International Journal of Environment and Sustainable Development

ISSN online: 1478-7466 - ISSN print: 1474-6778
https://www.inderscience.com/ijesd

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DOI: 10.1504/IJESD.2022.10050060

Article History:

Received:	12 September 2019
Last revised:	21 July 2020
Accepted:	26 January 2021
Published online:	11 October 2022

Green and blue infrastructure: means of reducing surface temperatures in the urban environment

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Abstract: Climate change may accelerate the urban heat island (UHI) effect with many consequences for the well-being of human populations in cities. Green and blue infrastructures (GBI) are presented as a way to mitigate the UHI effect. In our study, the influence of GBI (primarily less studied types) on surface temperature (ST) was tested using a thermal camera. Various types of GBI (e.g., tree shade and lawn) and their combination were compared. The studied GBI, including less common forms such as containers with ornamental plants, green roofs and fountains, reduced daytime ST. Moreover, they reduced the thermal amplitudes of surrounding areas (up to 30 m). The results imply that besides larger GBI (e.g., parks, rivers) smaller structures may significantly decrease the UHI effect. We recommend a combination of both blue and green structures especially in street canyons and the use of green roofs and walls when the space for adding GBI is limited.

Keywords: surface temperature; urban climate; microclimate; urban heat island; UHI; green infrastructure; blue infrastructure; greenery; vegetation; green roof; green wall; fountain; well-being; tree shade; climate change; thermal amplitudes.

Reference to this paper should be made as follows: Sedláček, J., Hais, M. and Pouchová, K. (2022) 'Green and blue infrastructure: means of reducing surface temperatures in the urban environment', *Int. J. Environment and Sustainable Development*, Vol. 21, No. 4, pp.388–406.

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1 Introduction

Cities containing a lack of water and greenery generally tend to have higher temperatures and thermal amplitudes. This phenomenon is known as the urban heat island (UHI) effect. The significance of this effect rises with increasing city area, population, and the rate of impervious surfaces (Jiang and Tian, 2010; Pal and Ziaul, 2017). The typical UHI profile shows a negative relationship between temperature and the amount of greenery along the rural-urban gradient, as described in many cities (Carlan et al., 2020; Foissard et al., 2019; Estoque et al., 2017). The UHI effect can be observed using air and surface temperatures (STs); the latter tend to be even more significant (because the thermal amplitudes of surfaces tend to be higher than those of air bodies), with differences reaching 7–12°C (Voogt and Oke, 2003; Yang et al., 2015). The intensity of the UHI effect in a city also differs diurnaly and annualy, it increases after the maximum incoming solar radiation of the day (2–4 PM) (Yang et al., 2015) and in the summer months with maximum temperatures (Peng et al., 2016). Moreover, the greatest rise in ST has been measured in the hours immediately after the highest solar altitude (Gallo et al., 2011). Generally, the UHI effect is not necessarily only negative. For example, this effect can save energy used for heating in colder climates (Taha et al., 1988). However, within temperate, subtropical, and tropical climate areas, the prevailing negative effects of the UHI (thermal discomfort, higher energy consumption for cooling, and air quality degradation, to name but a few) have increased public interest in the development of UHI mitigation strategies (Yang et al., 2015).

The main cause of the UHI effect is the lack of water and vegetation in cities compared to the surrounding rural landscape. Within landscapes with ample vegetation saturated by water, evapotranspiration transforms solar radiation into latent heat and, therefore, decreases the Bowen ratio (Daramola and Balogun, 2019; Yoshino, 1975; Pokorný, 2001). This causes lower diurnal and annual temperature amplitudes and, above all, lower temperatures in summer days (Hesslerová et al., 2013; Jo et al., 2001; Tiangco et al., 2008; Vorovencii, 2014; Xu et al., 2010; Brom et al., 2012). Thus, any land cover change tends to influence the local - regional climate. Any increase in plant biomass results in a gradual rise in transpiration and a more stable microclimate with reduced summer temperature peaks (Li et al., 2012). On the other hand, any natural or human disturbance leading to drainage or vegetation removal causes microclimate destabilisation and an increase in summer STs (Brom et al., 2012; Dong-Hoon and Kyoo-Seock, 2005; Sader, 1986).

The most oftenly discussed means of mitigating the UHI effect is the use of green and blue infrastructure (GBI) (Broadbent et al., 2019). A huge number of authors agree that green areas or water bodies inside a city tend to have lower temperatures compared to large impervious areas, especially on summer days (Gluch et al., 2006; Peng et al., 2016; Xu et al., 2010; etc.). Moreover, GBI decrease temperature via evapotranspiration solely when it is needed (primarily on summer days) while this process is not undergone to any great extent in winter (Susca et al., 2011). There is an ongoing discussion about the most effective form of GBI. Although Armson et al. (2012) think that a lot of smaller green patches are the most efficient cooling pattern, other authors (Doick et al., 2014; Li et al., 2012) prefer one larger single park. The same discussion is aimed at blue structures. For instance, Theeuwes et al. (2013) compared the stronger effect of one large lake versus several smaller lakes with smaller effect, but influencing more area.

There are a number of types of green structures within cities; the two main types being grassy patches and trees. Both of them can reduce the ST rapidly, although the latter seem to be even more efficient due to shading and the better water acquisition (due to longer roots) of trees (Armson et al., 2012; Shashua-Bar et al., 2009; Yu et al., 2020). Other green structures include green roofs, i.e., roofs covered with soil and vegetation (Feitossa and Wilkinson, 2020; Niachou et al., 2001), or green walls, which are walls overgrown by creeping plants (Wong et al., 2009). In addition, not only the type of structure, but also its particular location is an important factor in the cooling effect. For instance, the temperature of tree canopies is lower in parks than in streets due to reflection from man-made surfaces in the latter and the more intensive ambient radiation it causes at the same or even lower soil water content (Leuzinger et al., 2010). Less is known about the effect of blue structures in cities in comparison to green ones. However, existing studies agree that water bodies within a city are able to decrease thermal amplitudes and improve the thermal comfort of the inhabitants (Gunawardena et al., 2017; Theeuwes et al., 2013; Xu et al., 2010; Wu et al., 2019).

Although the UHI effect and the influence of GBI is well-known, there are a lack of studies focusing on particular topics, such as the effect of less usual structures (green walls) or the influence of smaller green (smaller groups of trees, containers with plants) and blue (fountains) patches on their immediate surroundings. Moreover, there are some inconsistencies between the conclusions of different studies, e.g., about whether vegetation has a cooling (Geletič et al., 2020; Rafiee et al., 2016; Saaroni et al., 2000; Upmanis et al., 1998) or warming (Schrijvers et al., 2015) potential during the night in comparison to surrounding surfaces.

Therefore, the objective of this study is not only to show the effect of GBI under the conditions found in Central-European cities, but also to answer the following questions:

- How does the ST of green structures reflect the diurnal cycle? Does the lower temperature of the canopies (compared to non-green surfaces) remain at night, or do the non-green structures also cool down?
- Which of the smaller green and blue structures or their combination has the highest cooling effect?
- Which structure has the lower ST during summer days: an illuminated lawn, or a shaded impervious surface? (In other words, which mechanism connected with the green structures has the greater cooling potential – that of tree shade or a lawn?)
- What is the contribution of less studied green and blue structures (green roofs, green walls, containers with ornamental plants, fountains) to the cooling effect in the urban environment?

- What influence do the smaller green and blue structures have on their surroundings? In other words: What is the diurnal thermal response of the 'buffer area' around the structures? Are there any implications (based on these results), which can help decision-makers make these structures as effective as possible?

2 Methodology

2.1 The study area

All data were obtained in the middle-sized city of České Budějovice, Czech Republic (48°59'N 14°28'E), population 94,000. The altitude of the city is roughly 380 m. The annual average temperature reaches 8.3ºC, the mean temperature is –1.9ºC in January and 18ºC in July ('Climate data for cities worldwide', https://en.climate-data.org/).

Several representative areas inside the city were chosen where either the impervious surfaces can be compared to green and/or blue structures or the effect of these structures on their surroundings can be studied. All of the chosen streets have the same azimuth and the heights of the buildings are nearly the same, and so gain the same amount of solar radiation over any given time period (Nuněz and Oke, 1977; Pierce et al., 2005).

The descriptions of the study locations can be found in Table 1. Their position and photographs of them can be seen in Figure 1 and Figure 2, respectively.

Table 1 Description of the study objects

	Name of the place	*Description of the place*		*Study objects*
1	The Black Tower	Two west-east oriented streets with comparable dimensions; the northern one without any vegetation while the southern one contains a few lime (*Tilia* sp.) trees whose canopies cover almost all of the street surface. Between the two streets, there is a building whose roof begins directly near the tree canopies.	a	24-hour surface temperature curves of trees, roof tiles and granite pavement in the street without any greenery.
			b	Daytime and nighttime temperature gradients on the roof with increasing distance from the trees.
2	Přemysl Otakar II. square (POS)	The main city square which is almost 100% covered by impervious surfaces. The only vegetation located on this square are containers with ornamental plants (commonly grown species, such as *Pelargonium*). Moreover, there is a fountain in the centre of the square.	a	Comparison of the temperature of a blue structure (fountain), a green structure (plants in container) and pavement.
			b	Thermal gradients from the fountain to different directions (north, east, south)
3	Lannova street (LS)	A west-east oriented street with a blue structure made of several small fountains and a green structure consisting of a few smaller trees (*Prunus* sp.).		Thermal Comparison of the blue structure (fountain), green structure (tree canopy) and illuminated pavement.

Table 1 Description of the study objects (continued)

Name of the place		*Description of the place*	*Study objects*
4	Green roof	A roof consisting of 2 parts: The ‘green’ part covered by soil and xerophytic plants and the ‘non-green’ part whose top part consists of a layer of gravel.	Comparison of the green and non-green parts of the roof.
5	Green wall	A house whose eastern side is particularly covered by European ivy (*Hedera helix*).	Comparison of the green and non-green parts of the wall.
6	The Vltava estate	A place which contains both green and blue structures: The former is represented by a few younger deciduous trees (*Acer* sp.) and some grassy patches, while the latter consists of a fountain which appears as a short man-made stream.	a Comparison of the temperature of water, concrete edge of the fountain and granite pavement outside the edge. b Comparison of the temperature of illuminated pavement/shaded pavement/illuminated grass/shaded grass.

Figure 1 The study area (see online version for colours)

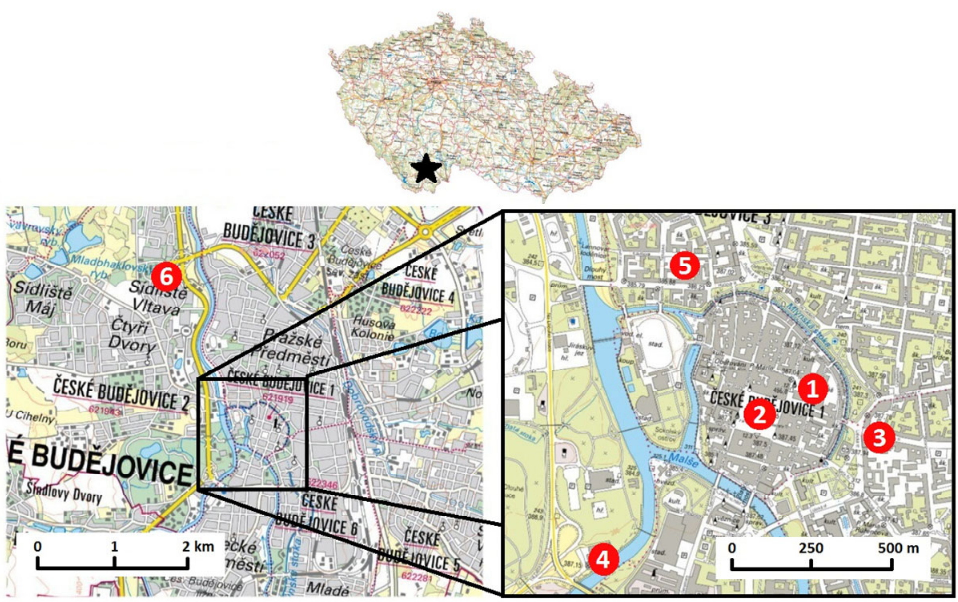


Figure 2 Photos of the studied structures (see online version for colours)

2.2 Data acquisition

All of the data for this study were acquired during the period from June to October 2018.

In this study, a Workswell Wiris 2nd thermal camera was used to measure the ST. The resolution is 640 × 512 pixels, sensitivity 30 mK, and precision ± 2% or ± 2°C. This camera takes a thermal image as well as RGB pictures at the same time. For the Black Tower location, the camera was stationary and the images were made at 15-minute intervals in the defined time period. For the other locations ambulant measurements were taken, in which images were made by pushing a trigger. In Table 2, information is given about the time when the data were obtained and the meteorological conditions at those times (‘Climate data for cities worldwide’, https://en.climate-data.org/).

Table 2 Maximum temperatures in the days of measuring

Study place	*Date of measuring*	*The maximum daily air temperature*
The Black tower	18.6.2018	25°C
The P. O. II. Square; part a: comparison	13.7.2018	26.4°C
The P. O. II. Square; part b: gradients	16.9.2018	22.8°C
The Lannova street	13.7.2018	26.4°C
The green roof	16.10.2018	21.2°C
The green wall	17.10.2018	19.1°C
The Vltava estate	13.7.2018	26.4°C

Thermal measurement in the urban environment is limited by the properties of particular locations in which the camera is installed. First, the camera should have an appropriate viewpoint to capture all of the objects of interest (buildings, vegetation, etc.). For this purpose, towers and high buildings are suitable, because of the high angle of data acquisition. However, such a place needs to be protected from adverse weather conditions (e.g., rain, high solar radiation exposure of the thermometer device) and human activities.

2.3 Data processing

The processing of the raw thermal images was carried out as follows. First, ThermoFormat software was used to correct the temperature values caused by the different emissivity of each surface. The used emissivities are summarised in Table 3 (Rubio et al., 1997; 'Emissivity values of common materials', http://support.fluke.com/find-sales/Download/Asset/3038318_6251_ENG_A_W.PDF; 'IR thermometers & emissivity metal emissivity table', http://www.energytek.com.tw/download_s.php?ds=27; Table of emissivity of various surfaces for infrared thermometry, http://www-eng.lbl.gov/~dw/projects/DW4229_LHC_detector_analysis/calculations/emissivity2.pdf).

Table 3 Emissivities used in this study

Material	*Emissivity*	*Material*	*Emissivity*
Concrete	0.75	Vegetation	0.98
Gravel	0.76	Xerophytes	0.94
Roof tiles	0.51	Water	0.97
Granite	0.45	Basalt	0.72
Plaster	0.91		

Second, the CSV data (calculated using ThermoFormat) were converted to ASC files, which were projected in ArcGIS. Next, either a number of reference points were randomly chosen from every compared surface (while comparing the temperature of a number of surfaces) or a line of points at defined intervals was created (when a thermal gradient was studied). Next, the raster values were extracted to the points. Finally, the values of the points were exported to a table and processed in Statistica. T-tests were used in order to determine the difference between the green/blue structures and conventional materials. The results were projected either to box-whisker plots or to charts which show the thermal gradients of the green/blue structures.

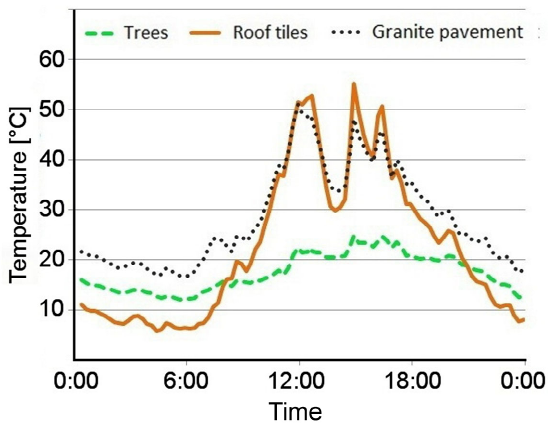
3 Results and discussion

3.1 Tree canopies

ST represents an integrated value of surface properties (e.g., reflectance, emissivity) and/or functional processes of solar energy transformation. The most important natural medium is water due to its high temperature capacity, the presence of which results in lower afternoon temperature maxima and lower diurnal temperature amplitudes in comparison to other materials (Li and Becker, 1990).

The 24-hour curves of average STs of the three types of objects in the study are presented in Figure 3. Tree canopies had the lowest thermal amplitudes as well as the lowest maximum temperatures (ca. 25°C, which was also the maximum air temperature) while both the roof tiles and the granite pavements reached values over 50°C during maximum insolation. This result confirms the cooling and buffering effect of vegetation described in many studies (Estoque et al., 2017; Leuzinger et al., 2010; Li et al., 2012; etc.). Conversely, Geletič et al. (2020) suggested that trees inside a Czech city can have a slight warming effect during the daytime. However, that study was aimed at air temperature and the results were based on a mere model. Thus, the influence of adding more trees on city air temperature should be a study object of further research. During a short overcast period (ca. 14:00), the difference between green and non-green surfaces remained, although it became less significant than under sunny conditions. A similar result was observed by Gallo et al. (2011).

Figure 3 Comparison of ST of trees, roof tiles and granite pavement (see online version for colours)



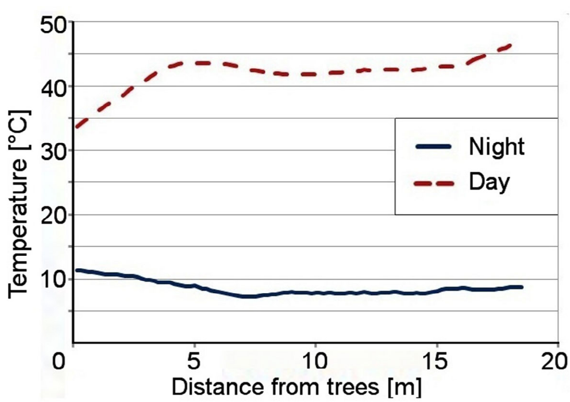
When comparing the ST of granite and canopy, the granite ST was higher not only during the daytime (up to 30°C), but also at night (5°C) which is similar to the results of Upmanis et al. (1998) who detected lower nocturnal temperatures for city vegetation compared to surrounding areas. In contrast, in this study, the temperature of roof tiles decreased in the evening hours even to a level below those of the tree canopies (the canopies stayed ca. 5°C warmer) and, thus, the roof tiles had a higher thermal amplitude in comparison to both of the other two surfaces. The difference between the nighttime thermal curves of the roof tiles and granite pavements might be caused by the canyon effect of the street (Nuněz and Oke, 1977). Compared to roofs, the longwave radiation from pavements to the sky is reduced due to the surrounding buildings, which trap part of the photons emitted by granite. Therefore, the temperature of the buildings, as well as the longwave radiation from them, increases and, consequently, pavements and buildings tend to warm each other. On the other hand, roofs are naturally located higher than granite pavements and there are usually no buildings or other structures above them . Thus, the prevailing part of the photons emitted by roofs leave the city surfaces and do not return. However, some studies (Geletič et al., 2020; Schrijvers et al., 2015) have suggested that the lower parts of street canyons could become colder compared to their surroundings during night time due to their decreased insulation and energy income during the day, which is a greater effect than the increased long-wave trapping effect. The difference between the results of that and this study was probably caused by the fact that this study was conducted in June, when the sun's elevation reaches its maximum values, so the solar radiation income during the day was enough to maintain increased ST during the night. Moreover, not only direct radiation, but also reflected radiation from the light-coloured wall surfaces of buildings in the street can increase ST (Maharoof et al., 2020; Nuněz and Oke, 1977).

Along with the shape of street canyons compared to roofed areas, the higher temperature of pavements might also be caused by the different structure and thermal response of the materials from which they are constructed. Roof tiles are used to insulate building and, thus, are not able to store a large amount of heat, while granite pavements are efficient heat storage bodies due to their thickness and greater heat conductivity (Pezeshki et al., 2018), and so are able to emit stored heat during the night time. This phenomenon has also been detected in asphalt pavement (Hesslerová et al., 2013), with the asphalt showing higher nocturnal temperatures compared to surrounding vegetation.

These results imply that street canyons have a significant potential to thermal stress for inhabitants. Moreover, the N-S oriented streets tend to reach even higher temperatures than the W-E oriented ones (Maharoof et al., 2020).

Roof surfaces were not thermally homogenous; those parts located near tree canopies were influenced by them during both the day and night (Figure 4). The canopies decreased the temperature of the roof tiles during the day. The difference between the edge of the roof (which is located near the trees) and the central part of the roof reached up to 10°C. The cooling effect lessened with increasing distance from the canopies. On the other hand, the canopies had a warming influence on the roof during the nighttime. The temperature of the tiles near the trees did not fall as much as ones more distant, with the difference reaching up to 4°C. For both the daytime and nighttime measurements, this effect was almost linear within the closest 5 and 7 metres from the trees, respectively, while it was not significant outside this closer part.

Figure 4 The buffering effect of tree canopies on the roof tiles ST (see online version for colours)

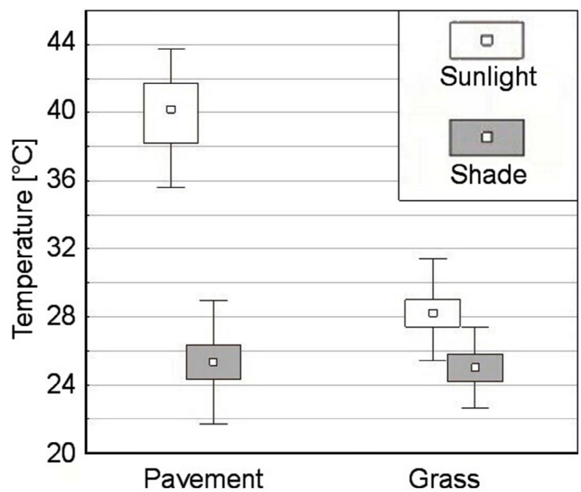


These results show that the canopies were characterised not solely by lower thermal amplitudes compared to non-green surfaces, but also by the buffering effect on their surroundings. This effect is known at the whole-city scale (e.g., Upmanis et al., 1998), but it is less known on the one-street scale. As the temperature of leaves is higher compared to tiles in the nighttime, while lower during the daytime, it influences the nearby non-green structures due to heat radiation from the warmer surfaces to the colder ones.

3.2 Comparison of grass and shade

As can be seen in Figure 5, both shade and grassy patches rapidly reduced ST. Moreover, the combination of both factors caused an even sharper temperature drop than any of them singly, with the decrease being up to 15°C in comparison to illuminated non-green pavement. Each of the structures alone decreased the ST by more than 10°C, although shade alone without grass was slightly more effective than illuminated grass. At the lawn location, the illuminated part was still significantly warmer than the shaded one, while within the shaded part there was only a slight difference between the grass and non-green pavement, probably due to lower transpiration in the shaded area (due to lower radiation) and the decreased cooling effect of the grass.

Figure 5 Comparison of the effect of tree shade and grass



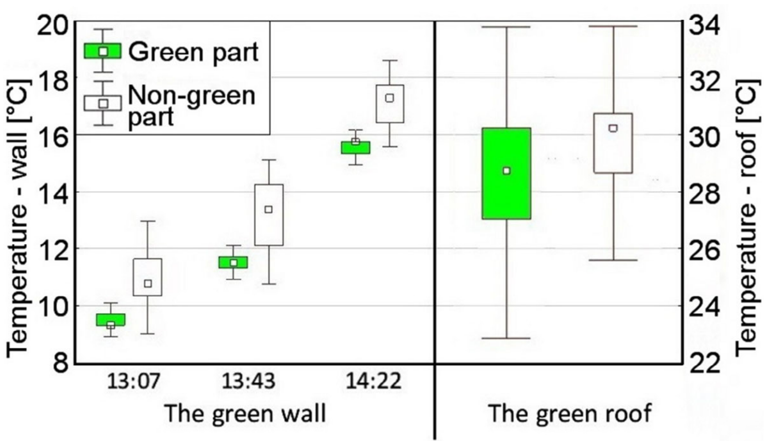
These results correspond in some respects with Armson et al. (2012) who reported that both grass and tree shade tend to reduce STs. However, according to their study, grass alone was slightly more effective than shade, while the opposite was the case in this study. This difference might be caused by the drier weather conditions in the Czech Republic during the drought in the summer of 2018 compared to the wetter climate in the United Kingdom where their study was made. Drought might have decreased the upper-layer soil water content available for the transpiration of grass and, thus, reduced the cooling potential of the lawn (as described in Makarieva and Gorshkov, 2007), while the trees, having longer roots able to obtain water from deeper soil layers, did not show a significant decline in transpiration. A similar principle was described in the study of Shashua-Bar et al. (2009), who studied the air temperature above green structures in an arid climate. Although grass alone was able to decrease the temperature to a certain extent, tree shade seemed to be more effective. Moreover, in their study, unshaded grass tended to have a higher water requirement than the whole green structure made of both grass and trees. The authors of that study also found that tree shade is more effective for air temperature reduction than the shade of man-made structures. Other studies (Gillner et al., 2015; Yu et al., 2020) have also underlined the role of tree shade.

Therefore, the combination of grassy surface and tree shade seems to be the most effective green structure in mitigating the UHI effect.

3.3 Green roof and green wall

The cooling effect of these structures is summarised in Figure 6. Generally, the green parts of both the wall and the roof were always slightly cooler than the non-green ones. Although the mean temperature of the green part of the roof was only 1.3°C lower compared to the non-green part, the cooling effect was still significant ($p < 10^{-5}$). The xerophytic vegetation was able to reduce the temperature despite the extremely dry weather in the summer of 2018, which probably caused a huge drop in the moisture content of the thin soil layer on the roof. The green wall also showed a slight but significant temperature decrease. European ivy (Hedera helix), although not directly exposed during the data gathering period, reduced the wall temperature by 1–1.5°C in comparison to a non-vegetated adjacent surface. This temperature reduction was comparable to the effectiveness of the green roof during solar radiation.

Figure 6 Thermal comparison of the green and non-green parts of the roof and the wall (see online version for colours)



The variability comparison of the two surfaces showed different results for each type of structure. For the roof, a higher temperature variance was observed in the green part due to small warm patches of bare soil between the vegetation, while for the wall the green part was more homogenous than the non-green due to an almost 100% coverage of European ivy.

The most important difference between the studied green roof and green wall is the connection of the European ivy to the ground and, therefore, its ability to gain water from the soil around the building. On the other hand, the xerophytes growing on the green roof can obtain water solely from the relatively thin layer of soil which comprises the upper part of the roof. Therefore, the green wall should be potentially more effective than the roof due to the water ability constraint on the roof. It can be expected that the difference between the green and non-green parts of the wall would have been much more significant if the wall had been under direct solar radiation.

In order to increase the cooling effect of green roofs, Niachou et al. (2001) suggested using a thicker layer of darker vegetation able to transpire at a higher rate. However, despite the higher effectivity of these plants during wet periods, this vegetation would not be able to transpire or even survive during dry periods (as mentioned by Du et al., 2019) unless the soil layer on the top of the roofs was thick enough, which is not always possible due to constraints in building construction. On the other hand, xerophytic plants, despite their lower transpiration rate and, thus, lower cooling rate, are able to transpire even in extreme drought when other plants are stressed and tend to stop transpiring. Therefore, these plants, such as Sedum sp., seem to be the most useful green roof plants in drier climate areas (Schindler et al., 2019).

Green roofs and walls not only cool roof surfaces, but also mitigate heat accumulation in buildings and, thus, reduce the consequent longwave radiation from them, which should also help reduce nocturnal temperatures in their surroundings. Moreover, these structures will probably positively influence life inside the buildings. As mentioned in other studies (Feitossa and Wilkinson, 2020; Niachou et al., 2001; Wong et al., 2009; etc.), both green roofs and walls are able to reduce energy consumption and increase human well-being.

3.4 Blue structures

The blue structure (a fountain with a short man-made stream) located in the study location showed an even sharper decrease in ST compared to the green structures located in the neighbourhood (Figure 7). There was more than a 25°C difference between the water body and surrounding pavement. Not only was the water colder, but also the concrete edge of the stream was ca. 17°C cooler than the pavement. This might have been influenced to some extent by the lighter colour of the concrete compared to the darker pavement, however, the edge had a lower temperature as well in comparison to the lighter pavement in the vicinity (around the green structures – see Figure 5), the temperature of which was measured almost at the same time. Therefore, the temperature decline might have been caused by the fact that some parts of the edge were sometimes wet due to human recreation in the stream and, thus, the contact of the edge with colder water and subsequent evaporation had a cooling effect on the edge. Another possible cause of the lower edge temperature is the increased longwave radiation from the edge to the water and subsequent heat exchange between these two surfaces, which caused the water and the edge to reach the same thermal equilibrium.

Although this study is not aimed at air temperature and human well-being, it is obvious that the lower temperatures of the water and edge surface (as well as any green structure) also influence the temperature of the air located above these structures. ST is one of the most important predictors of air temperature due to air warming by longwave radiation from the ground (Hesslerová et al., 2013). If the daytime ST is lower, then the longwave radiation also decreases, which reduces air warming. This improves the thermal comfort near water bodies, as described in Xu et al. (2010).

The water body (fountain in POS) had lower temperatures in comparison to impervious surfaces, moreover, it also reduced the temperature of the surrounding pavement which is similar to the effect of large water bodies described by Lin et al. (2020). This influence was dependent on the orientation to the fountain, as shown in Figure 8. The temperature rose to the north and south with increasing distance from the fountain. This corresponds with the results of Wu et al. (2018) where a significant thermal gradient was observed up to 300 m from a large water body.

Figure 7 Comparison of different surfaces within the blue structure

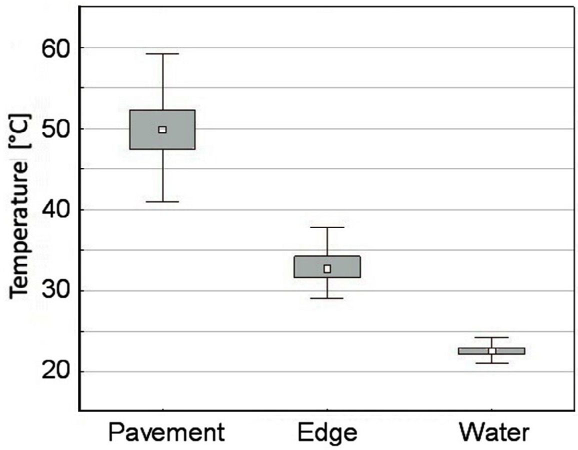
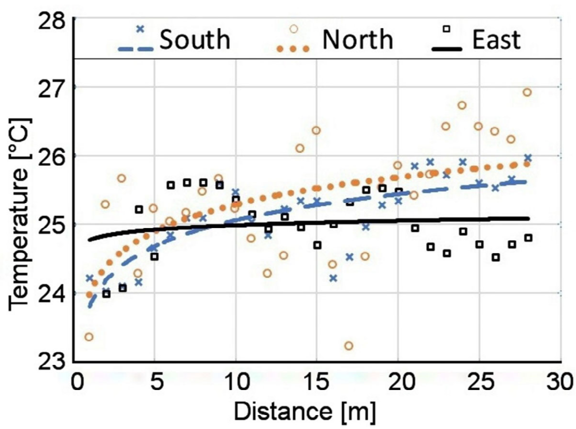


Figure 8 The cooling effect of the fountain depending on directions (see online version for colours)



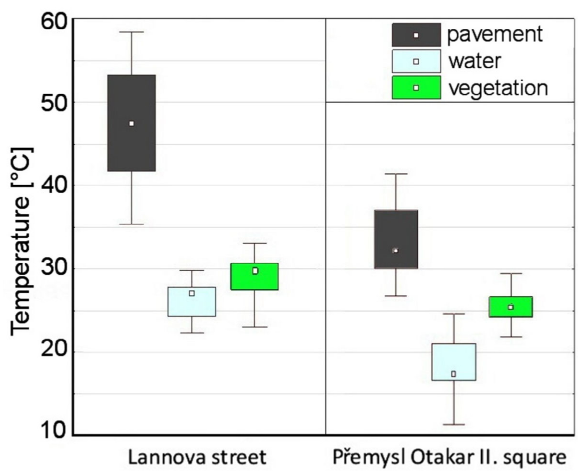
The southern line seemed to be slightly cooler compared to the northern one, probably due to decreased longwave radiation from the shaded walls of buildings on the southern side of the square (although the pavement where the temperature was measured was still illuminated) in comparison to the illuminated walls of buildings on the northern side. This phenomenon should be studied more in further research and, if the results show that this effect is significant, it might be useful to create GBI primarily on the northern side of squares and estates. There was almost no thermal gradient to the east from the fountain with the temperature staying roughly the same to the end of the study area (approx. 30 m distance). This phenomenon may be caused by the prevailing western winds which move the colder air located near the fountain to the eastern part of the square and, thus, reduce the ST of this part of the square. This corresponds with the model by Theeuwes et al.

(2013), which described the plume of colder air that tends to be oriented from the blue structure to its neighbouring area located in the downwind direction.

3.5 Comparison of green and blue structures

The temperatures of the three surfaces (conventional pavement, green structure, and blue structure) for both study locations are summarised in Figure 9. The temperatures of all surfaces were measured exactly at the same time for each location. An exception to this was that there was a ca. 10-minute period between obtaining the data on LS and POS due to the fact that only one thermal camera was available. However, there was no significant weather change during this period, so the thermal characteristics of the locations are comparable.

Figure 9 Comparison of ST of a green structure, a blue structure and pavement (see online version for colours)



Generally, pavement always showed the highest temperature of the three surfaces while water showed the lowest. The higher temperature of the pavement in LS compared to that in POS may be caused by the darker material (higher emissivity), which the pavement is made of compared to the lighter paving used within the square. The water in the fountain located in the centre of POS tend to be roughly 10°C cooler in comparison with the water in the fountains within LS, probably due to the larger (and thus more thermally stable) amount of water on POS along with the direct contact of water with the warmer pavement on LS, which might have warmed the water.

The green structures of POS and LS tended to have significantly lower temperatures in comparison with the pavements. However, for both study locations, the vegetation seemed to be less effective than the water bodies, probably due to constrained transpiration by the soil water content (Makarieva and Gorshkov, 2007). The leaves of young trees (on LS) were slightly warmer than the ornamental plants in containers (in POS), but this might have been caused primarily by the darker pavement on LS which influenced all of the surrounding surfaces. However, the tree canopies tended to be more effective with almost 20°C thermal difference while the plants in containers were only 7°C cooler than the pavement in their surroundings.

This results show that small blue structures tend to have even more significant cooling potential than small green structures and should be preferred in streets and housing estates, where larger trees or water bodies cannot exist.

3.6 Recommendations for decision-makers

There are several managerial implications arising from the results of this study which decision-makers should take into consideration to ensure that the cooling and buffering effect of green and/or blue structures is maximised:

- Trees should be planted not only in parks, but also in as many streets and estates as possible in order to maximise their buffering effect on the surrounding surfaces.
- GBI should be created more in street canyons where there is a huge potential for the thermal stress of inhabitants.
- The importance of tree shade rises with drought; in other words, within areas with wetter climate, lawns are more effective in reducing ST, while in drier areas, tree shade tends to reduce ST more than lawn.
- If there is a place inside the city where trees cannot be grown, even smaller structures such as fountains or containers with ornamental plants should be put there in order to improve human wellbeing.
- Green roofs are useful to reduce the temperature slightly but continually even in extreme dry periods. Green walls, although less used today, seems to be even more effective. Both of these structures tend to reduce the energy consumption of the buildings and improve thermal comfort.
- Green and/or blue structures should be created so that the most frequented streets and squares are located in the downwind direction from them.

4 Conclusions

Green and blue structures inside the city were analysed in order to determine their influence on STs. The results showed that these structures have not only lower thermal amplitudes (and, above all, lower temperatures during insolation) compared to non-green surfaces, but also influence their surroundings. The green structures (tree canopies) showed an almost linear change in the ST of the nearby roof tiles during both the day (cooling effect of the canopies) and night (warming effect); on the other hand, the pavement in the non-green street canyon stayed warmer than the trees during the night due to heat accumulation.

Not only conventional green structures (trees, lawns), but also the less common ones, such as the green roofs and walls and containers with ornamental plants, showed significantly lower ST than non-green surfaces. Blue structures showed even lower ST than green structures. The most significant cooling effect of the main fountain was found in the downwind direction.

A number of recommendations for decision-makers were brought forward to aid in maximising the cooling potential of GBI and reducing the UHI effect.

Acknowledgements

We would like to thank to Milan Novák for adapting the thermal camera for manual data acquisition. Many thanks also to Christopher Steer and Keith Edwards for the language correction.

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