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Micro and macro urban heat islands in an industrial city: Bradford, UK

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A B S T R A C T

The urban heat island (UHI) phenomenon refers to the temperature difference(s) between urban/built environments and suburban/natural areas. It affects energy use, health, water quality, and in brief, the quality of life in cities. Understanding the magnitude of this issue could help urban planners and decision makers to better implement green interventions into their cities. This paper shows the results of field measurements carried out to study the UHIs in Bradford, as one of the most deprived cities in the UK with minimum green infrastructure. In the first phase of the study, air temperatures were measured in twenty locations (four areas) with different land covers in Bradford. These measurements were called micro UHI study, as the air temperatures were measured in areas within the boundaries of the city. Data were collected in late summer and early winter. The results showed that the UHI is more sensible in the colder day (with average 0.6 °C cooler air temperature in a green area compared to the city centre). Greener areas experienced higher wind and lower air temperatures compared to dense urban settings in December. In the second phase of the study (macro scale), diurnal air temperatures from a residential (urban) versus a rural site were compared during a heat wave episode (seven days). It was observed that the rural site was 0.8 °C cooler than the residential/urban site. The maximum temperature differences occurred during the nights/early mornings between the two sites (3.2 °C at 5:00am).

1. Introduction

As global temperatures rise and extreme weather events become more common, higher air temperatures in the built environment are becoming more difficult to endure. In the summer, UK city centres are more frequently experiencing record breaking temperatures surpassing 40 °C [6]. Experiencing warmer temperatures has implications for both the natural environment and urban areas. Extreme heat and poor air quality puts urban residents' health at risk. During 2022, around 2985 deaths were associated with 5 heat episodes exceeding all previous records, there were an average of 387 deaths from London alone [17].

Luke Howard is known as the first scholar who detected air temperature differences in urban settings, when studying the urban climate of London, England, during the early 19th century [19]. His-measurements indicated that the urban centre maintained a higher temperature than its suburban rural edge during the night [21,30]. This phenomenon is called the urban heat island (UHI) effect. Under worst case conditions, the UHI effect can be experienced as up to 10–15 °C hotter in urban centres [27], resulting in pressures on the environment and its inhabitants [32,33].

UHIs are caused by the changes that urban development makes to the energy balance of the prior rural site on which a city or town is built [28]. City centres are typically constructed from hard materials with a severe lack of green space and vegetation. The hardscape is often built from low albedo (solar reflectance) materials which, when combined with a dense urban canopy, results in increased solar radiation being absorbed, reflected, and confined within the concentrated building layout. High rise buildings also act as wind barriers which reduce the level of air flow, leaving warm air and pollution at ground level [2,24].

The UHI effect is most pronounced during the night due to materials continuing to absorb solar radiation throughout the day. After sun set, the hard scape materials slowly release the thermal radiation creating a more significant temperature difference between the urban centre and rural outskirts [18,22]. "*Materials used in building and urban fabric affect the urban thermal balance and contribute highly to urban overheating*" [31]. The built environment is predominantly made up from hardscape materials, for example: only 20 percent of the landscape of London is classed as public green space [3] with the remainder being constructed of hardscape materials. Characteristics of construction materials, specifically their solar reflectance (albedo), thermal emissivity and heat capacity all determine how solar energy is captured and dissipated within the urban environment.

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By the year 2050, it is predicted that 68 % of the world's population will live in an urban environment, which is substantial rise in comparison to the current 55 % [23]. The increasing demand for residential spaces and job opportunities within the built environment create added pressures in UHI's, by means of increased building density, hard surface materials, energy consumption and pollution. This potential amplification of the UHI effect puts more people at risk of heat related illnesses and mortality. In a recent study, Cichowicz and Bochenek [9] showed the correlation between urban heat islands and air pollution through a comprehensive review of published papers from 1968 to 2022. They argue that as cities are being more populated and heated, more pollution would affect urban dwellers. In another review study, Cheval et al. [8] looked at the growing populations that would need to tackle heat waves on top of urban heat island in cities. Considering the future demographic shifts within cities, it is important to analyse the intensity and the spatial distribution of UHIs.

The built environment and how people use the space collectively contribute to the UHI effect. While higher urban temperatures may have some positive effects, such as lengthening plant growing seasons, many are negative. Higher urban temperatures do not just impact on human health [11,34], but also contribute to respiratory difficulties, heat exhaustion, and heat related mortality [4,15]. UHIs can exacerbate the impact of heat waves during which young children and older adults with underlying medical conditions are more at risk [7]. Higher temperatures result in increased energy usage for cooling which has potential to increase emissions of pollutants and greenhouse gases [1]. The peak urban electricity demand in the USA increases by 1.5–2.0 % for every 0.6 °C increase in summertime temperature [14]. UHI can also impact on water quality through thermal pollution with the potential to place stress on aquatic ecosystems [36]. The warming that occurs in urban areas might be considered as an example of local climate change with similar impacts to global climate change. Taking steps to mitigate UHI will therefore also have the added benefit of helping to address global climate change [25].

The consequences of urban heat islands make it important for decision makers to understand the spatial (and temporal) variations of this phenomenon in their cities. This research studied the UHI in Bradford, UK (Fig. 1). Bradford has an approximate population of 546,400 residents, with a total of 23,500 people living within the city centre [26]. Historically, the city of Bradford has a strong sense of identity associated with the textiles industry, and more recently well known for its the influx of migrant populations creating a diverse community. It was recently named the 2025 City of Culture presenting the opportunity for the city to showcase its diverse cultural mix. In addition to arts-based funding, this prestigious accolade has attracted additional investment for regeneration and improvements to the urban landscape within the city and wider area [5].

Fig. 1 shows the location of the city in the UK (left panel), the high deprivation conditions of the city (middle panel), and the lack of green infrastructure within the city centre (right panel). The Bradford-Shipley Canal Road Corridor (CRC) is shown in Fig. 1 right panel (highlighted with the red ellipse). It has been identified by the City as one such area of significant regeneration potential with the aim to "*maximise the regeneration potential of the corridor, through the reinstated Bradford Canal*" [10].

Regeneration of this area provides opportunity for creativity and sustainability to be explored through the landscape. The plan for the new development also offers potential to offset the impacts of Bradford's Urban Heat Island, through the implementation of green intervention. The strategic aims and Community Vision for the area set out in the Area Action Plan include, "*making Bradford a more attractive District*" and the creation of "*a greener, cleaner and more sustainable environment… making best use of our resources and positively affect climate change*" [10]. These strategic aims would therefore also fit with proposals to reduce the UHI through the implementation of landscape-based mitigation measures. This paper evaluates the local UHIs in this part of Bradford and how local microclimates are being affected based on their land covers. The next section shows the locations of the measurement campaigns, data loggers, and the dates that data were collected in Bradford.

2. Methodology

This study was done in two phases. The first phase used a hand-held data logger to measure in situ air temperatures in four microclimates with different land covers in Bradford. Using a hand-held device allowed to record temperatures at several locations. The four areas (microclimates) are located in urbanised parts of Bradford. We considered this as micro urban heat island measurement.

In the second phase, recorded data from governmental weather stations were used to retrieve hourly air temperatures for an urban versus rural site comparison. Our aim was to analyse the UHI in Bradford from a macro lens.

Phase 1 (micro UHI) is introduced and discussed in sub-Sections 2.1, 2.2 and 3.1.

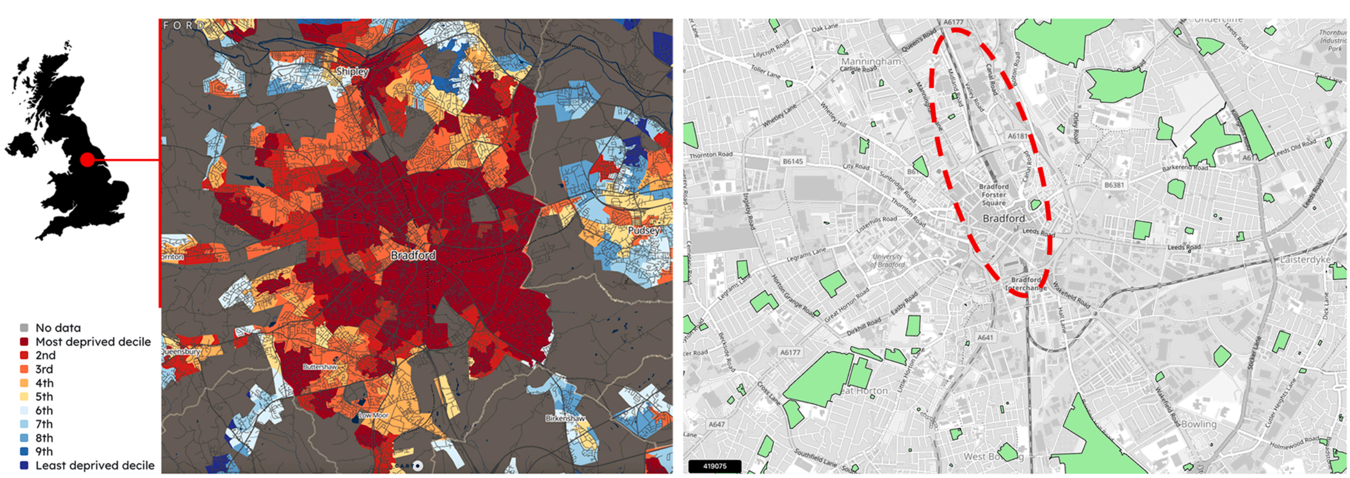

Fig. 1. Left panel: the location of Bradford in the UK. Middle panel: the map of deprivation showing Bradford city centre as one of the most deprived areas in the UK. Right panel: accessible green infrastructure within Bradford city centre. The dash ellipse shows the new development area, the Bradford-Shipley Canal Road Corridor (CRC). The deprivation map (middle panel) is an output of the Consumer Data Research Centre, an ESRC Data Investment, ES/L011840/1; ES/L011891/1″, Contains OS data © Crown copyright and database right 2022.
The green infrastructure map is from Natural England, Contains, or is derived from, information supplied by Ordnance Survey. © Crown copyright and database rights 2021. Ordnance Survey 100,022,021.

Phase 2 (macro UHI) is covered in Section 3.2.

2.1. Study areas (phase 1)

An investigation was carried out to assess Bradford's urban heat island through measurements of air temperature and wind speed within four sample areas at increasing geographical distance from Bradford city centre. The sample areas are shown on Fig. 2:

Area 1– Bradford city centre, high rise buildings (three floors and above) primarily services and office space within the city centre. The panorama from Area 1 shows the centre of the city around the Wool Exchange, which is a conservation area and is made up of a street network that remains from the historic and later Victorian lay out of Bradford. The streets in this area are narrow with tall Victorian buildings and form small spaces where they meet [35].

Area 2– A low rise (one to three floors) residential area with a lack of green space. It is 700 m southwest of the city centre. The streets in the left half of Panorama Area 2 are intact residential areas from the Victorian period while on the right the former character of the Victorian era has been lost with both modern housing and derelict buildings in view.

Area 3– A low rise (one to three floor) residential area with green space. It is 1000 m northeast of the city centre. Panorama 3 shows the pathway running through green spaces, to the left of the photograph is modern semi-detached housing built in the 1970–1980 style while some housing in this area date from the 1960–1970s (detail on property ages derived from local estate agents).

Area 4– Green space. It is 1800 m from the urban centre. The Panorama Area 4 shows Peel Park, the first publicly owned park in Bradford, this green space covers an area of 22.6 ha, with tree lined paths, a small lake and play facilities (Bradford District [29]).

The 4 sampling areas were selected through online research, to reflect changes in the urban landscape with increasing distance from Bradford city centre.

2.2. Field measurements

Kestrel 5400 Heat Stress Tracker was used to take air temperature and wind speed measurements at 5 points within each of the 4 sample areas (Fig. 3). These readings were averaged to provide a representative sample area measurement. Two primary data collection visits were made to Bradford, one in September (25/09/23) and the second in

Fig. 3. Kestrel 5400 Heat Stress Tracker used for air temperature measurements.

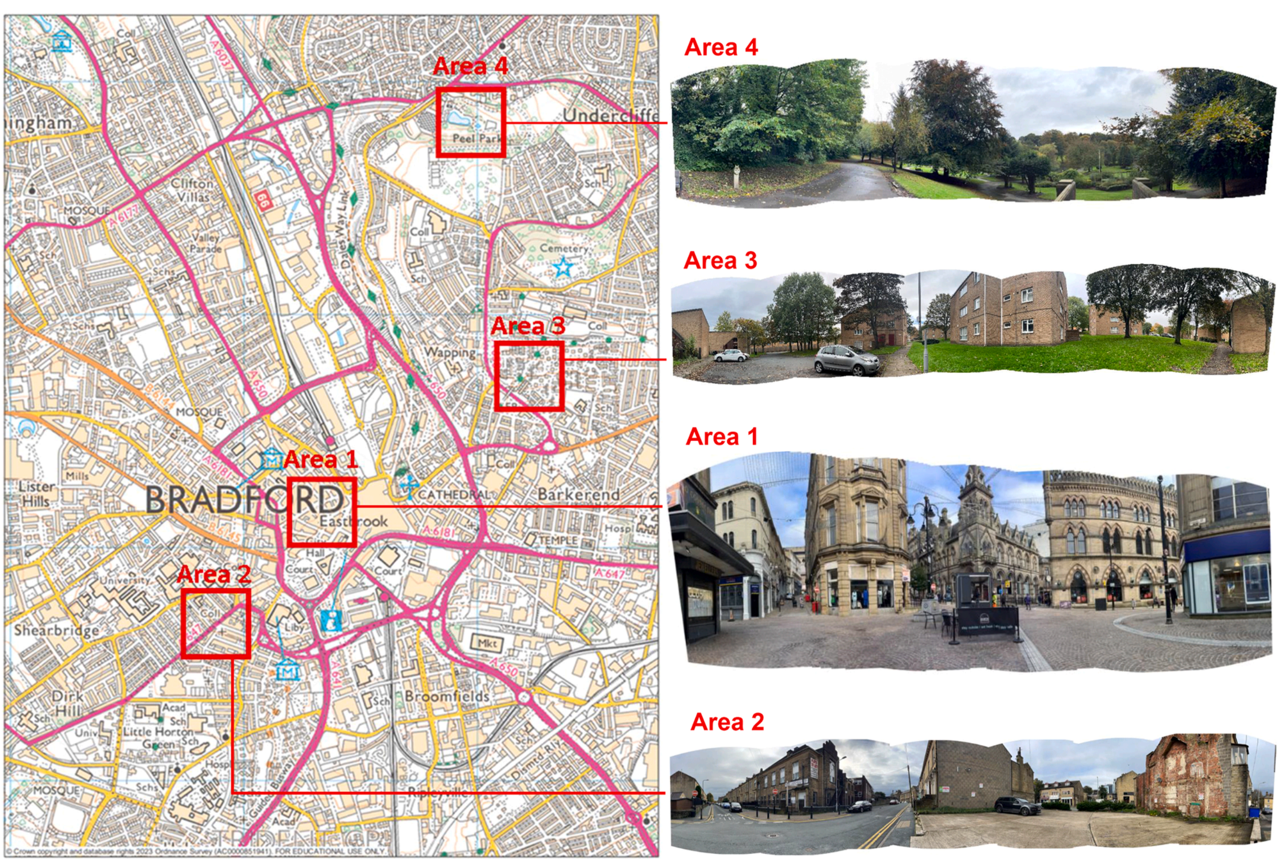

Fig. 2. The four sampling areas in Bradford for the measurements of air temperature and wind speed. Contains Crown copyright and database rights 2021 Ordnance Survey (100,025,252).

December (08/12/23). On both occasions, measurements were made during the middle of the day between 11am and 2pm as time was needed to travel between the different sample areas.

The timings of the measurements were recorded at each location. The order of measurement was Areas 1,2,4 followed by area 3 last due to ease and speed of driving routes between the areas. Weather conditions for the Bradford area between 12 noon and 6pm on the days data was collected are shown in Table 1:

The 5 points at which data recordings were made within each of the 4 sample areas are shown on the Ordinance Survey (OS) Map in Fig. 4, which also incorporates aerial and ground views of the locations.

3. Results

3.1. Field measurement results (phase 1, micro scale)

The average air temperatures and wind speeds are depicted in Fig. 5. The left panel in this figure shows that on the 25/09/23, Area 3 (low rise with green space), recorded the highest average air temperature and average wind speed. Wind speed was lowest in Area 1 (high rise) which result from less movement within the urban canopy layer of the city with tall buildings acting as a barrier to air flow. Wind speed in Area 2 (low rise with no green space) and Area 4 (green space) were similar.

Air temperatures measured across the 4 areas do not represent the typical profile of an UHI, trending upwards moving from Area 1 (high rise) to Area 3 (low rise with green space); the opposite trend than expected. However, the difference in air temperatures between Area 1 and Area 3 is small at 0.2 °C, and the overlap in Standard Error (SE) of the 5 measurements within these areas indicated that there is no significant difference between them. Area 4 (green space) is the lowest recorded air temperature which UHI theory would predict, and the standard error calculated in this instance confirms a significant difference from the previous 3 areas.

Fig. 5-right shows the data collected on 08/12/23 with less variation in wind speed in the 4 areas. The average air temperature profile is also different with average air temperatures falling from Area 1 (high rise) to Area 4 (green space) which is consistent with the thermal profile of an UHI. The difference between the highest and lowest air temperatures is 0.6 °C. However, on closer examination the overlap of standard error indicates the only significant difference in air temperatures is between Area 1 and Area 4.

In summary, comparison of the data recorded in September and December does not show a consistent trend in the average wind speeds recorded across the 4 sampling areas. Wind speed was higher on the 08/12/23 consistent with the published weather conditions for the Bradford Area. Differences in the wind speed profiles might be different flow effects due to the wind directions on each day or temporal changes in wind speed and direction while travelling between locations. Comparing the air temperature profiles recorded in September and December, while the profiles appear different, standard error calculation shows that on both occasions the only significant difference in air temperatures was between Area 1 (high rise) and Area 4 (green space) which is consistent with the UHI effect.

It should be noted that neither of the sampling days provided optimum conditions for measurement of UHI effect. The highest UHI canopy layer temperatures are likely to occur on calm clear nights following a cloudless day with no or weak wind [28]. Furthermore, time differences in taking measurements at the 4 locations had the potential to affect results, both in terms of changes in the synoptic weather and to compensate for heating that occurs as the day progresses. Mitigation of these limitations might be achieved through the installation of static weather stations allowing simultaneous continuous recording over 24-hour cycles.

In terms of the sampling locations, while the 4 areas were selected through online research to reflect changes in the urban land cover with increasing distance from the urban centre of Bradford city centre, Area 2 (low rise with no green space), was not on the same side of Bradford City centre or in the vicinity of the Bradford-Shipley corridor. The location of Area 2 was selected as online planning research was unable to identify a suitable area of low-rise buildings with no green space in the vicinity of the Bradford-Shipley corridor. However, the risk with sites such as Bradford with "bowl shaped" topography, is the potential of the air flow and weather patterns to affect results.

Note: air temperatures and wind speeds were measured in 5 locations within each area in phase 1. The detailed of recordings are shown in Appendix 1.

Table 1
Weather data during the 2 days of measurement [12].

Date	Weather conditions	Temperature (Min-Max)	Wind
25/09/23	Sunny spells	9 - 11 °C	Westerly 3.9 m/s
08/12/23	Light rain/ scattered cloud	7 - 8 °C	South southwest 4.0 m/s

3.2. Urban heat island results (phase 2, macro scale)

The UK Met-Office maintains weather station records from numerous locations around the UK and is available on the Weather Observations Website [20]. To analyse the magnitude of urban heat island effect in Bradford, two weather stations are chosen: Westwood Park residential area (urban), and Bingley (rural, natural) which are shown in Fig. 6. Hourly air temperature data were retrieved for a heat wave episode, from 4th to 10th of September 2023.

Under anticyclonic conditions in late summer, the graphs show that the average air temperatures measured at Westwood, situated within an urban area closest to the urban centre of Bradford shows higher values than Bingley. On the 4th and 9th of September, the peak temperatures occur at 18:00 and 16:00. This late afternoon period is a time when the built environment is also heating up their microclimate, thus acting as a heater.

The Bingley site (rural area) on average is 0.8 °C cooler than the residential area (during the one week of heat wave). The average difference during the hottest day (9th of September) was 1.0 °C for the 24-hour period. Maximum difference of air temperature between the two sites was 3.2 °C at 5:00am (10th September) when the rural site could cool off during the night, but the residential area covered with man-made materials is still warm.

Dividing the days to a warming period (early morning till early afternoon) and a cooling time (early evening till early morning), it is obvious that temperatures are fairly similar during early mornings (warming period). However, the two sites do not cool off similarly. The heat capacity of the materials delays the cooling effect. Therefore, the lowest air temperature for the residential area occurs with few hours delay. This shows the importance of the natural/green spaces within cities to help residential areas to cool off during the night (and especially during heat waves). It should be mentioned here that in large cities, the anthropogenic heat plays a major role in heating up the microclimates (the heat released by the metabolism of the buildings). The temperature fluctuations (daily maximum minus minimum) were similar at around 11.1 °C for Westwood (residential) and 10.8 °C for Bingley (rural site).

4. Discussion

The UHI effect has been proven to reduce the thermal comfort of residents and putting them at risk of heat related illness and mortality (especially during the night). There are many contributing factors to the UHI effect, including the urban landscape. However, through landscape architecture, these impacts can be negated, creating more liveable cities capable of handling the increasing pressures of global population

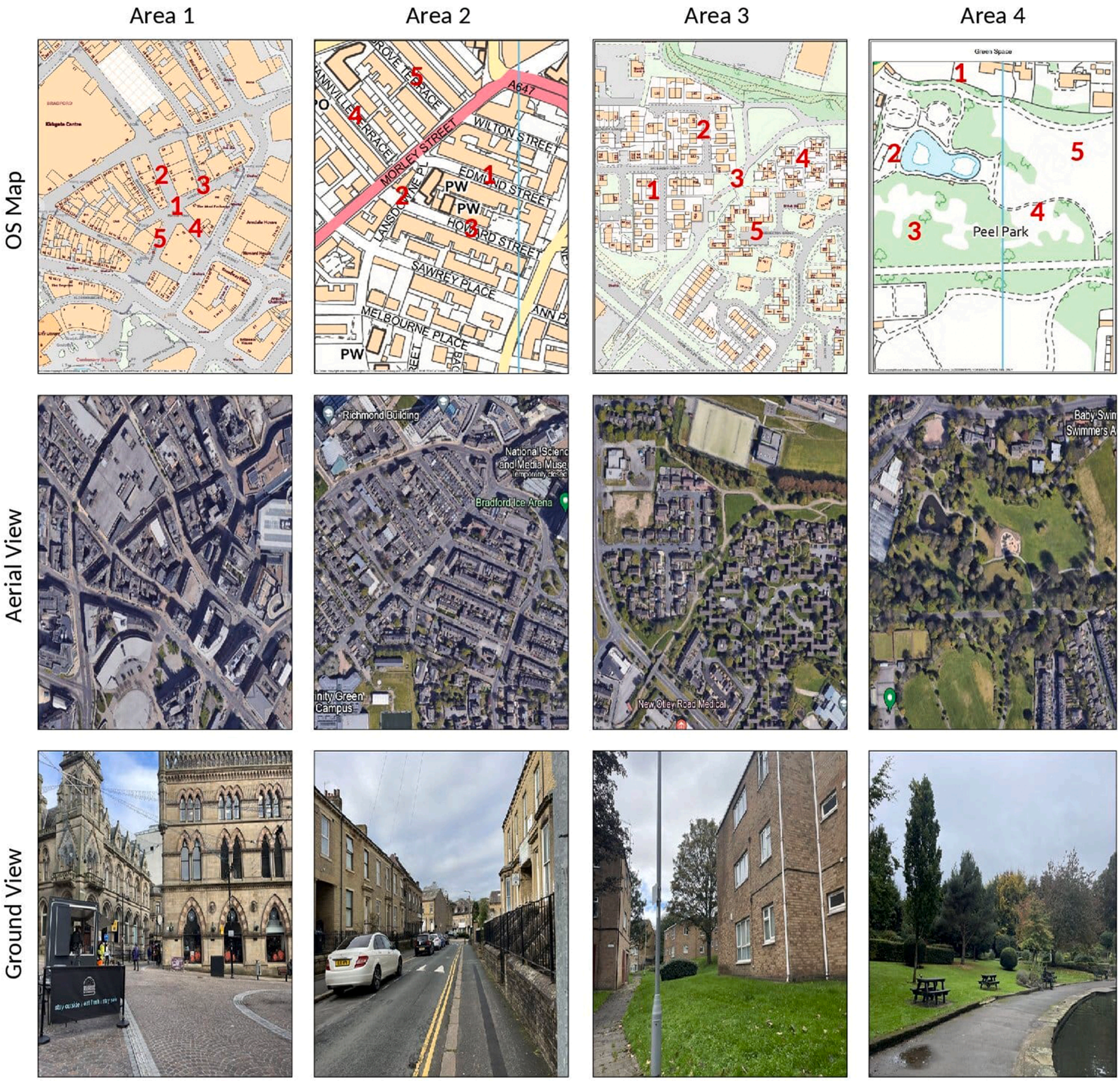

Fig. 4. Top row: OS maps retrieved for the four areas [13]. Middle row: aerial views showing the land cover [16]. Bottom row: ground views of the 4 sample areas.

growth and climate change.

The urban landscape is typically composed of hardscape materials with high building density and reduced green space and waterbodies. The repercussions of this are increased land surface temperatures, increased air temperatures and reduced air flow between buildings, fashioning a physically and mentally unhealthy environment for urban residents.

Urban designers and policy makers could provide a broad range of mitigation strategies, including street tress, sustainable urban drainage systems (SUDS), green walls, green roofs and high albedo materials. Case studies from around the world support the practices and demonstrate the benefits of creating green space. The development of Sponge Cities in China and SUDS in Sheffield, lead to urban environments still capable of reducing the risk of flood damage, which is increasingly becoming a more prominent issue as the global climate changes. Both projects encourage the retainment of water by improving the permeability on site to reduce downstream flooding and which also promotes the growth of vegetation. The increase of street trees in Barcelona, the green roof on Chicago City Hall and green walls in industrial parks in Vietnam, all promote the use of vegetation and green space. Vegetation is capable of reducing land surface temperatures through shading and air temperatures through evapotranspiration. The common factor in all the above case studies is the creation and implementation of nature-based solutions that landscape architects have promoted by designing sustainable vegetated landscapes.

The resultant effects of these landscape architectural strategies are to create socio- economic opportunities for people, and environmental benefits for biodiversity. From a social perspective, urban residents are able to use the space for social gatherings, exercise and to improve their mental wellbeing. Economically, the strategic use of green spaces could increase business income, property value and reduce energy consumption. The creation of green spaces also attracts wildlife, increasing the

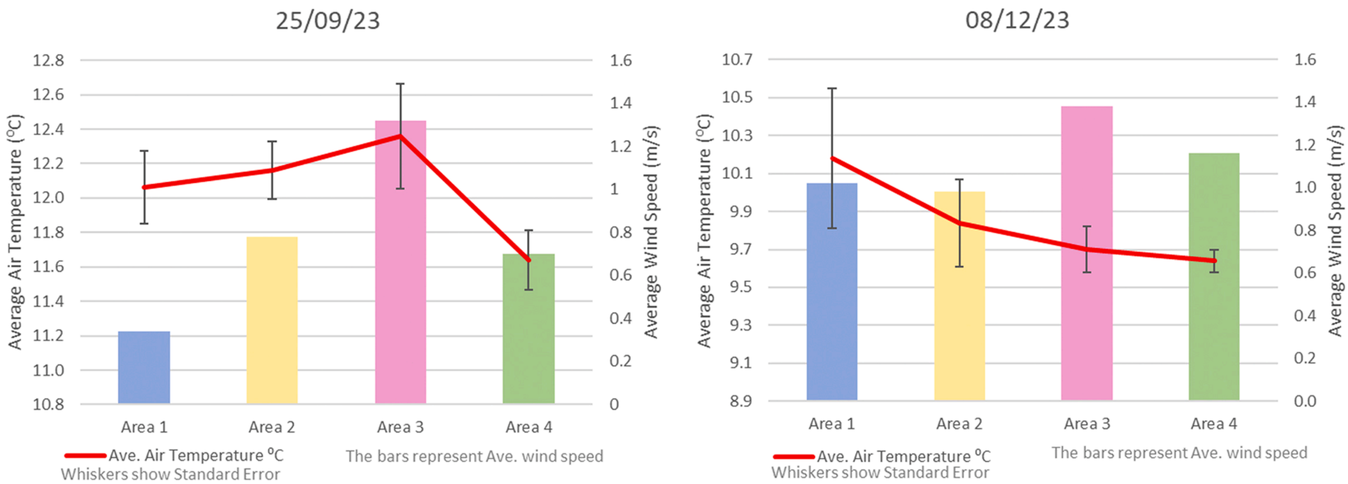

Fig. 5. Measured air temperatures and wind speeds in the four areas in September and December.

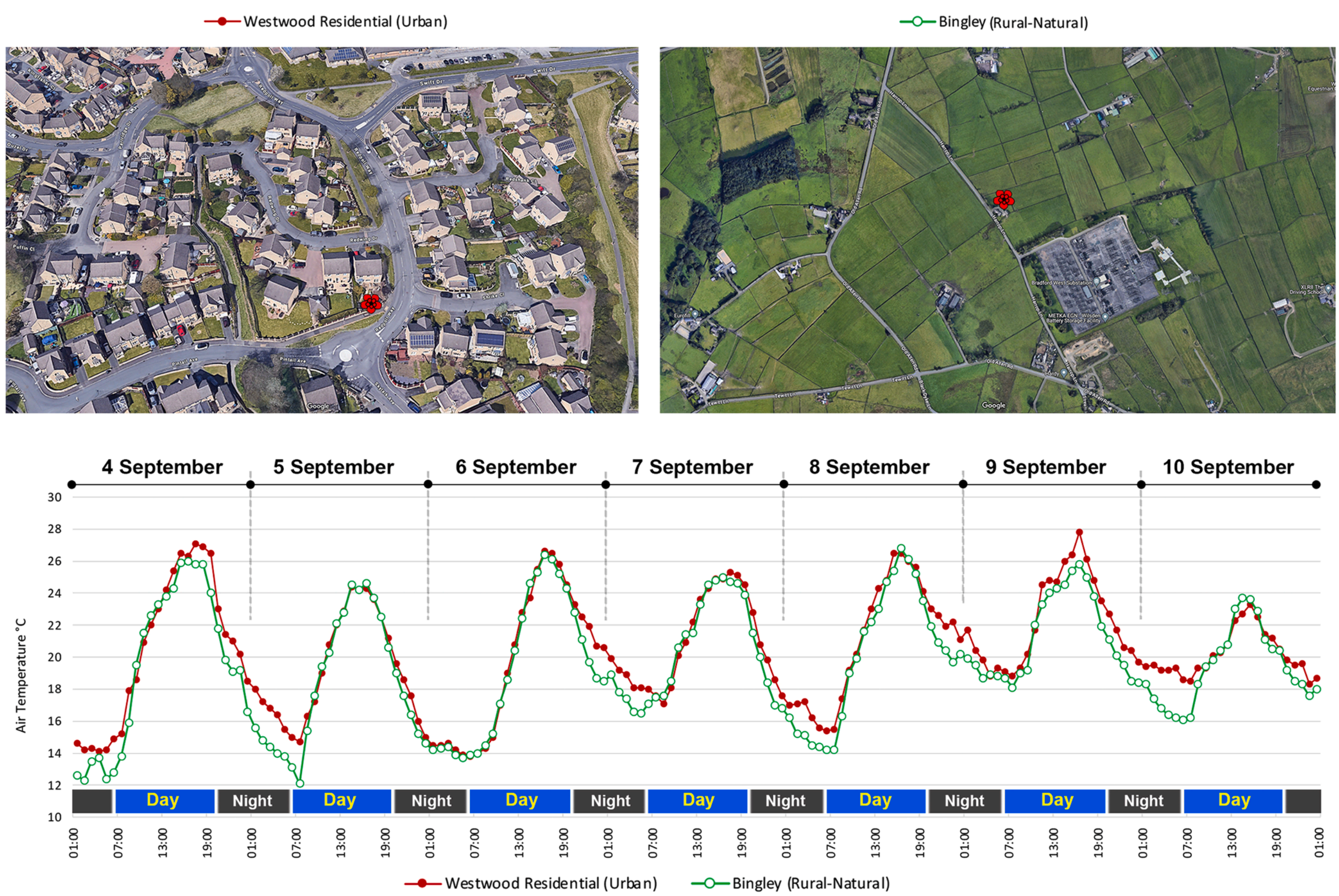

Fig. 6. Top panels: aerial views of the location of the weather stations (the red sign shows the location of the weather stations). Bottom panel: the hourly air temperatures over a week of heat wave in September 2023.

biodiversity and ecology of the place.

In the context of Bradford, the utilisation of green infrastructure would create profound improvement on the quality of life of residents and the surrounding environment. Currently, Bradford city centre is generally barren, with very little in the way of high-quality green spaces. The Bradford Shipley Canal Road Corridor offers the opportunity to invest in transformative landscape interventions by the addition of green infrastructure. With the introduction of green roofs, green walls, street trees, and SUDS, the city of Bradford would experience a reduction in temperature and healthier spaces for both residents and wildlife. In order to maximise the cooling potential of green infrastructure, the strategies should be used together in unison, creating a green city that mitigates the effects of the UHI.

5. Conclusions

This paper studied the urban heat island effect in Bradford in two phases. The first one (micro study) used a hand-held data logger, and it focused on four areas within Bradford city centre. The second phase (macro study) used governmental weather stations to compare a residential area (urban) with a rural-green site.

In the first phase, the primary data collected for the Bradford Shipley Canal Road Corridor has highlighted the significant effectiveness of a relatively small green space (Area 4) in driving down daytime temperatures even whilst being bounded by built up areas and only 1800 m away from an urban centre. Its combination of lawned areas, trees, and shrubs, together with a body of water, nicely demonstrates the potential for landscape interventions of a similar nature to mitigate the UHI effects.

Temperature measurements from sample areas 1, 2 and 3 were much more closely aligned, particularly on the 25 September 2023 when the average wind speed was lower. The generally higher wind speed of the 8 December 2023 was associated with a temperature trend more in line with the expected results. Further sampling would be needed to establish whether this trend is consistent. In addition, measurements in summer/ spring days could reveal a more comprehensive overview of the UHI effect.

The periods of the year that primary readings were taken were late summer and early winter (September and December). Repeating this research during a period of warmer weather might reveal the subtle impact in the level of urbanisation between areas 1, 2 and 3.

Certainly, at a greater spatial sampling, the secondary data from the Westwood residential (urban) and Bingley (rural) weather stations provided further understanding of the UHI effect around Bradford. It clearly demonstrated that urbanised centres experience higher temperatures during the night compared to their surrounding rural areas, suggesting that green infrastructure can have an outstanding impact on the reduction of temperatures during the night, mitigating the UHI effect in hot summers.

The primary and secondary data from micro and macro analysis presented here indicate how Bradford can reduce its UHI effect to create a better quality of life for its residents. Bradford Shipley Canal Road Corridor currently has little green infrastructure but has the potential to integrate green space to create a cooler, more biodiverse and aesthetic place to live. Extreme heat and rain are two main environmental issues accelerated by the change of climate in most UK cities. The integration of green infrastructures such as street trees, sustainable urban drainage and green roofs could all provide Bradford (and other UK) city centres with increased permeable ground, shading and water management strategies which in turn reduce the risk of flooding, decrease air and land surface temperatures, attract wildlife, and increase biodiversity, hence creating a more sustainable and beautiful environment for people to live.

CRediT authorship contribution statement

Georgiana Templeton: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Mohammad Taleghani:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix 1

See Fig. 7

Measurements on 25/09/2023

Area 1 – High Rise			
Reading No.	Time	Air Temperature (° c)	Wind Speed (MPS)
1	11:49	12.0	0.4
2	11:50	11.5	0.6
3	11:43	12.1	0
4	11:46	12.8	0.7
5	11:52	11.9	0
Average		12.06	0.34
Standard Deviation		0.47	0.33
Standard Error		0.21	0.15

Area 2 - Low Rise with no Green Space			
Reading No.	Time	Air Temperature (° c)	Wind Speed (MPS)
1	12:19	12.1	0.8
2	12:23	12.0	0.5
3	12:25	12.3	0.5
4	12:29	11.7	1.4
5	12:34	12.7	0.7
Average		12.16	0.78
Standard Deviation		0.37	0.37
Standard Error		0.17	0.17

Area 3 - Low Rise with Green Space			
Reading No.	Time	Air Temperature (° c)	Wind Speed (MPS)
1	13:28	12.4	1.1
2	13:32	11.3	2.3
3	13:35	12.2	1.1
4	13:42	12.9	1.6
5	13:46	13.0	0.5
Average		12.36	1.3
Standard Deviation		0.68	0.67
Standard Error		0.30	0.30

Area 4 - Green Space			
Reading No.	Time	Air Temperature (° c)	Wind Speed (MPS)
1	13:01	11.6	0.7
2	13:05	12.0	0.7
3	13:07	11.9	0.6
4	13:09	11.0	0.9
5	13:12	11.7	0.6
Average		11.64	0.7
Standard Deviation		0.39	0.12
Standard Error		0.17	0.05

Measurements on 08/12/2023

Area 1 – High Rise			
Reading No.	Time	Air Temperature (° c)	Wind Speed (MPS)
1	11:53	11.5	0.50
2	11:54	10.2	1.90
3	12:00	10.2	0.70
4	12:01	9.7	0.70
5	12:03	9.3	1.30
Average		10.2	1.02
Standard Deviation		0.83	0.58
Standard Error		0.37	0.26

Area 2 - Low Rise with no Green Space			
Reading No.	Time	Air Temperature (° c)	Wind Speed (MPS)
1	12:15	9.6	1.10
2	12:16	9.4	0.80
3	12:18	9.6	0.40
4	12:21	10.7	1.30
5	12:22	9.9	1.30
Average		9.8	0.98
Standard Deviation		0.51	0.38
Standard Error		0.23	0.17

Area 3 - Low Rise with Green Space			
Location No.	Time	Air Temperature (° c)	Wind Speed (MPS)
1	13:55	10.1	0.80
2	13:53	9.8	0.80
3	13:56	9.5	1.10
4	14:03	9.7	1.90
5	14:05	9.4	2.30
Average		9.7	1.38
Standard Deviation		0.27	0.68
Standard Error		0.12	0.31

Area 4 - Green Space			
Reading No.	Time	Air Temperature (° c)	Wind Speed (MPS)
1	13:12	9.8	0.90
2	13:17	9.7	0.90
3	13:27	9.7	0.60
4	13:29	9.5	1.00
5	13:34	9.5	2.40
Average		9.6	1.16
Standard Deviation		0.13	0.71
Standard Error		0.06	0.32

Fig. 7. Detailed measurements of air temperatures and wind speeds in each area of the study in phase 1.

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