difference between green roof and white gravel roof for each hour of the day, starting with midnight, for the three measured levels. Extra figures containing median values and percentiles (Figs. 7 and 8), average absolute values (Fig. 9), and a table with P-values of Kolmogorov–Smirnov test (Table 2) can be found in additional material.

Fig. 6a) and d) show the diurnal pattern 30 cm above dry (red) and well prospering (blue) green roofs. At this level above the roofs, there was hardly any temperature difference between green roof and white gravel (T_{dif}), especially for the dry green roofs. At this level, well prospering GR4 still showed a slight warming effect during the day with highest average value reaching 0.5 °C in the morning. This morning peak was also slightly visible in the data from the dry year. For the rest of the day and night, average hourly value of T_{dif} at T30 stayed under ±0.2 °C.

The diurnal pattern of T_{dif} 15 cm above roof surface (Fig. 6b) and e) differed between both years. While dry green roofs showed very small differences with white gravel at night, well prospering green roofs showed temperatures lower than white gravel. This cooling was mostly between 0 °C and 0.5 °C. During the day (8:00–19:00), T_{dif} of the well prospering green roofs reached positive values, meaning the green roof was warmer than the white gravel. Around 19:00, average T_{dif} dropped to 0 °C and the cooling effect of well prospering green roofs was again visible after sunset. A positive peak in T_{dif} during morning hours above dry green roof had an earlier onset, but also diminished faster. Around noon, dry green roofs seemed to already have a similar temperature as the white gravel and during the afternoon (14:00–17:00) dry green roofs were even slightly colder than white gravel.

Diurnal pattern of T_{dif} of the soil temperature (Fig. 6c) and f) was almost identical for the well prospering and the dry green roofs. Small differences were visible in magnitude of the cooling and warming effect of the two scenarios and between the two green

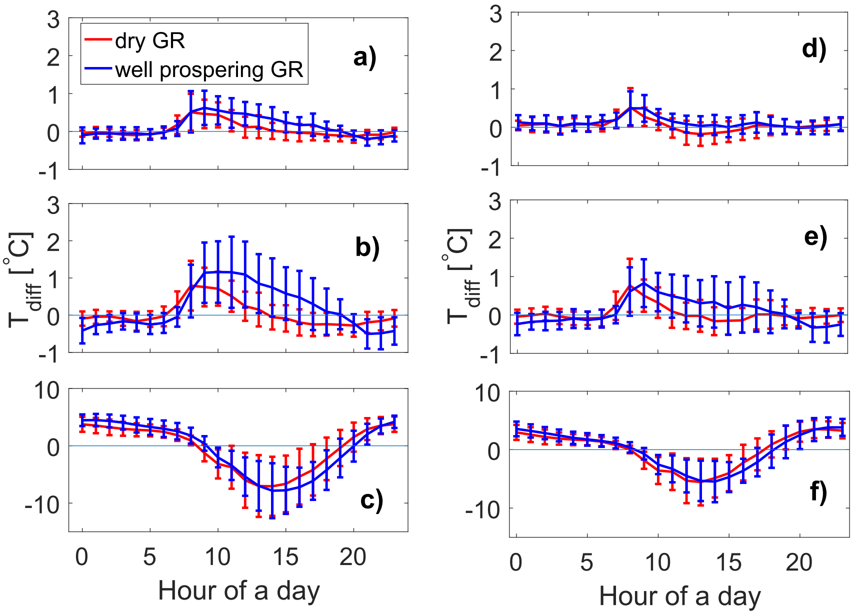

Fig. 6. Averages and standard deviations for each hour of the day for temperature difference (T_GR – T_WG) 30 cm above the roof surface (a) and (d), 15 cm above the roof surface (b) and (e), and in the soil (c) and (f) for well prospering green roof (blue, Aug 2013) and dried out green roof (red, Aug 2012). Left column (a,b, and c) represents measurements for GR4 and right column (d,e, and f) for GR7.

roofs. During morning and early afternoon we observed an upward shift in values of the well prospering green roof compared to the dry green roof. This shift was equalized around noon (12:00–14:00). During the afternoon and early evening (14:00–21:00), the well prospering green roof was colder than the dry green roof (differences up to 1 °C). Although the nocturnal cooling effect of the green roof was reduced when the vegetation wilted, the dry layer of substrate with dead vegetation on top had a lower surface temperature than the white gravel roof.

4. Discussion

The largest differences in temperature were measured in the soil between extensive sedum-covered green roofs and white gravel. This corresponds with previous research indicating that green roofs have a lower temperature than traditional white gravel roofs, e.g. Refs. [10,31,32]. However, surfaces of the green roofs were not colder during the entire 24 h period. At night they were generally slightly warmer than the conventional roof. This also corresponds with previous research (e.g. Refs. [22,33,34]).

Data from air temperature measurements suggest that sedum covered green roofs may not always have the cooling effect on the urban environment during daytime, as some modeling studies have predicted [35]. On the contrary, we measured a warming effect of the green roof predominantly during the daytime in comparison to the white gravel roof. The green roofs were especially warm during morning hours when the soil was still warmer or had a similar temperature as the white gravel. With the sun shining on the roof, a lower albedo of the green roofs, together with the special metabolism of sedum, is likely to have caused the air above the green roofs to warm up more than above the white gravel.

Sedum is a CAM (Crassulacean acid metabolism) genus and its species are often used on green roofs in temperate climates, because of their high resistant to drought [36–38]. CAM plants transpire at night, while during daytime are stomata of CAM plants closed to prevent water loss [39]. Thanks to this mechanism, CAM plants are relatively drought resistant, but they do not transpire and consequently decrease the air temperature during daytime, but at night.

The cooling effect of green roofs on the surrounding environment is mostly evident at night. Although the cooling reaches relatively low values (average 0.5 °C), it has been repeatedly measured for situations with optimal soil moisture conditions. The nocturnal cooling effect is lost when the green roofs are dry (yr. 2012), because the plants can no longer transpire. Under the conditions of our testing site, conditions limiting the cooling effect are high soil moisture levels (above 0.12 m^3m^{-3}) combined with cloudy sky. Presence of clouds at night generally increases the incoming long-wave radiation, which decreases the radiative cooling.

The effect of a different initial soil moisture content is visible in both the air and the soil temperature. The tipping point observed around 0.12 m^3m^{-3} can be the result of the low moisture pressure in the substrate ($pF < 4.2$) or the result of plant physiological properties of sedum. As the pF curve of the substrate is unknown, it was not possible to establish why this tipping point occurs.

Higher air temperatures 15 cm above green roofs, compared to 15 cm above white gravel, during the day time are probably caused by lower albedo values and different roughness lengths. The sedum mixture growing on these roofs had mostly a reddish color with bright yellow flowers (albedo 7%). Overall, the green roofs are significantly darker than the predominantly white and gray stones of the gravel. The height of the sedum plants is not uniform, with some of them reaching up to 8 cm during bloom. This height could increase the roughness length of the green roof and hinder the ventilation of the air layer closest to the surface.

Measurements 15 cm above the dry green roofs show some interesting results, i.a. in the afternoon. We can only speculate, why is the air above the dry green roofs colder than above the white gravel in the afternoon. This may have been caused partly by evaporation from the soil. After rainfall, part of the moisture is trapped in the substrate and the drainage layer of the green roof, and evaporates later. For the rest of the day and night, the air temperature above the dry green roof is very close to the temperature above the white gravel. This means that the green roof not only looses its nocturnal cooling effect when the vegetation is dry, but also has a slight heating effect during daytime. Decrease in the nighttime cooling caused by the damaged vegetation was also described by Ref. [25] in Manchester, UK.

Measurements 30 cm above the roof surface show a similar pattern for all years and roof types. It is postulated that at this height, the air layer is already relatively well mixed and the measurements are influenced more by the air advected from the surroundings than by the roof cover type. Although measurements at this height do not provide many interesting insights into the variability of green roof behavior with respect to soil moisture, influence of the roof cover at this level is still evident as, for example, in the morning peak in T_{dif} at T30 described in section 3.2.

Similarities in T_{dif} 30 cm above roof top during both measured years, for the well prospering and the dry green roof analysis, support our methodology regarding the variability in weather conditions. Assuming measurements 30 cm above the roof top are mostly influenced by surrounding areas and general weather patterns, minimal differences between T_{dif} in 2012 and 2013 suggest that the influence of diurnal temperature variability is small.

Several possible challenges need to be taken into account. Our analysis is based on comparing different days and years. When we compare several days with different initial soil moisture level, instantaneous weather conditions may still influence the result. Although the data are separated over two scenarios according to incoming radiation and normalized for air temperature differences, wind speed and relative humidity might also play a role in the thermal behavior of green roofs. Similarly, the results for dry vs. well prospering green roofs can still be influenced by a different number of sun hours (116.6 for given period in 2012 and 107.3 in 2013 [40]), different amount and distribution of precipitation, and slightly different sedum development and composition.

As mentioned in the Methods section, there are inter-field variations in vegetation coverage. These differences in plant composition may affect soil temperature, surface temperature, and, consequently, air temperature above the green roof. Since there is only one measurement location per green roof, the variations are not measured. However, the variability is partly represented in the differences between GR4 and GR7. It is visible from Figs. 5 and 6 that both roofs exhibit slightly different magnitudes in terms of the cooling/warming effect. Nonetheless, the general pattern of the temperature differences, or their sums, stay the same for both examined green roofs. Similarly, although data for GR2, GR3, GR5, GR6, and GR8 are not shown in this article, the general pattern of diurnal behavior and temperature differences with white gravel were consistent for all the monitored roofs.

Further research is needed in order to fully understand the influence of spatial variability of vegetation. Several measurement points equally distributed over each green roof can contribute to the understanding of the complex system of unmaintained sedum-covered green roofs. Additionally, the effect of surrounding areas on the measurements should be studied more in depth. Although the measurement points were positioned in the middle of the field in order to minimize the effect of surrounding areas, the results suggest that measurements 30 cm above the ground experience strong influence of surrounding areas.

5. Conclusion

We examined the influence of sedum-covered green roofs on the air temperature 15 and 30 cm above the green roofs. Two green roofs were compared with a conventional white gravel roof under different soil moisture scenarios, and under extreme water stress. Our results support other studies showing that, under normal conditions, the sedum-covered green roof exhibits a slight warming effect on its surrounding during the day, and cools down the immediate environment at night. The nighttime cooling effect was, however, weaker than daytime warming, which resulted in a net warming effect of the green roof on the surrounding environment over the whole 24 h period.

Under the conditions of our site, the cooling effect of extensive green roofs on the outdoor environment, as often claimed in landscaping literature, was not confirmed for day time as compared to a white gravel roof, and was shown to be limited at night time. This was most likely because of the predominantly CAM type plants growing on the monitored green roofs. Consequently, CAM plants, more specifically sedum, might not be the best choice for a green roof, when aiming to mitigate higher daytime air temperatures during a summer. Further research is needed in order to better understand the influence of spatial variability of green roofs on air temperature.

Our research further suggests that availability of water in the substrate plays an important role in the cooling behavior of the vegetation. The effect of soil moisture showed different patterns for cloudy and sunny days. These patterns need to be further verified over longer periods and including more detailed analysis of meteorological variables.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2016.10.021.

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