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The impact of surface characteristics on ambient temperature at urban micro scale: comparative field study in two climates

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Abstract

This paper presents the results of two field studies to examine the differences in ambient temperatures in a micro-scale environment (at distances of 50–200 m between measuring points) in two different climates during typical summer weather conditions at two similar sites in terms of construction and activities. The analysis considered the land use around the measuring locations split into three categories (built, green and open) as well as climatic conditions and studied the effect of these on ambient temperature at each measuring location. It was found that, similarly to macro-scale studies at the urban level, measuring locations with a higher green cover have a lower ambient temperature compared with measuring locations with a higher built and/or open land cover. The results provide measured evidence in two different climates that small green areas distributed within the urban environment can provide a reduction in the ambient temperature thus contributing to the mitigation of urban heat island.

Keywords: urban; micro-scale; temperature; green; land cover

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1 INTRODUCTION

The mitigation of urban heat islands (UHI) has been the subject of a growing number of research studies [1]. Mitigation technologies have been developed and guidelines for urban planners and designers have appeared in many countries (for example, [2–4]). Action plans to mitigate UHI include key strategies such as: (a) increasing tree and vegetative cover (b) installing green roofs (c) installing cool—mainly reflective—roofs and (d) using cool pavements, and suggest that their combination can enhance their effectiveness [3].

The impact of surface reflectivity (cool roofs and other surfaces) on ambient conditions has been studied [5] as well as methods for enhancing reflectivity [6] and the impact on the energy demand by buildings [7–11]. The effect of vegetation on the ambient air temperature in urban areas has also been the subject of many research works including tropical climates; Wong and Yu [12] confirmed the cooling effect of green areas at the macro level in Singapore through field measurements, Yokoharu *et al.* [13] presents a study of the effect of paddy fields on the residential areas in Tokyo concluding that the temperature typically increased steadily away from the intersection of the green area with the built area, reaching a steady temperature at somewhere between 100 and 200 m. Ng *et al.* [14] used ENVI-met to study the effect of greenness on air temperature in Hong Kong and concluded that 'for planners and policy makers, it may be stated that "the cooling effect of about 1 K is possible when tree coverage is larger than 1/3 of the total land area"'. Zoulia *et al.* [15] reported measurements during the daytime in Athens, Greece and found that at the micro-scale level, the temperature profile inside a park and the immediate surrounding urban area did not show a clear evidence of the influence of the Park. However, when the air temperature of the Park was compared with locations of the urban fabric in the wider city centre area (macro-scale), the Park was found cooler than the urban locations in particular during the

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night, whereas Watkins and Kolokotroni *et al.* [16] found that in London a small reduction in air temperatures was found during the daytime for locations with a high percentage of greenness.

The above-mentioned findings indicate that the influence of the green area on changes in the ambient temperature is a contextual phenomenon. Further, the urban albedo which indicates the characteristics of the urban surface too is a contextual index. Therefore, there is a need to look at the influence of vegetation and other surface characteristics on changes in the ambient temperature at the micro level. At the same time, comparing similar micro-scale contextual setting in different climatic geography will through some light into the influence of geography on changes in the ambient temperature. The aim of the study is to compare the micro-scale effect of surface characteristics and vegetation cover as well as prevailing weather conditions on the ambient temperature using two similar sites in terms of construction and activities but different climates. Regression analysis is used to explain the impact of green cover and surface characteristics and the results are discussed in the context of prevailing weather conditions.

2 METHODOLOGY

2.1 Study area and measurement protocol

The microclimatic study was conducted in two University Campuses in the city of Uxbridge in United Kingdom (Brunel University), and the city of Cuiabá in Brazil (Federal

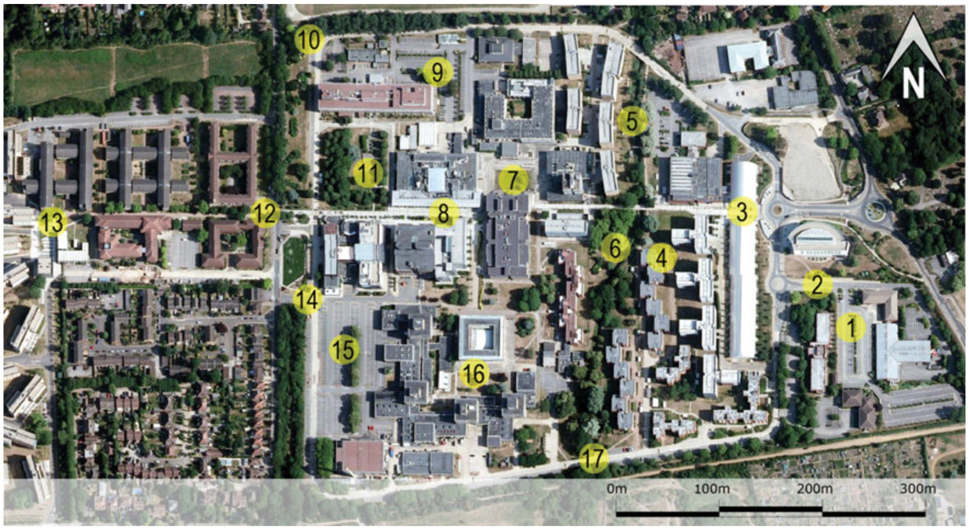

Figure 1. *Map of the Uxbridge case study with measurement points marked (base picture by Google maps).*

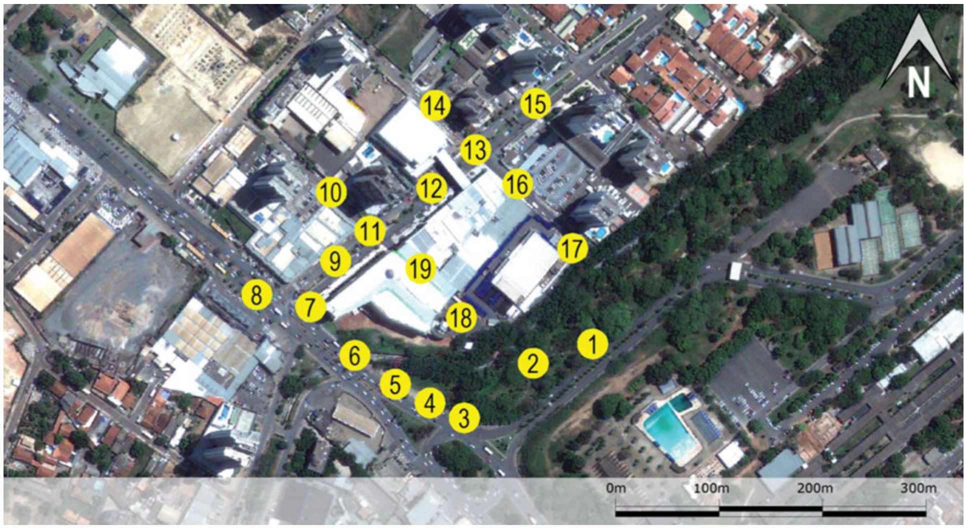

Figure 2. *Map of the Cuiabá case study with measurement points marked (base picture by Google maps).*

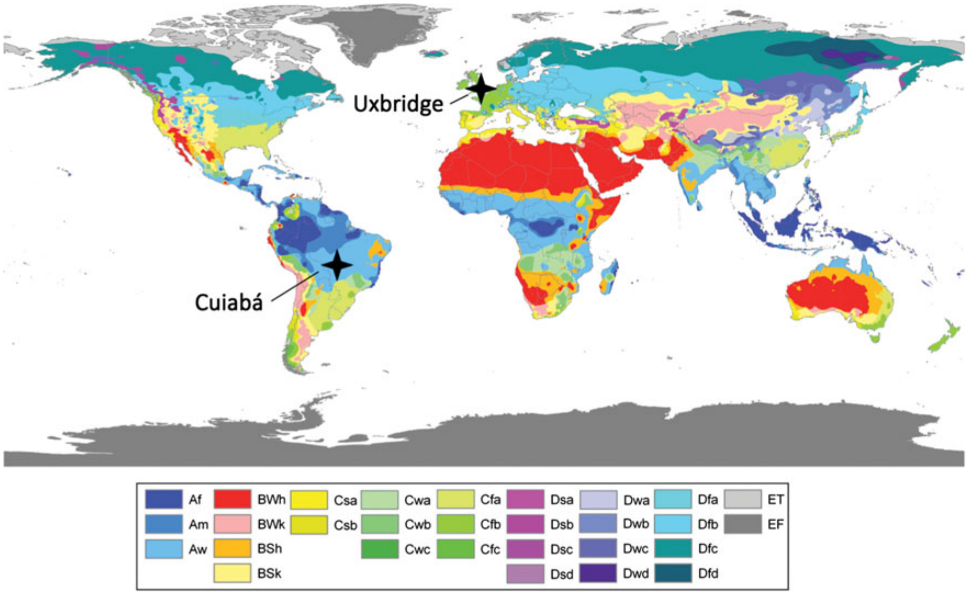

Figure 3. *Position of the two case study areas on a Köppen climate classification world map, (adapted from [24]).*

University of Mato Grosso). Figures 1 and 2 present Google maps of the surveyed areas with the measurement points marked. Both campuses include buildings of similar construction characteristics and are used for similar activities which facilitate the control of the land use variation impact. They are located near an airport; Heathrow in the case of Brunel Campus (at a distance of 6.5 km) and Marechal Rondon in the case of Mato Grosso campus (also at a distance of 6.5 km) from which additional weather variables were utilized. Uxbridge is in the North Hemisphere in a suburban area at the western edge of London [latitude 51°31′58″N, altitude 24 m, Köppen climate classification: (Cfb) Maritime Temperate climates], whereas Cuiabá is located in the Southern Hemisphere in the centre of south America in Brazil (latitude 15°35′56″S, altitude 125 m, Köppen climate classification: (Aw) Tropical wet and dry). The relative location of the two measurement case-studies on a world map is shown in Figure 3.

Cuiabá is known as the hottest city in Brazil. According to the National Institute of Meteorology [17], based on the period of monitoring data collected from 1961 to 1990, the annual average dry bulb temperature in Cuiabá is ~26°C; the lowest recorded temperature was 3.3°C on 18 July 1997 and the highest 43.1°C on 16 October 2009. In general, the highest maximum and minimum average temperatures of the year are observed in October and July, respectively. Cuiabá is an urban area located in a geographic depression zone characterized by low average wind speeds; in average wind speed is <2.0 m/s [18].

Uxbridge is located 20 km west of the centre of London and is characterized by typical south east England weather conditions. It is a suburb of London and its location has been used in previous UHI studies by the authors [19]. As mentioned before, the climate in London is moderate/cold with a diurnal dry bulb temperature range >8°C for two-thirds of the summer (May to September). The average summer dry bulb temperature is 16°C, whereas the summer mean daily maximum temperature is 21.2 [20] and the absolute mean maximum temperature is 31°C. The mean wind speed is 3.5 m/s and at Uxbridge the predominant wind direction is from the South West.

Measurements were carried out at 17 points (Uxbridge) and 19 points (Cuiabá) on different dates at each location. For the UK case study, measurements were carried out during the typical summer season, 20–22 July 2008 with typical external summer design conditions. For the Brazil case study, measurements were carried out during the spring, 26–28 October 2010. The atmospheric conditions of the measurement days are shown in Table 1, whereas Figure 4 presents the cloud cover and wind conditions in more detail. The maximum temperature reached at the meteorological station near Cuiabá was 36°C, whereas the maximum temperature reached at the Meteorological station near Uxbridge was 23°C; minimum temperatures were 11°C in Uxbridge and 22°C in Cuiabá—these conditions are typical of external weather *summer* design conditions for the two locations. Note that although the measurements in the city of Cuiabá have occurred in the spring, this is regarded as typical of external weather summer design conditions. This is due to the city being located in the area defined as Aw (Tropical wet and dry) in the Köppen classification, which has the characteristic of only two seasons: hot dry—from April to September (autumn and winter) and hot wet—from October to March (spring and summer). *The maximum external air temperatures occur in October.*

Relative humidity is higher in Cuiabá than in Uxbridge, wind speed is higher in Uxbridge, while mean hourly solar

Table 1. *Atmospheric conditions of the study days.*

Dates	Air temperature (°C) (min–max)	Humidity (%) (min–max)	Average wind speed (m s^{-1})	Mean solar irradiance 12.00–14.00 (Wm^{-2})
Heathrow				
20 July 2008	12.0–18.0	42–77	4.2	714
21 July 2008	11.0–21.0	40–71	4.1	514
22 July 2008	11.0–23.0	49–77	2.2	502
Marechal Rondon				
26 October 2010	24.0–33.0	41–89	4.0	821
27 October 2010	22.0–36.0	22–73	1.7	801
28 October 2010	23.0–36.0	34–78	2.5	665

Note: Data were sourced from Heathrow and Marechal Rondon airports apart from solar radiation for Uxbridge, which was measured on site.

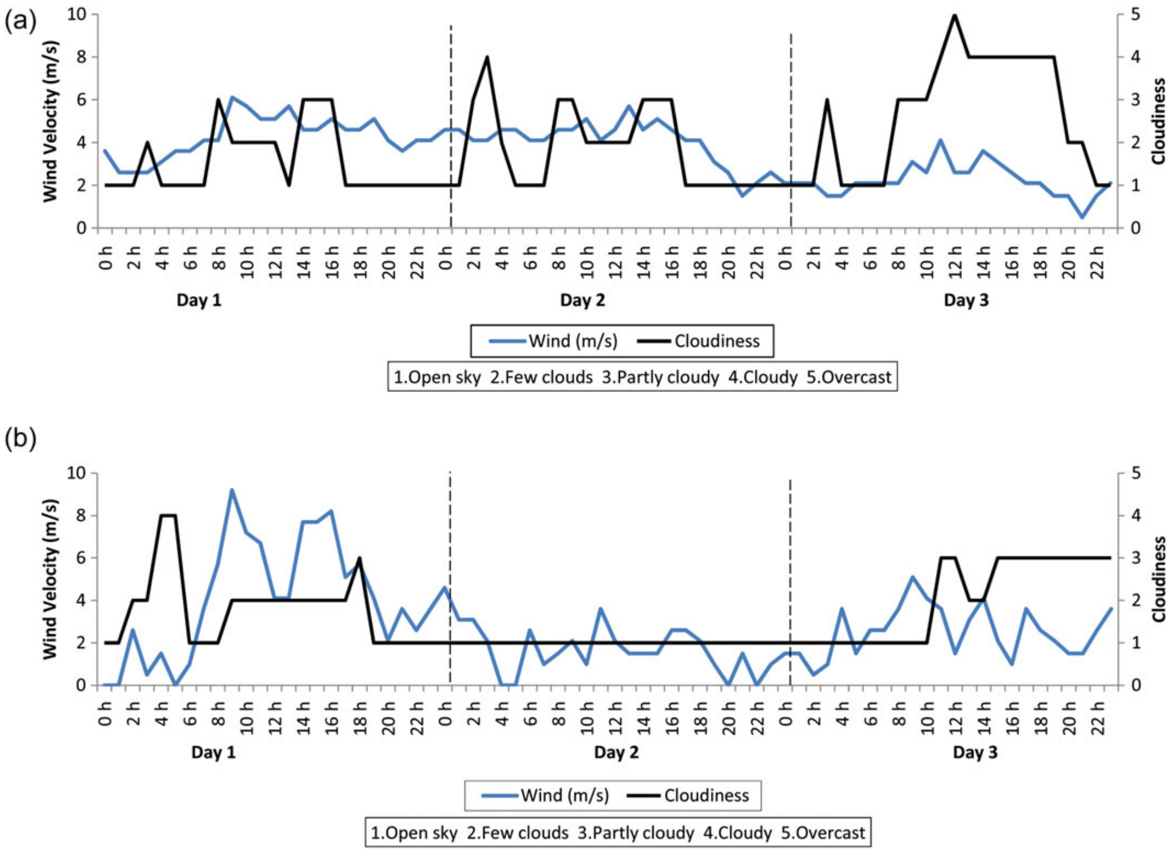

Figure 4. *Cloud and wind conditions during the measurement days—(**a**) Uxbridge and (**b**) Cuiabá. (source: http://www.wunderground.com).*

irradiance during the mid-day is higher in Cuiabá. From Figure 4, it can be seen that Days 1 and 2 in Uxbridge were characterized by above average wind speed and partially cloudy skies, while Day 3 had lower than average wind speed and more clouds. In Cuiabá higher than average wind speed was observed during Day 1 with few clouds in the sky, Day 2 was very calm and without clouds, whereas Day 3 had low cloud cover and low wind speeds.

It should be noted that additional measurements were carried out in the Mato Grosso site during winter (July 2010). However, because of the winter conditions in terms of solar irradiance and sun position, this data set is not studied in the present paper. Similar work in London [21] has shown significant differences between summer and winter measurements.

Three days' measurements were carried out in each case which is typical of published work for short-term measurements to examine the effect of green spaces but for a single location rather than a comparison. For example, Zoulia *et al.* [15] uses a 4 days' measuring data to examine the effect of urban green areas on the heat island in Athens, [12] carried

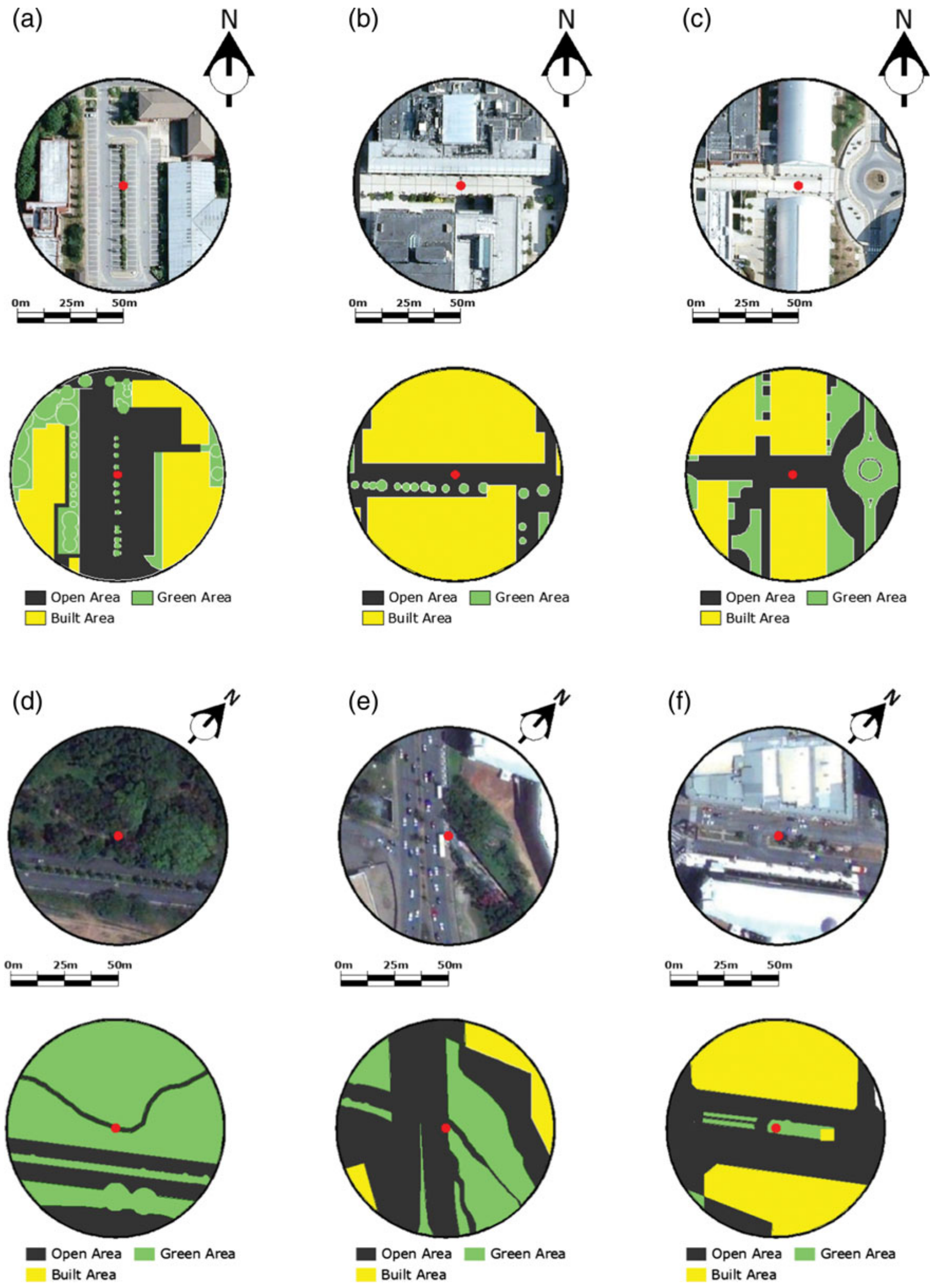

Figure 5. *Three examples of the quantification of the independent variables of the land cover for each site. Uxbridge (**a**) point 15, (**b**) point 8 and (**c**) point 3; Cuiabá (**d**) point 1, (**e**) point 6 and (**f**) point 9. Points can be cross-referenced with points presented in Figures 1 and 2 and Table 2.*

out measurements over 2 days in Hong Kong across the city, while [13] measured for 5 days in Tokyo, but data of 1–4 days were used for the analysis. For this paper, it was thought that 3 day measurements will give a good representation of the characteristics of the two sites so that a comparison can be attempted; it was not possible to carry out longer measurements (for example weeks) which would have given a more comprehensive data set. Nevertheless, a 3 day database sample from each location can reveal characteristics of the site as indicated by previous published work cited above; it should be noted that such comparison presented in this paper is novel.

Measurements were taken during daytime and night-time periods, at 14 and 21 h (local time), respectively. They covered the study area in a loop that took about 30–40 min to complete in each case and the points were 50–200 m apart. Measurements of air temperature were taken at a height of

~1.5 m from the ground and were measured using (a) in Uxbridge a Kester 400 anemometer and a pyranometer; the anemometer measured air temperature, wind velocity and relative humidity, whereas the pyranometer measured global solar irradiance on the horizontal and (b) in Cuiabá an Instrutherm HT260 thermohygrometer measuring air temperature and relative humidity; during the measurements, equipment was shielded from solar radiation by being placed inside a ventilated enclosure. Wind and global solar irradiance data were sourced from the meteorological station of Marechal Rondon. There was no rainfall in Uxbridge and Cuiabá during the measurement days.

2.2 Methods of analysis

The data collected were analyzed in both cases using the SPSS statistical software (version 18.02). Regression analysis was carried out to examine which independent variables had a higher impact on day time and nocturnal temperatures. Following from this, a trend analysis was carried out on the temperature pattern according with two groups defined based on a threshold value for one of the independent variables (percentage of greenness).

The dependent variable for the analysis was air temperature. It was debated whether to use UHI intensity, defined as the air temperature difference between a location within the city and a reference rural location at a specific time. However, because of the nature of the measurements (based on a neighborhood scale site rather than a city-wide scale), it was decided that air temperature would give a better measure of the similarities and differences between the two locations and climates.

Table 2. *Calculated data of the independent variables.*

Point	Uxbridge			Cuiabá		
	Built area	Green area	Open area	Built area	Green area	Open area
1	0.34	0.21	0.45	0.00	0.75	0.25
2	0.15	0.43	0.42	0.01	0.82	0.17
3	0.43	0.12	0.45	0.00	0.66	0.34
4	0.38	0.43	0.19	0.00	0.66	0.34
5	0.21	0.47	0.32	0.00	0.59	0.41
6	0.22	0.65	0.13	0.09	0.29	0.62
7	0.47	0.12	0.41	0.21	0.11	0.68
8	0.72	0.04	0.24	0.23	0.03	0.74
9	0.25	0.20	0.55	0.49	0.04	0.47
10	0.05	0.63	0.32	0.39	0.04	0.57
11	0.18	0.61	0.21	0.43	0.06	0.51
12	0.26	0.45	0.29	0.51	0.06	0.43
13	0.41	0.27	0.32	0.43	0.05	0.52
14	0.14	0.20	0.66	0.51	0.03	0.46
15	0.01	0.21	0.78	0.33	0.09	0.58
16	0.56	0.20	0.24	0.41	0.00	0.59
17	0.03	0.73	0.24	0.25	0.29	0.46
18				0.41	0.27	0.32
19				0.82	0.01	0.17

The independent variables used for analysis were chosen to explain the variations in the dependent variable as researched extensively in the literature and investigated by the authors in the previous work [22]. The two sites studied do not include high rise buildings and the dependent variables focused on the land cover divided into three groups: built area, green area and open area. The built area represents the plan density ratio, greenness represents the green density ratio (includes all green areas from grass to trees) and the open area represents the balance.

Data for the independent variables were calculated from visual recognition using aerial images and by location visits. For each measurement point, the three categories of land cover were calculated considering a 50 m radius with respect to the measurement point. Figure 5 presents an example of this quantification for three points in Uxbridge and three points in Cuiabá; the results are presented in Table 2.

Table 3. *Decimal fraction of greenness of each measuring point.*

Point	Uxbridge	Cuiabá
	Greenness group	Greenness group
1	0.21 (2)	0.75 (1)
2	0.43 (1)	0.82 (1)
3	0.12 (2)	0.66 (1)
4	0.43 (1)	0.66 (1)
5	0.47 (1)	0.59 (1)
6	0.65 (1)	0.29 (2)
7	0.12 (2)	0.11 (2)
8	0.04 (2)	0.03 (2)
9	0.20 (2)	0.04 (2)
10	0.63 (1)	0.04 (2)
11	0.61 (1)	0.06 (2)
12	0.45 (1)	0.06 (2)
13	0.27 (2)	0.05 (2)
14	0.20 (2)	0.03 (2)
15	0.21 (2)	0.09 (2)
16	0.20 (2)	0.00 (2)
17	0.73 (1)	0.29 (2)
18		0.27 (2)
19		0.01 (2)

Table 4. *Data range of the independent variables for the two green classifications.*

Independent variable	Uxbridge		Cuiabá	
	Green cover 1	Green index 2	Green index 1	Green index 2
Built area	0.37 (0.07)	0.18 (0.03)	0.39 (0.04)	0.00 (0.00)
Green area	0.17 (0.02)	0.55 (0.04)	0.09 (0.02)	0.69 (0.04)
Open area	0.45 (0.05)	0.25 (0.03)	0.50 (0.03)	0.29 (0.04)

Note: The values in brackets represent the standard deviation. Rounding was used so the total is <1.

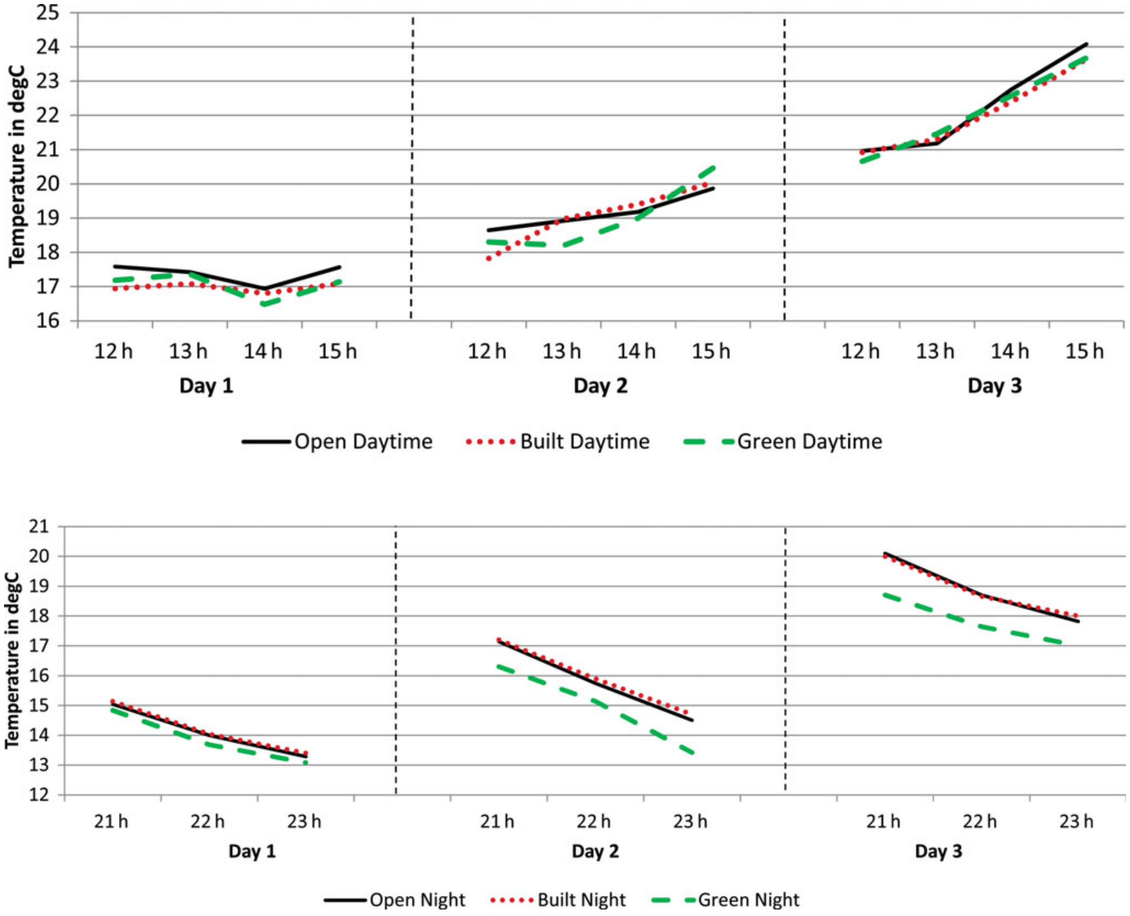

Figure 6. *The measured average air temperature of all similar points (open, built and green) of the 3 days at a specific hour in Uxbridge during the daytime and night separated by measuring day and predominant land cover.*

The work continued by focusing on the influence of green areas on air temperature within the studied areas. Previous work in London [16] and recent research in tropical climates [14] suggested that the 30% green cover would make an impact on air temperature in the range of 0.5–1°C. To test this in this work, the measurement points were classified as green 1 (>30% green cover) and green 2 (<30% green cover); this is shown in Table 3, whereas Table 4 shows the data range of the independent variables for the two green classifications.

3 RESULTS AND DISCUSSION

The land area cover results presented in Table 2 have been further analyzed to classify each point according to their land cover characteristics, and this is presented in Figure 6 for the Uxbridge site. The temperatures presented are measured an average air temperature of the 3 days at a specific hour of all similar points (open, built, green) during the daytime and night separated by measuring day and predominant land cover. It can be observed from Figure 6 that the predominantly green points have a lower air temperature during the night. Similar results are presented for the Cuiabá site in Figure 7. The temperatures presented are the measured average air temperature of all similar points (open, built and green) during the daytime and night separated by measuring day and predominant land cover in this case the separation of green areas can be observed both during the night and day.

To examine the green land cover effect on air temperature at each measured point, Figure 8 presents a plot of the average day and night air temperature at each measurement point together with the percentage of green land cover of the measuring point. It can be seen that there is even a visual relation between greenness and lower measured temperature in particular at night for both sites. The effect is also observed during the day in Cuiabá. As an example, point 8 in Uxbridge (mainly built land cover—0.72) is 0.5°C warmer than point 10 (0.32 open area and 0.05 built area) and 1°C warmer than point 11 (0.21 open area and 0.18 built area). The same effect can be observed between points 16 and 17, which has a 1°C temperature difference and vary in the built and green cover, while they have the same open cover. In Cuiabá, we can observe the

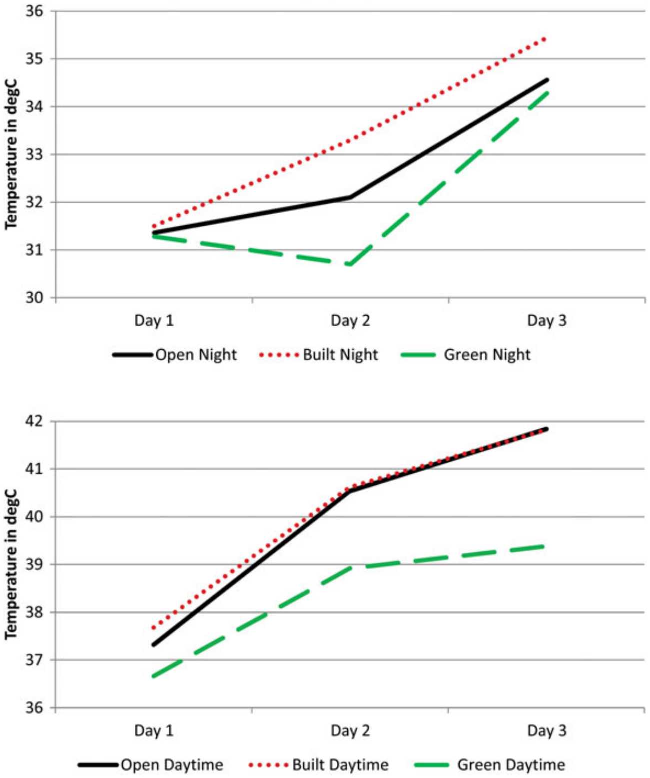

Figure 7. *Measured average air temperature in Cuiabá of all similar points (open, built and green) during the daytime and night separated by measuring day and predominant land cover.*

same effect with a difference of almost 2°C at night between mainly green and mainly built points.

In Figure 9, results are presented for the two green groups for each measurement day for the two sites. In this case too, predominantly green points—group 1—are cooler than points with less green.

To examine this effect in more detail, a regression analysis was carried out using the three categories of land cover as the independent variables and the results are presented in Tables 5 (Uxbridge) and 6 (Cuiabá). The dependent variable was UHI intensity calculated as the difference between the measured air temperature at each point minus the air temperature of a reference point; the reference point was measured the temperature in Langley Park [19] for Uxbridge (5 km west) and measured temperature at Marechal Rondon for Cuiabá. The analysis was performed using the method Forward, which uses the criteria according to the probability of F-to-enter (value <0.050) to allow each independent variable to enter in the model. Therefore, a model is not generated if the selected variables during the measurement period do not present a significant relationship with the UHI intensity (dependent variable).

In case of Uxbridge (Table 5), it is observed that a model can be generated in three of six periods measured (nocturnal of the 3 days). The independent variable selected by the model to explain the variations in air temperature was the 'green area' for Day 2 and 3, whereas the built area was highlighted for Day 1. The negative sign $(-)$ shows that a relationship is inversely proportional, i.e. with the increase of 'green area' amount the trend is to register lower temperatures.

From Table 6 showing the analysis results for Cuiabá, it is observed that a model can be generated in five of six periods measured. In four of these five cases, the independent variable selected by the model to explain the variations in air temperature was the 'green area' with the negative sign $(-)$, as expected. Other independent variables were identified as relevant to explain the variation in outdoor temperature on the study days. The 'open area' entered the model in the daytime of Day 3, and presented a positive sign $(+)$ which is evidence that the contribution of this independent variable is proportional, i.e. with the increase in 'open area' amount, the trend is to register higher temperatures. This can be explained by the fact that the amount of space counted as 'open area' covered materials such as asphalt and pavement, which are characterized by having a low albedo, which helps to store thermal energy during the measurement period characterized by clear sky (not overcast) days.

Overall the strongest relationship was found for Day 2 in Cuiabá ($R^2 = 0.82$ day and 0.62 night). Also during the daytime of Day 3 ($R^2 = 0.93$) but also there are cases where no connection was found. This might be explained by two hypotheses: (1) there are other variables related to these variations that are not considered in the model presented here and, (2) the variation of atmospheric conditions (wind and cloudiness) can mitigate the real effect of the variable.

Analyzing the second hypothesis in more depth, it can be observed in Table 1 and Figure 4 (atmospheric conditions of the study days) that the average wind speed on Day 2 in Cuiabá has very low wind speed, no clouds and high solar irradiance. Also the night of Day 3 has low wind speed and cloud cover during the day, but cloud cover increased during the afternoon and night. This is in agreement with the original work on the subject [23], that the effect of the UHI is more evident under the ideal conditions of weak winds and low cloud cover skies, which conditions contribute to the differentiation of microclimates between surfaces.

Similar observations can be made from the trends of measured temperature. For example, in Cuiabá, average air temperatures are similar in green and less green points during the day on Day 1; air speed was higher during this day in comparison with the other two (see Table 1) and in particular during the daytime (see Figure 4) while wind speed was less at night when the difference in air temperature is observed. Similarly in Uxbridge, the effect of the green land cover is more pronounced during Day 3 when wind speed was lower in comparison with the other two days.

Sky conditions are also a contributory factor. During the daytime, solar irradiance was higher on the first 2 days in Cuiabá with the lower values during Day 3 at the time of measurements. Day 2 was the clearest day in terms of cloud cover and also the calmest in terms of wind speed (see Figure 4); the

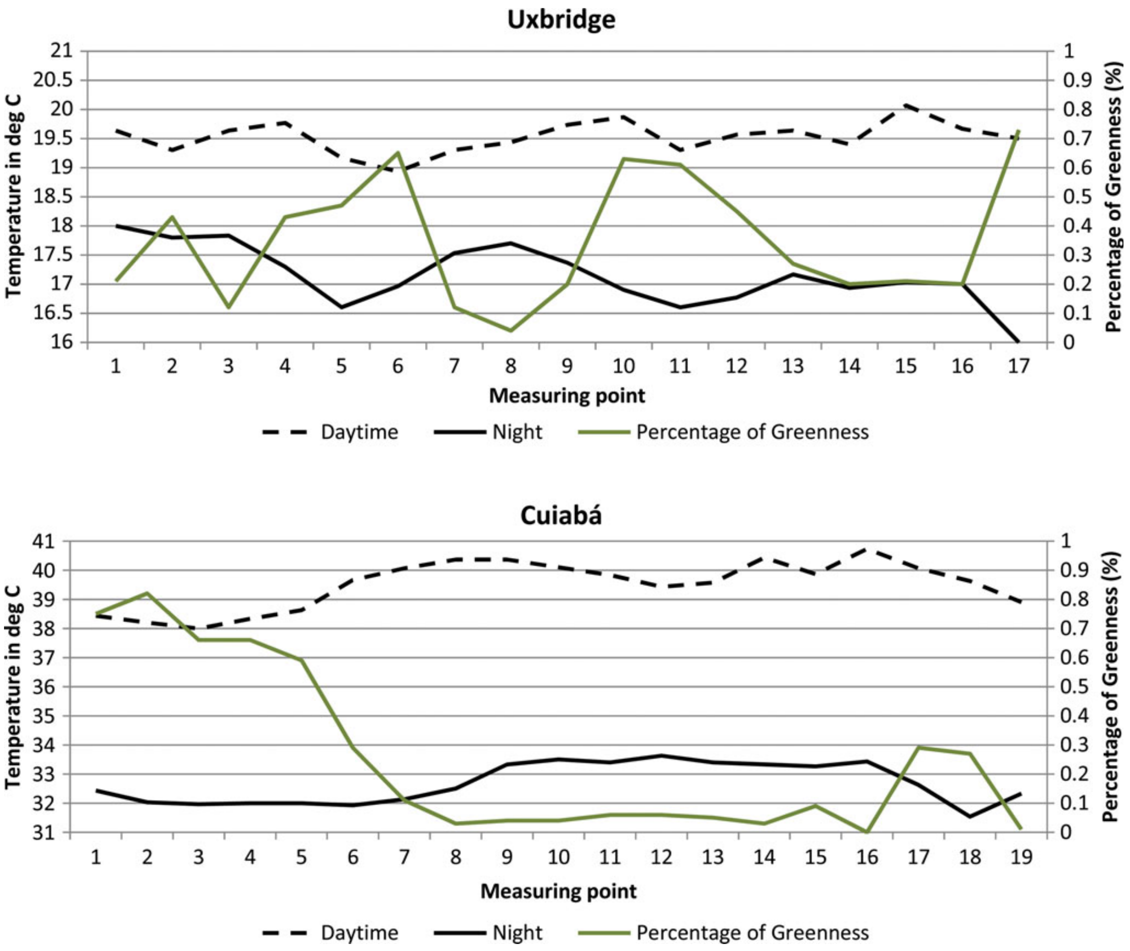

Figure 8. *Average measured air temperatures at each point in Uxbridge and Cuiabá in relation to the green land cover.*

highest separation of air temperatures at night between the three land cover categories and the two green categories appear on this day. Day 1 has the least difference in air temperatures.

In Uxbridge, Day 3 had the lowest wind conditions and Day 1 had the lowest solar irradiance during the time of the measurements. The highest separation of air temperatures between the three land cover categories and the two green categories appears on Day 3.

An attempt to include climatic conditions as additional independent variables on the statistical model did not succeed but this might be because of the limited number of measurements. Further work, will use a computational program to model the two environments and following calibration will carry out a parametric study of the impact of land cover and prevailing climatic conditions.

4 CONCLUSIONS

This paper presented the results of a field study of measured ambient air temperatures in a micro-scale urban environment. Measurements were carried out during three summer days in two different climates in Uxbridge (UK) and Cuiabá (Brazil) within the environment of two university campuses having similar construction and use characteristics. The measurements cover an area of <1 km in radius and were taken in measuring points in close proximity separated by 50–200 m. The area around measuring points of a 50 m radius was classified according to its land cover to examine its impact on ambient air temperature.

Analysis of the measurements has shown that the influence of the attributes of the groups (green, built and open) even in a relatively small urban area results in considerable differences in temperature and the magnitude of the difference depends on the prevailing weather conditions with larger separation during calm and sunny days. The results provide measured evidence in two different climates that small green areas distributed within the urban environment can provide a reduction in ambient temperature thus contributing to the mitigation of UHI and is important for urban designer in big cities, which do not have considerable space to it.

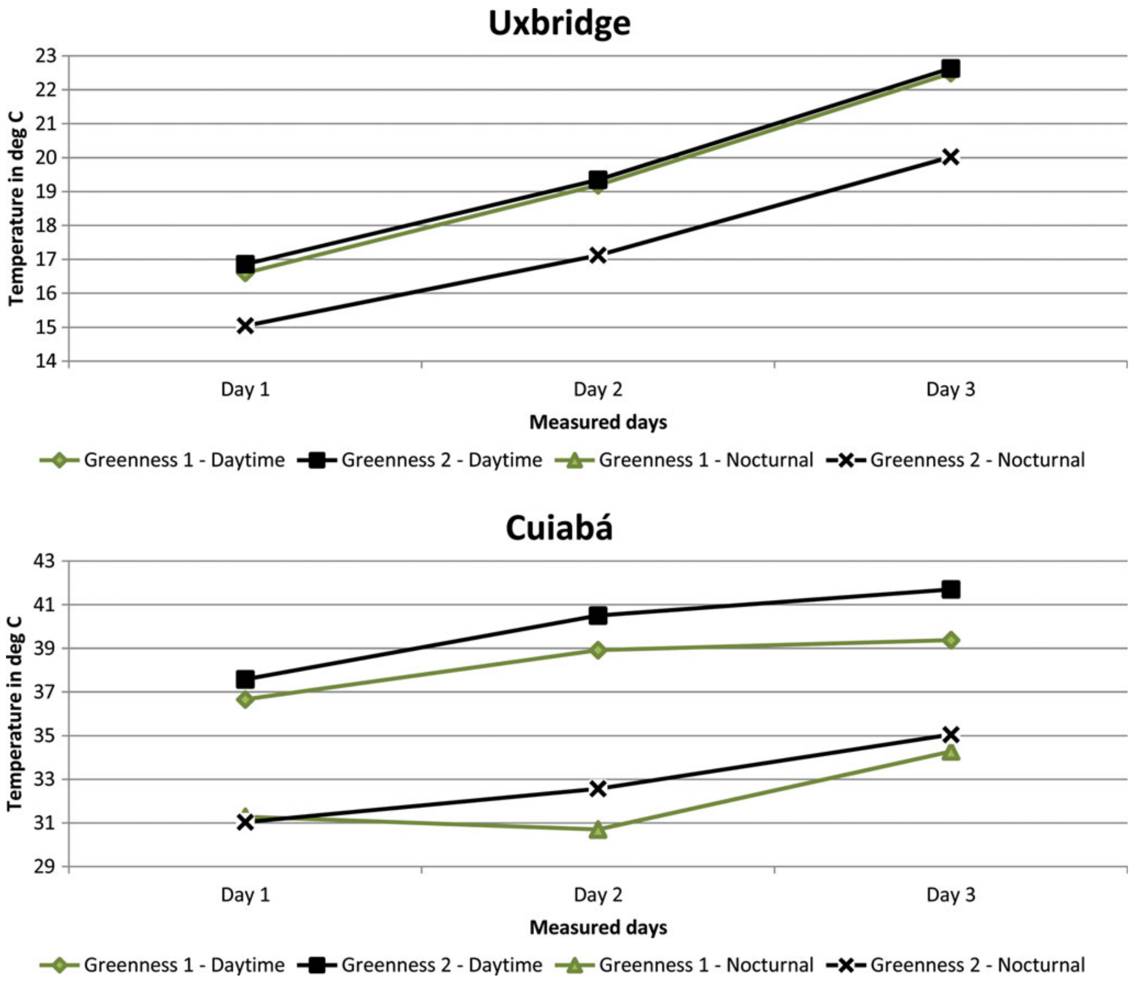

Figure 9. *Average measured air temperatures in Uxbrige and Cuiabá separated by green land cover (1) than 30% and (2) more than 30%.*

Table 5. *Results of regression analysis—Uxbridge.*

Description	Daytime			Nocturnal		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Constant	—	—	—	1.351 (0.000)	5.705 (0.000)	4.723 (0.000)
Built area	—	—	—	0.485	—	—
Greenness	—	—	—	—	−1.621	−2.544
Other materials	—	—	—	—	—	—
R^2	—	—	—	0.28 (0.027)	0.49 (0.002)	0.67 (0.000)
F-statistic	—	—	—	6.009	14.788	30.991
Critical *F*-statistic	—	—	—	4.54	4.54	4.54

Note: (1) The values in brackets represent the significant level.

Table 6. *Results of regression analysis—Cuiabá.*

Description	Daytime			Nocturnal		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Constant	6.664 (0.000)	38.966 (0.006)	8.993 (0.000)	—	2.912 (0.000)	2.202 (0.000)
Built area	—	−33.774	−1.993	—	—	2.221
Greenness	−1.259	−35.526	−5.188	—	−3.286	—
Other materials	—	−31.139	—	—	—	—
R^2	0.22 (0.039)	0.81 (0.022)	0.93 (0.004)	—	0.64 (0.000)	0.62 (0.000)
F-statistic	5.016	5.016	11.470	—	31.036	27.939
Critical *F*-statistic	4.45	4.45	4.45	—	4.45	4.45

Note: (1) The values in brackets represent the significant level.

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