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Riparian thermal conditions across a mixed rural and urban landscape

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ABSTRACT

Riparian corridors have the potential to function as thermal refuges, moderating extremes of local temperature variation. However, although demonstrated at individual sites, and over short periods, the consistency of this effect at wider temporal and spatial scales is poorly understood. The aim of this study is to assess the temperature differences between riparian corridors and adjacent non-riparian habitats and to explore the influence of environmental characteristics on these differences. Air temperature was monitored hourly at 20 paired locations (riparian and non-riparian) for two consecutive years. Urban index and canopy cover were characterised by calculating the percentage of impervious surface area and tree canopy cover within a 100 m radius from the centre of each sampling site. Canopy cover reduced summer thermal stresses in both urban and rural areas whereas high urban index tended to increase the daily thermal indices. Rivers had a significant mitigating effect on the urban riparian thermal condition, particularly in extreme hot weather. Riparian corridors were generally 1 °C cooler than non-riparian locations in summer and could be up to 3 °C cooler at some sites in extreme hot weather. Furthermore, riparian corridors at some sites were warmer than non-riparian locations in winter. These findings suggest that the proximity of rivers can modify riparian thermal environments, potentially reducing the heat stress of riparian corridors across landscapes.

1. Introduction

An increase in global mean surface temperature of between 1.7 and 4.8 °C has been predicted by the end of the 21st century (IPCC, 2014), and thermal stresses associated with local urban heat islands are likely to exacerbate such effects in urban environments (Gago, Roldan, Pacheco-Torres, & Ordóñez, 2013). Temperature changes have the potential to alter ecosystem functions at landscape scales, including reducing the ability of ecosystem to alleviate the impacts of extreme climatic events, and affecting biogeochemical cycle (Arnfield, 2003; Gago et al., 2013; Kaye, Groffman, Grimm, Baker, & Pouyat, 2006; Pataki et al., 2011; Trammell, Tripler, Carper, & Carreiro, 2017). Furthermore, temperature changes may affect species structure and distribution. Warming can trigger trees to burst buds earlier, attracting migratory birds into an area and changing species composition at local scales (Kellermann & van Riper, 2015; Thomas, Bourgault, Shipley, Perret, & Blondel, 2010; Wallace, Villarreal, & van Riper, 2013). In addition to changing the structure and functioning of ecosystems, an alteration of urban thermal regime can greatly influence the health and thermal comfort of humans (Oleson et al., 2013). In response to this threat, attention is increasingly being focused on developing long-term sustainable ways of ameliorating these changes in the urban thermal environment (Gober et al., 2009). Bodies of fresh water have been recognised as having the potential to moderate local thermal effects (Coutts, Tapper, Beringer, Loughnan, & Demuzere, 2013; Saaroni & Ziv, 2003; Steeneveld, Koopmans, Heusinkveld, & Theeuwes, 2014; Xu, Wei, Huang, Zhu, & Li, 2010). The effects of water bodies on the surrounding thermal environment are driven by heat exchange between water and air and the process of evaporation, and can be significant - a small (4 ha) pond in a city park provided a cooling effect of approximately 1.6 °C on air temperature during periods when the water was cooler than the air (Saaroni & Ziv, 2003). Similarly, a lower air temperature was observed in a

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street opening to a paddy field compared to those that did not (Yokohari, Brown, Kato, & Yamamoto, 2001).

Several studies have shown that flowing waters can have similar thermal effects on riparian environments (Table 1). Brosofske, Chen, Naiman, and Franklin (1997) and Rykken, Chan, and Moldenke (2007), studying two different forest stream systems, found that maximum mid-afternoon temperatures in summer were about 3 and 6 °C lower near to small (1–5 m width) forested streams compared to locations 50 m and 30 m away. Anderson, Larson, and Chan (2007) compared riparian and upslope locations in the headwaters of a montane region in Oregon, USA. They documented a cooling effect of rivers of approximately 1.5 and 4.5 °C, for forested and partly-harvested riparian corridors, respectively. The cooling effect of rivers has also been observed in lowland urban river systems. For example, Hathway and Sharples (2012) demonstrated that the area immediately adjacent to a medium sized (22 m width) urban river in the UK in spring was 1.5 °C cooler than a location 30 m and Murakawa, Sekine, Narita, and Nishina (1991) reported a cooling effect on air temperatures up to 200 m away from a large urban river in Japan.

Whilst there is evidence of the potential effects of water bodies on thermal conditions not all studies demonstrated this. For example, Brooks and Kyker-Snowman (2009) studying headwater streams in New England, USA and found no difference in air temperature between riparian corridors and locations 30 m from the stream. Previous studies of the effects of rivers on thermal microclimate have been spatially restricted (both in terms of the number of sites and spatial extent of the river systems examined) and have been carried out over relatively short periods (usually few days or weeks within a single season) (Table 1). Understanding riparian temperature across large temporal scales (e.g. inter- and intra-annual, within and over seasons) is essential for river and riparian management as annual and seasonal temperature changes are important to predict river heat budgets, river thermal sensitivity to climates, riparian microclimates and river-riparian thermal energy interchange (Garner, Hannah, Sadler, & Orr, 2014; Garner, Malcolm, Sadler, Millar, & Hannah, 2015), and the extent to which such effects can create ecologically important environmental effects. For example, we have previously reported that even small variation in riparian thermal condition is related to changes in riparian tree phenology (Tsai, Young, Warren, & Maltby, 2016). Furthermore, it is important to understand how riparian temperature responds to environmental changes due to land-use transformation and, in particular to differences between urban and rural environments. Such data are essential for future urban design and planning. Thermal regime of riverine systems may have an important role in maintaining various ecosystem services in human-dominated landscapes, including providing thermal refuges from the impact of extreme weather, providing areas for urban ecosystem conservation and restoration, and providing an arena for urban citizens for social activities (Arthington, Naiman, McClain, & Nilsson, 2010; Bolund & Hunhammar, 1999; Maynard, 2015; Olive & Minichiello, 2013; Woodward et al., 2016).

In order to appreciate more fully the extent to which rivers can play a role in influencing thermal conditions and in turn ecological function, it is important to conduct studies at broader spatial (incorporating a wider range of environmental situations) and temporal scales (in particular across different seasons). The aim of this study is to characterise the seasonal thermal pattern in riparian environments at multiple sites across a river network embedded in a mixed rural and urban landscape. The specific objectives are to: (1) document the seasonal thermal variation in riparian and non-riparian locations; (2) compare the daily and seasonal temperatures between riparian and non-riparian locations in rural and urban areas; (3) explore effects of location (riparian vs. non-riparian), the area of canopy cover, and the degree of urbanisation on thermal patterns.

Table 1
Magnitude and direction of temperature difference between riparian and non-riparian locations reported in previous studies of thermal microclimate of rivers and streams.

Land use	Reference	Location	Elevation (m)	Season	River width (m)	Distance (m) (i.e. measuring location from the river)	Measuring period (day)	Temperature (measuring period)	Numbers of sites/replication	Canopy cover	Temp. diff. (°C)
Forest	Brosofske et al., 1997	headwater Streams, the Cascade Mountain Range, Washington, USA	150–600	Summer	2–4	50	6–15	mean (1200–1600)	5	70–80%	+3
									5	clearcut	+2
								mean (0000–0400)	5	clearcut	−0.5
	Anderson et al., 2007	headwater streams, the Coast Range and the Cascade Range, Oregon, USA	200–750	Summer	0.2–3.7	50	8–10	maxima (0000–2400)	5	fully forested	+1.5
									5	partly harvested	+4.5
	Rykken et al., 2007	headwater streams, the Willamette National Forest, Oregon, USA	415–1268	Summer	2.1–3.6	20	12	mean (1500)	5	fully forested	+6
									5	partly harvested	+5
									5	clearcut	+5
	Brooks & Kyker-Snowman, 2009	Quabbin Reservoir Watershed, New England, USA	–	Spring, Summer and Autumn	2.7–5.9	30	8	mean, maxima and minima (0000–2400)	9	>90%	0
Urban	Murakawa et al., 1991	the Kyobashi River, Hiroshima city, Japan	10–50	summer	270	200	1	mean (1200–1700)	1	–	+5
	Hathway & Sharples, 2012	the River Don, Sheffield city, UK	50	Spring and Summer	22	30	3	mean (0600–2100)	1	–	+1.5

- no data available; the + or − before the value of 'Temp. diff.' indicate that the temperature in non-riparian was warmer or cooler than that in riparian areas respectively.

2. Methods

2.1. Study area

This study was based in and around the city of Sheffield, which is located in the county of South Yorkshire, in northern England, UK (53° 22′ 51″ N, 1° 28′ 14″ W [city centre]). Sheffield is located in the catchment area of the River Don and lies at the confluence of the River Don and four of its main tributaries: the River Loxley, River Rivelin, River Porter, and River Sheaf (Fig. 1). The climate in Sheffield is temperate with mean annual precipitation of 826.0 mm (1971–2012), average annual monthly maximum temperature of 21.4 °C, and average annual monthly minimum temperature of 0.8 °C (Met Office, 2013).

2.2. Measuring sites and locations

Twenty study sites were identified along the River Don, River Loxley, River Rivelin, and River Sheaf. Ten sites were within the main urban areas (i.e. the shaded area in Fig. 1), which had predominantly industrial, commercial, or residential land use. These sites were classified as ‘urban,’ while the remainder were classified

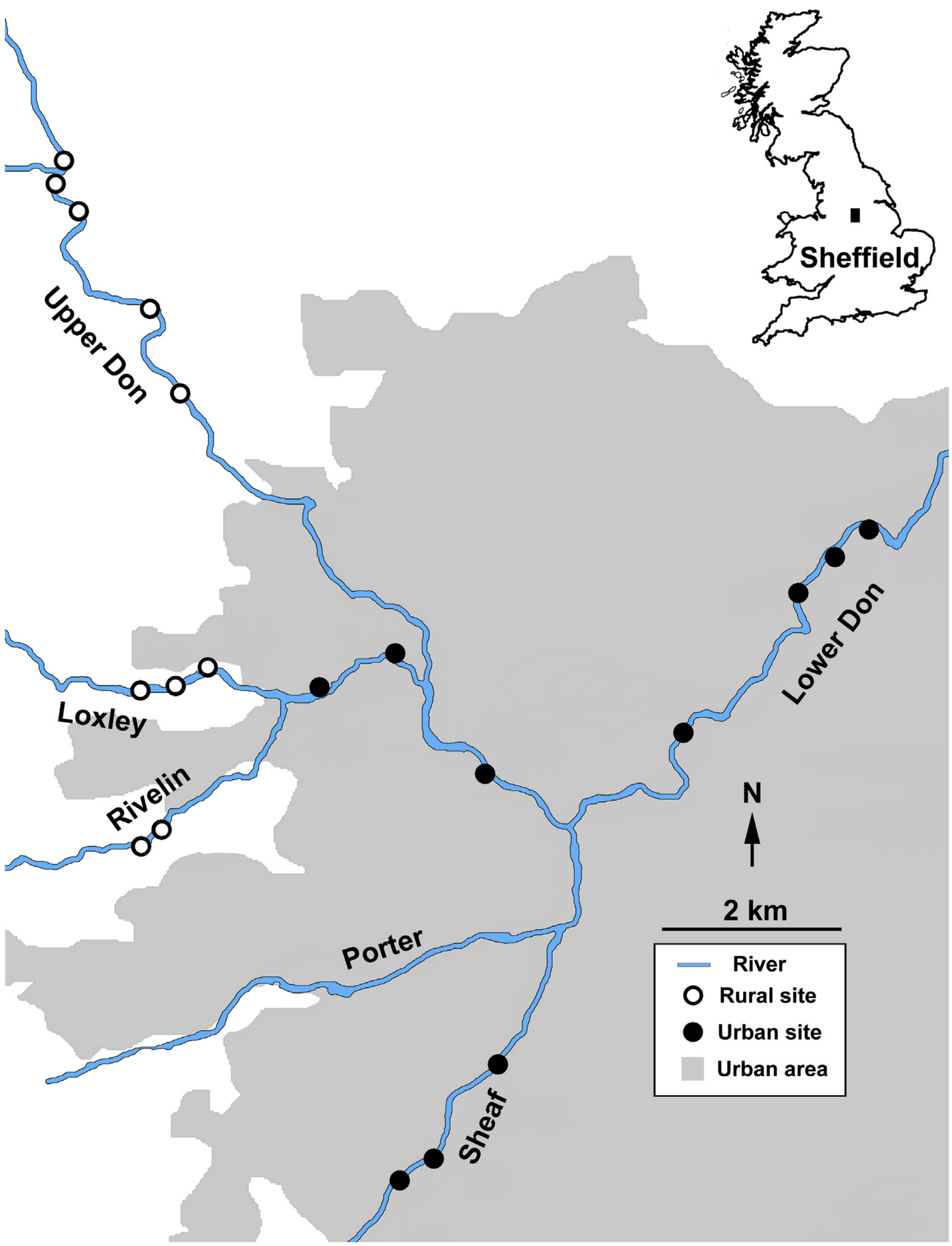

Fig. 1. Rural (open circles) and urban (filled circled) study sites; five rivers (i.e. Don, Loxley, Rivelin, Porter, and Sheaf) (blue lines) running through the urbanised areas (shaded area) of Sheffield, UK. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as 'rural' (Fig. 1). Of the twenty sites, ten (five urban and five rural) were on the River Don, two (both rural) on the River Rivelin, five (two urban and three rural) on the River Loxley, and three (all urban) on the River Sheaf (Fig. 1). At each site two measurement locations were selected: riparian (<5 m from the river) and non-riparian (>40 m from the river). Sampling locations were areas of greenspace (minimum area: 1655 m^2), each having a number of mature ash (*Fraxinus excelsior*) and sycamore (*Acer pseudoplatanus*) trees in addition to any other vegetation (Tsai et al., 2016). The riparian location was always within 5 m of the river, but the non-riparian location was the nearest area available that satisfied both the distance (>40 m from the river) and habitat criteria. As a result, the distance between the river and the non-riparian location varied from 42.3 m to 393.6 m, with a mean distance of 140 m.

To quantify and describe the land-use characteristics of sites, two indices of the surrounding landscape were assessed: urban index (UI) and canopy cover (CC). The former was calculated as the proportion of the terrestrial area having impervious/non-vegetated cover (i.e. buildings, roads, parking lots) within a 100 m radius from the centre of each sampling location (Lu & Weng, 2006). CC was measured as the proportion of the terrestrial area within a 100 m radius from the centre of each sampling location having tree canopy cover. The area of water bodies (i.e. rivers and ponds) in each 100 m radius area was not included in the calculation of either index. UI and CC around each sampling site were measured using GIS-based map analysis (ESRI® ArcMapTM 10.0 and Geospatial Modelling Environment, GME© Spatial Ecology LLC, version 0.7.2. RC2) with data resource from Digimap (Ordnance Survey, 2009) and Bing Map (Microsoft, 2012).

2.3. Temperature monitoring

Temperatures in the sampling locations (i.e. riparian and non-riparian) at each site were recorded continuously for two years between March 2010 and February 2012 using thermal loggers (−55 to 100 °C, ±0.5 °C) (DS1921G# 1-Wire® Thermochron®). Loggers recorded temperature hourly (i.e. an hourly average) and were retrieved monthly for data download and replacement. Loggers were replaced with either previously unused loggers, or loggers previously used at other sites, ensuring any inaccuracies or biases in individual loggers were not consistently associated with any particular site or location. From March to September 2010 two temperature loggers were set up in the riparian location and two in the non-riparian location at each site, but after September 2010

Table 2
Environmental characteristics of riparian corridors and non-riparian locations for each of the 20 study sites.

Area	Site	Geographical information (Longitude, Latitude)	River	River width (m)	Riparian locations			Non-riparian locations		
					Distance from the river (m)	Urban index (%)	Canopy cover (%)	Distance from the river (m)	Urban index (%)	Canopy cover (%)
Rural	41–73	53° 23′ 00″ N, 01° 32′ 41″ W	Rivelin	6.3	5	9.1	60.1	79.4	12.7	47.2
	42–74	53° 23′ 02″ N, 01° 32′ 29″ W	Rivelin	8.7	5	9.4	57.1	46.5	10.6	47.0
	49–73	53° 24′ 04″ N, 01° 32′ 40″ W	Loxley	5.8	5	11.6	58.2	59.3	8.8	79.8
	49–75	53° 24′ 01″ N, 01° 32′ 12″ W	Loxley	7.2	5	6.8	71.3	52.3	4.8	78.2
	50–78	53° 24′ 10″ N, 01° 31′ 31″ W	Loxley	7	5	8.6	78.0	52.4	12.6	63.8
	63–76	53° 25′ 58″ N, 01° 31′ 56″ W	Don	13.5	5	17.8	63.6	42.3	17.4	57.9
	67–75	53° 45′ 56″ N, 01° 31′ 56″ W	Don	11.7	5	1.7	61.3	74.3	1.5	24.3
	72–72	53° 27′ 05″ N, 01° 32′ 58″ W	Don	12.2	5	1.1	60.9	66.8	3.0	41.4
	73–71	53° 27′ 16″ N, 01° 33′ 08″ W	Don	19	5	4.2	16.8	164.7	10.9	29.7
	76–71	53° 27′ 30″ N, 01° 33′ 10″ W	Don	11.8	5	7.3	48.2	115.3	15.4	45.7
Urban	26–87	53° 20′ 53″ N, 01° 29′ 35″ W	Sheaf	3.2	5	48.4	40.6	190.9	41.1	43.8
	27–88	53° 20′ 59″ N, 01° 29′ 13″ W	Sheaf	6.5	5	54.3	26.1	82.2	65.5	14.1
	31–92	53° 21′ 37″ N, 01° 28′ 29″ W	Sheaf	5.1	5	92.6	12.8	93.1	88.1	6.7
	45–91	53° 23′ 28″ N, 01° 28′ 37″ W	Don	23.5	5	87.1	5.7	246.4	93.4	8.4
	47–100	53° 23′ 44″ N, 01° 26′ 29″ W	Don	39	5	83.7	19.6	493.8	70.7	7.1
	49–83	53° 24′ 00″ N, 01° 30′ 25″ W	Loxley	7.8	5	67.4	19.1	119.3	14.4	32.9
	50–87	53° 24′ 09″ N, 01° 29′ 32″ W	Loxley	11.5	5	86.2	7.6	207.6	64.2	17.8
	53–106	53° 24′ 33″ N, 01° 25′ 17″ W	Don	15.5	5	54.5	17.8	92.4	62.3	40.2
	56–108	53° 24′ 55″ N, 01° 24′ 49″ W	Don	20.5	5	80.5	5.3	172.1	80.8	25.6
	56–110	53° 24′ 57″ N, 01° 24′ 22″ W	Don	19	5	82.5	22.1	393.6	53.6	28.6

only one logger was used in each sampling location. The loggers were deployed in small white vacuum-sealed bags and, to minimise the direct effect of solar radiation, were attached to trees in consistently shaded, sheltered locations about 1 m above the ground.

2.4. Data analysis

The averages of daily means, maxima, and minima on each day for riparian and non-riparian locations across the 10 rural and 10 urban sites were calculated. Then the differences in the averages between riparian and non-riparian locations were presented using locally weighted scatterplot smoothing (LOWESS) to show the trend of the temperature differences throughout the study. Additionally, temperature data were grouped by season: the average of daily means, maxima, and minima in seasons (spring [March–May], summer [June–August], autumn [September–November], winter [December–February]) for riparian and non-riparian locations of each site were calculated and used for building the linear mixed-effects models of the relationship between the average daily mean, maximum, minimum temperatures in seasons and UI, CC, and Location (riparian vs. non-riparian). For the models of the annual pattern, 'site' and 'year/season' were included as random effects, and 'site' and 'year' were set up as random effects for the models of the seasonal pattern. Statistical analyses were carried out using R (R Core Team., 2013), and R packages, lme4 (Bates, Mächler, Bolker, & Walker, 2015) and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2013) were used for running mixed-effects models and calculating the *p*-values. Because on average rural sites occur at slightly greater altitudes than urban ones, interpretation of differences between rural and urban sites as categories is not straightforward, and our analyses focus on the patterns within urban and rural areas separately, rather than comparison of the two as a whole.

3. Results

3.1. Urban index and canopy cover

The UI of riparian corridors ranged from 1.1 to 17.8% (7.8 ± 1.6% [mean ± SE]) in rural sites and from 48.4 to 92.6% (73.7 ± 5.1%) in urban sites, and that of non-riparian locations from 1.5 to 17.4% (9.8 ± 1.7%) in rural sites and from 14.4 to 93.4% (63.4 ± 7.4%) in urban sites (Table 2 and Fig. 2). The CC of riparian corridors ranged from 16.8 to 78.0% (57.6 ± 5.2%) in rural sites and from 5.3 to 40.6% (17.7 ± 5.6%) in urban sites, and that of non-riparian locations from 24.3 to 79.8% (51.5 ± 5.9%) in rural sites and from 6.7 to 43.8% (22.5 ± 7.1%) in urban sites (Table 2 and Fig. 2).

3.2. Variation and differences in riparian and non-riparian temperatures

The annual pattern in temperatures for riparian and non-riparian locations in both rural and urban sites were similar. Spring, autumn, and winter average daily mean temperatures were higher in 2011 than in 2010 at all locations and sites (Table 3 and Fig. 3). In general, riparian locations had higher seasonal average daily minima and lower seasonal average daily maxima than non-riparian locations (Table 3 and Fig. 3).

Temporal variation in the temperature difference between riparian and non-riparian locations at urban and rural sites is presented in Fig. 4 for daily mean, maximum, and minimum temperatures. Temperature differences were most marked for daily minima at urban sites, where riparian locations may be up to 3 °C cooler than non-riparian locations. In rural sites, daily mean temperatures were lower in riparian than non-riparian locations from spring to autumn, but higher in winter. In urban sites, differences in daily mean temperatures were more variable, reflecting variation in differences in daily minimum temperatures. In 2010, differences in daily mean temperatures were similar between riparian and non-riparian locations from spring to early summer but fluctuated considerably in autumn and winter, whereas riparian temperatures were consistently lower than non-riparian temperatures throughout 2011. Daily maximum temperatures were consistently higher in non-riparian than riparian locations in rural sites throughout the two years but there was little difference in daily minimum temperatures (Fig. 4). In urban sites, daily maxima were consistently higher in non-riparian than riparian locations in 2011 but not in 2010, while daily minimum differences were consistently lower in non-riparian than

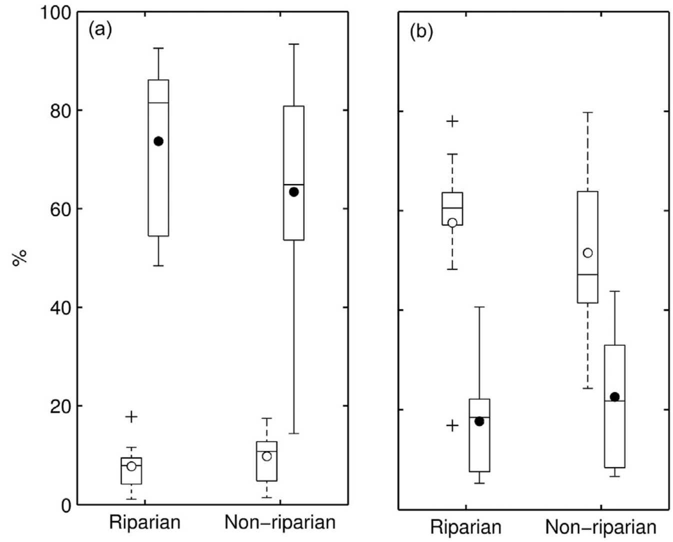

Fig. 2. Box plot of the percentage of urban index (a) and canopy cover (b) for rural (open circles and boxes with dashed lines) and urban (filled circles and boxes with solid lines) sites. Mean and median line are represented by a circle and a solid line, respectively, within each box. Boxes around the median line and mean marker show 25th and 75th percentile with whiskers representing the maximum and minimum values, and the crosses indicate upper and lower outliers.

Table 3
The average daily mean, maximum, minimum temperatures for riparian and non-riparian locations in 10 rural and 10 urban study sites in four seasons between March 2010 and February 2012.

Season	Index	Rural Sites				Urban Sites			
		Riparian		Non-riparian		Riparian		Non-riparian	
		2010	2011	2010	2011	2010	2011	2010	2011
Spring	Mean	7.8	8.9	8.0	9.3	9.8	10.1	9.8	10.2
	Maximum	24.3	20.0	24.6	21.7	26.0	20.5	26.3	23.8
	Minimum	−4.1	−2.4	−4.4	−2.5	0.8	−1.4	0.5	−1.8
Summer	Mean	13.9	13.3	14.2	13.8	15.5	14.8	15.4	15.0
	Maximum	22.0	22.2	23.0	24.1	25.7	23.9	25.5	27.4
	Minimum	4.9	3.7	4.8	3.8	7.0	6.5	6.6	4.7
Autumn	Mean	8.3	10.7	8.4	11.0	9.5	11.6	9.4	11.9
	Maximum	18.5	22.3	18.6	24.0	20.5	22.7	20.2	27.0
	Minimum	−7.3	0.4	−7.5	0.7	−4.9	3.3	−7.2	2.2
Winter[a]	Mean	2.2	4.1	2.2	4.1	3.0	4.5	3.1	4.9
	Maximum	11.8	15.2	12.6	16.4	13.4	14.9	14.0	16.1
	Minimum	−9.3	−5.6	−9.8	−5.8	−7.5	−3.3	−9.0	−4.7

[a] Winter is the period of December of the year and January and February of the next year.

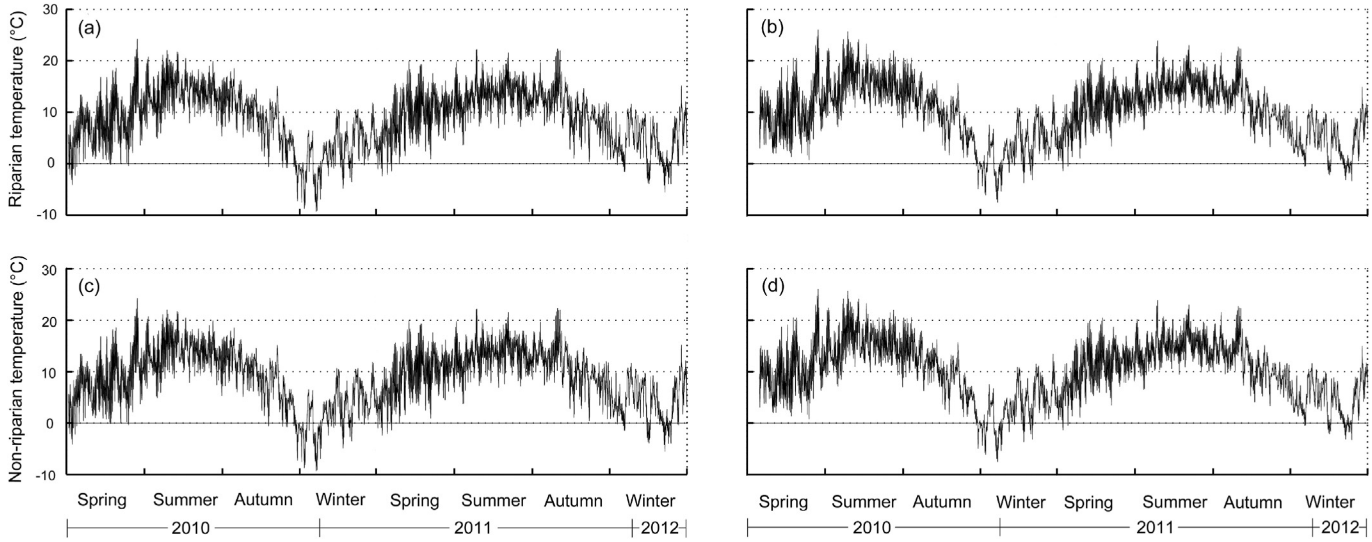

Fig. 3. Mean hourly temperatures of rural riparian (a), urban riparian (b), rural non-riparian (c), and urban non-riparian (d) locations for 10 rural and 10 urban sites. Winter includes the month of December, January and February.

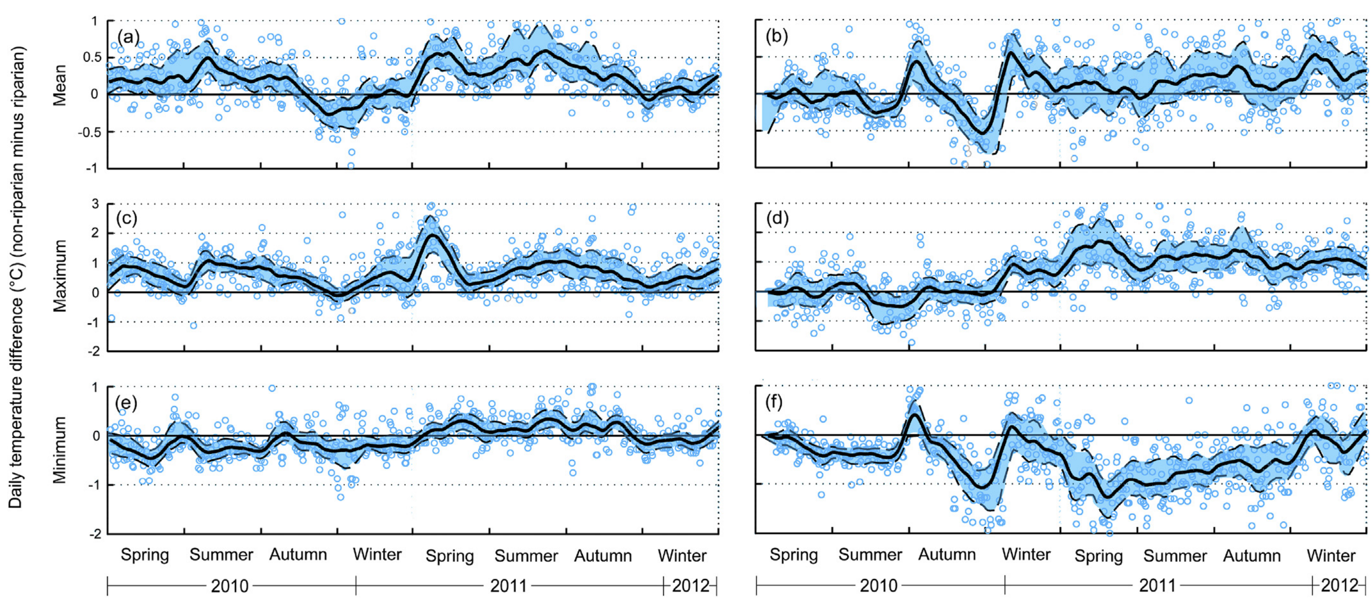

Fig. 4. Average differences in rural daily mean (a), urban daily mean (b), rural daily maximum (c), urban daily maximum (d), rural daily minimum (e), and urban daily minimum (f) temperatures between riparian and non-riparian locations in 10 rural and 10 urban sites. Values above the zero line indicate that non-riparian temperatures were higher than riparian temperatures. Blue open circles represent actual data. Black solid lines, black dashed lines, and blue areas indicate smoothed trends using LOWESS and 95% confidence intervals, respectively. Winter includes the month of December, January and February. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

riparian locations in 2011 and frequently in 2010 (Fig. 4).

3.3. *The relationships between air temperatures and environmental factors*

UI was positively related to average daily mean and minimum temperatures at rural sites, and with average daily mean and maximum temperatures at urban sites (Table 4). CC had a negative relationship with average daily maxima in rural and urban sites, but a positive association to average daily minima in rural sites (Table 4).

Breaking down the analysis by seasons indicates that the positive relationship between UI and temperature was most marked for urban sites in summer and for rural sites in autumn; sites with greater UI had higher daily mean, minima, and maxima temperatures (Table 5). UI was also positively correlated with daily mean and minimum temperatures in urban sites in autumn and in rural sites in spring (Table 5). CC was negatively correlated with summer daily maximum temperatures at all sites and with summer daily mean temperature at rural sites (Table 5). Summer daily mean and maximum temperatures were higher in non-riparian than riparian locations at all sites (Table 5). Rural non-riparian locations also had higher average daily means and maxima in spring (Table 5). In urban areas, non-riparian locations had higher average daily maxima in autumn and winter, higher average daily means and maxima in summer and winter and lower average daily minima in spring and summer (Table 5).

Table 4
Results of mixed-effects models for testing the effect of Location (riparian vs non-riparian), UI (urban index) and CC (canopy cover) on average seasonal daily values (means, maxima, minima) for annual patterns including 'site' and 'year/season' as random effects. Asterisks indicate the significance of the p value estimated based on Satterthwate's approximation. Coeff. and SE represent the estimated coefficient and standard error of each independent variable in each model.

Index	Effect	Rural		Urban	
		Coeff.	SE	Coeff.	SE
Mean	Rip vs. Non-rip	NS	–	NS	–
	UI	0.05**	0.02	0.01 ($p = 0.07$)	0.01
	CC	NS	–	NS	–
Maximum	Rip vs. Non-rip	0.44**	0.17	0.81***	0.20
	UI	NS	–	0.02 ($p = 0.08$)	0.01
	CC	−0.02*	0.01	−0.04*	0.01
Minimum	Rip vs. Non-rip	NS	–	−0.55***	0.14
	UI	0.11***	0.03	NS	–
	CC	0.01*	0.01	NS	–

***$p \le 0.001$, **$p \le 0.01$, *$p \le 0.05$, NS not significant ($p > 0.1$).
The positive values of coefficients of 'Rip vs. Non-rip' represent that thermal variables were higher in non-riparian than in riparian locations. The positive values of coefficients of 'UI' and 'CC' represent positive correlation with thermal variables.

4. Discussion

Riparian corridors were cooler than non-riparian locations, which is consistent with previous studies (Brosofske et al., 1997; Hathway & Sharples, 2012; Murakawa et al., 1991). The cooling effect of Sheffield rivers was generally about 1 °C, but was up 3 °C during extremely hot weather. In addition to the cooling effect, we also observed a mild warming effect of urban rivers during the winter.

4.1. Cooling effects

A riparian cooling effect was observed in both in rural and urban areas, suggesting that these rivers have a moderating effect on local temperature across both landscapes. Previous studies have also observed the cooling effect in forested riparian corridors (Anderson et al., 2007; Brosofske et al., 1997; Rykken et al., 2007), but here we see it in systems with much lower CC (i.e. mean for riparian locations: 58% [rural] and 17.7% [urban]). However, the magnitude of cooling effect observed in the current study was relatively small compared with those in the previous studies. Daily maximum temperatures in rural riparian corridors in this study were about 0.5 and 0.8 °C cooler than non-riparian locations in spring and summer, respectively. This may be partly due to the differences in timing and scale of measurement. Previous studies summarised in Table 1 have focused on the cooling effect in hot weather and only monitored temperatures over a short period of time. Our study focused on the entire seasonal pattern, across two years and across a large number of sites. There are clearly individual sites and occasions in which temperature differences are closer in magnitude to some of those from previous studies. One interesting comparison in this regard is with the study by Hathway and Sharples (2012) because this was also conducted on the River Don in Sheffield, but at a very urbanised location in the city centre. They demonstrated that the river had a 1.5 °C cooling effect, and that this effect was greater in spring than in summer, possibly because higher river water temperature in the summer may limit the cooling capacity of the river (Hathway & Sharples, 2012). In the current study, the cooling effect on riparian corridors in urban sites was not so obvious in spring, but was about 1.1 °C in summer, which is similar to the cooling mitigation observed by Hathway and Sharples (2012).

4.2. Warming effects

The current study revealed not only a cooling effect, but also a warming effect in the riparian corridor when the weather was relatively cold, in particular as air temperatures fell below 0 °C (Fig. 4). This warming effect was apparent in urban but not in rural sites, with the temperature difference for urban sites being as much as 2 °C. The diurnal thermal range of rivers is smaller than that of surrounding air temperatures because water has a relatively high specific heat capacity (Steeneveld et al., 2014). Possible explanations for the warming effects in urban riparian locations include relatively warm urban rivers limiting the decline in air temperature in cold weather (Theeuwes, Solcerová, & Steeneveld, 2013). The other cause of this effect may be due to the thermal instability of environments resulting from an increase in sensible heat flux in urban areas (Oleson et al., 2013). The fact that the percentage CC was lower in urban than rural sites, may explain why the warming effect was only observed in urban study sites as increasing vegetation reduces the extent of local daily thermal range (Davis, Jung, Pijanowski, & Minor, 2016; Huang, Zhao, Wang, Zhu, & Li, 2008; Park, Kim, Lee, Park, & Jeong, 2017; Roy, Byrne, & Pickering, 2012). To date, the warming effect of surface waters on local temperatures has been poorly documented and understood, in particular the case of the warming effect of rivers on riparian corridors. We are aware of only one study, that of Brosofske et al. (1997), who found a 0.5 °C warming effect in the riparian zone compared to a location 67 m from the river on summer mornings. Similarly, we found a slight warming effect, about 0.7 and 0.5 °C, of urban riparian corridors in spring and summer, respectively.

4.3. Topographic effects

Moore, Spittlehouse, and Story (2005) showed that steep valleys may enhance the thermal effect of rivers on riparian corridors due to cold air sinking down slope in hot weather, suggesting that the geometry of valleys may also have an effect on riverine thermal conditions. Furthermore Brooks and Kyker-Snowman (2009) suggested that the reason why they found no difference in temperatures between riparian and non-riparian locations, was possibly due to the flat topography of their study sites (i.e. stream valley slope about 8%). In the current study, the valley slope were less steep than those of Brooks and Kyker-Snowman (2009) (i.e. average of 7.7% for rural sites and 3.5% for urban sites, calculated for the distance between riparian and non-riparian locations), yet the thermal effect of rivers on riparian temperatures was still significant. These results suggest that the effect of rivers is not simply dependent on local topography.

4.4. Effects of impervious surfaces and canopy cover

UI and CC were also important landscape characters affecting riverine local thermal conditions. As expected, UI was strongly associated with daily thermal indices (i.e. mean, maximum, minimum) in both rural and urban areas: the higher the proportion of UI, the higher daily temperature. The effect of canopy cover on air temperature was relatively weak and only discernible for summer in both areas. Trees could effectively reduce air temperature through shading effects and the process of evapotranspiration when leaves were present (Georgi & Dimitriou, 2010), suggesting one reason why the canopy cover effect on reducing extreme air temperature may be more apparent in the growing season than at other times.

One thing that is clear in our results is that there is considerable site-to-site variation in both temperatures and the effect of the river on the riparian/non-riparian difference. The intensity of

Table 5
Results of mixed-effects models for testing the effect of Location (riparian vs non-riparian), UI (urban index) and CC (canopy cover) on average daily values (means, maxima, minima) and for seasonal patterns including 'site' and 'year' as random effects. Asterisks indicate the significance of the p value estimated based on Satterthwate's approximation. Coeff. and SE represent the estimated coefficient and standard error of each independent variable in each model.

Season	Index	Effect	Rural		Urban	
			Coeff.	SE	Coeff.	SE
Spring	Mean	Rip vs. Non-rip	0.26**	0.09	NS	–
		UI	0.04*	0.02	NS	–
		CC	NS	–	NS	–
	Maximum	Rip vs. Non-rip	0.81*	0.32	NS	–
		UI	NS	–	NS	–
		CC	NS	–	NS	–
	Minimum	Rip vs. Non-rip	NS	–	−0.73*	0.31
		UI	0.07 ($p = 0.08$)	0.04	NS	–
		CC	NS	–	NS	–
Summer	Mean	Rip vs. Non-rip	0.36**	0.13	0.33 ($p = 0.07$)	0.18
		UI	NS	–	0.02*	0.01
		CC	−0.01*	0.004	NS	–
	Maximum	Rip vs. Non-rip	0.70*	0.26	1.12**	0.33
		UI	NS	–	0.04*	0.02
		CC	−0.02*	0.01	−0.05*	0.02
	Minimum	Rip vs. Non-rip	NS	–	−0.45 ($p = 0.06$)	0.02
		UI	NS	–	0.02 ($p = 0.06$)	0.01
		CC	NS	–	NS	–
Autumn	Mean	Rip vs. Non-rip	NS	–	NS	–
		UI	0.09**	0.03	0.02*	0.008
		CC	NS	–	NS	–
	Maximum	Rip vs. Non-rip	NS	–	0.71*	0.34
		UI	0.11*	0.04	NS	–
		CC	NS	–	NS	–
	Minimum	Rip vs. Non-rip	NS	–	NS	–
		UI	0.11*	0.05	0.02 ($p = 0.07$)	0.01
		CC	NS	–	NS	–
Winter	Mean	Rip vs. Non-rip	NS	–	0.28*	0.13
		UI	NS	–	NS	–
		CC	NS	–	NS	–
	Maximum	Rip vs. Non-rip	NS	–	0.87***	0.24
		UI	NS	–	NS	–
		CC	NS	–	NS	–
	Minimum	Rip vs. Non-rip	NS	–	NS	–
		UI	NS	–	NS	–
		CC	NS	–	NS	–

***$p \leq 0.001$, **$p \leq 0.01$, *$p \leq 0.05$, NS not significant ($p > 0.1$).
The positive values of coefficients of 'Rip vs. Non-rip' represent that thermal variables were higher in non-riparian than in riparian location. The positive values of coefficients of 'UI' and 'CC' represent positive correlation with thermal variables.

urbanisation in terms of proportion of impervious surface (i.e. UI) does not take any account of local built topography (i.e. structure or layout of the buildings), which may influence local airflow and in turn have an effect on local thermal conditions (Hathway & Sharples, 2012; Krüger, Minella, & Rasia, 2011). It is likely that some of the site-to-site variation will be a result of this local variation in airflow. Similarly, other variables, such as the proportion of dark material used in buildings and the height of buildings, which influence micro-scale heat budgets may also differ between sites (Qaid, Bin Lamit, Ossen, & Raja Shahminan, 2016), but the spatial and temporal scales of our investigation and the public nature of most of the sites precluded monitoring this level of detail.

5. Conclusion

The creation of thermal refuges is an important element in ecosystem restoration programmes in urbanised landscapes where urban heat islands occur (Dugdale, Bergeron, & St-Hilaire, 2015; Pincebourde, Murdock, Vickers, & Sears, 2016). The current study provides one of the most spatially and temporally extensive assessments of the effects of urban rivers on the thermal conditions in riparian habitats, and supports the idea that thermal refuges could be provided by the consideration of such habitats into the design of resilient cities. Moreover, urban riparian corridors, in providing linear, continuous, green and blue infrastructure through urban areas, also play essential roles in connecting fragmented habitats (Chen et al., 2016; Matsuba, Nishijima, & Katoh, 2016). In addition to the documentation of the effect of the rivers, results from the current study could also be used to predict the effect of land-use transformation (e.g. changes in the proportion of impervious surface) on the extent of riverine thermal effect. As a consequence of their particular river-mediated temperature characteristics, riparian corridors may form important habitats and enhance functional connectivity in human-dominated landscapes.

Conflict of interest

The authors declare that they have no conflict of interest.

Author contributions

PW and LM originally formulated the idea, CT, TY, PW and LM developed methodology, CT and TY conducted fieldwork, CT carried out the analyses, CT, PW and LM wrote the manuscript.

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