Urban Forestry & Urban Greening 93 (2024) 128212

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Economic value of the hot-day cooling provided by urban green and blue space

Laurence Jones [a,*], David Fletcher [a], Alice Fitch [a], Jake Kuyer [b], Ian Dickie [b]

[a] UK Centre for Ecology & Hydrology, Environment Centre Wales, Deiniol Road, Bangor LL57 2UW, UK
[b] Economics for the Environment Consultancy, London, UK

ARTICLE INFO

Keywords:
Green infrastructure
Blue infrastructure
Cities
Natural capital
Ecosystem services

ABSTRACT

Increasing high temperatures due to climate change are exacerbated by urban heat island effects, resulting in a range of human health and economic impacts. The green and blue infrastructure (GBI) in cities that underpins nature-based solutions (NBS) can help alleviate hot-day temperatures. In this study we bring together multiple data sources to evaluate the cooling benefit provided by urban GBI in terms of avoided losses in labour productivity, for eleven City Regions in Great Britain, over a ten-year period. We defined the urban extent to include the green (woodland, grassland and parks, gardens) and blue (rivers and canals, lakes and ponds) features within cities, and derived aggregate cooling factors for urban areas in each City Region, applying additional cooling factors to buffer zones around larger GBI features. We collated gridded meteorology data to assess the number of hot-days exceeding 28 °C Wet Bulb Globe Temperature in each City Region over the period 2008–2017, and applied response functions to evaluate loss of worker productivity for ten economic sectors. For the GBI features (aggregated adjacent features >200 m^2), gardens make up the biggest component (26% of urban extent) closely followed by grassland and parks (24%), with woodland at 6%. The aggregate cooling factor of GBI ranged from 0.64 – 0.89 °C across the eleven City Regions. The economic benefit of cooling was greatest for London, due to its greater exposure to hot days, and its greater contribution to the economy than other City Regions. In the hottest year of 2015, the cooling benefit in London was £ 13.97 m. The cooling benefit varied considerably from one year to the next, depending on meteorology, and will increase under climate change.

1. Introduction

In the context of rising global temperature extremes, how we manage cities is critical to addressing a range of potential impacts on ecosystems and people. Global temperatures are forecast to rise substantially by the end of the century (Tebaldi et al., 2021), and cities in many parts of the world are projected to experience greater warming than the regional averages (Zhao et al., 2021). These average projections also mask considerable variation in temperature extremes, and heatwaves are already becoming more prevalent worldwide, increasing in intensity, duration and frequency (Perkins-Kirkpatrick and Lewis, 2020). Heatwaves cause a wide range of impacts on people, particularly for those living in cities where temperatures are already higher than rural surroundings due to the Urban Heat Island (UHI) effect (Kim and Brown, 2021). For example, the 2003 heatwave in Europe caused an estimated 14,600 deaths in France (Pirard et al., 2005) and 9600 deaths in Germany (An Der Heiden et al., (2020)), and heat is an increasing issue for health and human comfort worldwide (Ren et al., 2022, Yang et al., 2019). Less frequently reported are other impacts such as a decline in worker productivity or increase in energy use for cooling (Hatvani-Kovacs et al., 2016, Costa et al., 2016). The effects of climate change can be non-linear where they hinge on exceedance of particular temperature thresholds. For example, response functions for worker productivity typically use a Wet Bulb Globe Temperature threshold of 28 °C (Costa et al., 2016), and the frequency at which hot day temperatures exceed this threshold in temperate climates will greatly increase under climate change. Labour losses are likely to become an increasingly important impact of climate change (Hsiang et al., 2017).

Green and blue infrastructure (termed GBI in this paper) in urban settings underpins the ability of nature-based solutions (NBS) to provide benefits to people (Jones et al., 2022). The many benefits of GBI are widely described, and increasingly quantified. GBI types such as parks, green roofs, lakes and rivers provide benefits such as removal of air pollution to reduce harmful exposure to pollutants (Jones et al., 2019,

---

* Corresponding author.
E-mail address: LJ@ceh.ac.uk (L. Jones).

https://doi.org/10.1016/j.ufug.2024.128212
Received 16 June 2023; Received in revised form 11 January 2024; Accepted 12 January 2024

Tiwari et al., 2019, Nowak et al., 2014), reduction in noise pollution (Fletcher et al., 2022, Van Renterghem et al., 2012), reduction of flood risk (Berland et al., 2017), improvement of urban water quality (Livesley et al., 2016), cooling of cities (Aram et al., 2019, Bowler et al., 2010), in addition to a range of benefits for physical and mental wellbeing, relaxation and social interaction (Jones et al., 2022).

GBI influences temperature through a number of mechanisms (Chen et al., 2014). Vegetation provides cooling through evapotranspiration from the vegetation and the underlying soil system, while taller vegetation such as trees and shrubs provide additional cooling through shading (Gunawardena et al., 2017). Water has a large specific heat capacity and blue features provide cooling through evaporation, with moving waters being particularly efficient at cooling because inflowing water brings colder water from rural areas upstream and moving water transfers heat away from the hotter urban areas as it flows downstream. For static water bodies, the capacity to provide cooling is largely dependent on water volume and depth, as well as surface mixing (Manteghi et al., 2015). Wind direction can also influence cooling potential and reach. The cooling effect of both water bodies and green space is greater on their downwind side as cooled air is transferred by the wind (Santamouris et al., 2017).

Many studies have focused on quantifying UHI, and spatial mapping of hot areas using remote sensed data, primarily from satellites, such as Land Surface Temperature (LST) (Guo et al., 2021, Chen et al., 2014). This has the advantage of producing spatially explicit outputs and mapped products, allowing investigation of hot and cool spots in the city, the latter often referred to as Urban Cool Islands (Ren et al., 2018). However, LST is dominated by incident radiation interacting with the thermal properties of the urban fabric (Palme et al., 2018). Air temperatures are influenced to a greater extent by other properties such as wind speed and origin, and the cooling benefits reported in the literature from studies based on LST are typically over-estimates when compared with measured air temperatures (Aram et al., 2019).

Relatively few studies have quantified the cooling effects of a range of GBI types on air temperature, at city scale (Aram et al., 2019, Marando et al., 2019), and fewer yet have conducted health or economic assessments of the cooling benefits (Iungman et al., 2023, Barboza et al., 2021). There is a need to develop calculation methods that can be used to evaluate the economic benefit of hot-day cooling in a spatially-contextual manner, which is scalable or is applicable to multiple cities and time points.

Therefore, in this paper we develop an economic assessment of the cooling benefit provided by GBI, with a focus on lost economic productivity on hot days exceeding a 28 °C wet bulb globe temperature (WBGT) threshold. This study combines information from a range of data sources, including urban morphology derived from satellite data and mapping data, mapping of green and blue infrastructure types in urban areas combined with satellite data, meteorological data on hot days, and economic data. Using new approaches, we 1) calculate aggregate cooling by urban green and blue infrastructure over a defined city area, 2) estimate the economic benefit of that cooling, in terms of avoided productivity losses during hot days above a 28 °C WBGT threshold, and 3) show how that cooling benefit varies over a sequence of 10 years (2008–2017), using UK cities as an example.

2. Methods

2.1. Datasets

2.1.1. Land cover of green and blue space urban features

The approach to derive urban green and blue space land cover categories combines remote sensing data, survey mapping data and a morphology layer of urban settlements. Together, these datasets allowed us to develop a comprehensive assessment of the area of green and blue space within urban areas of Great Britain.

Firstly, we defined the urban footprint boundary (urban extent), within which all GBI features could be considered part of the urban fabric. The approach we used modified an existing urban morphology GIS layer, which represented built land-use but not natural areas. Data were obtained from the Office of National Statistics Built Up Area layer 2011 (BUA2011), which is a vector map of polygons representing urban built up area, but which exclude larger areas of woodland, parks, grassland and waterbodies within cities which should be considered a relevant part of the urban landscape. Our approach applied a variable sized buffer to each urban morphology polygon using Eq. 1, with the dimensions of the buffer being proportional to the size of the urban area. We then dissolved overlapping boundaries for each polygon and as a last step reduced the new boundary by the same buffer width to return to the dimensions of the outer boundary of the original extent. A fuller explanation of the method is provided in Jones et al. (2019). The coefficient was derived through multiple iterations of the approach to arrive at a buffer size which captured most urban green and blue infrastructure features without merging adjacent settlements.

$$\text{Buffer width} = 0{\cdot}012 * \sqrt{\text{Polygon area}} \tag{1}$$

The effect of this procedure is to encapsulate any areas enclosed by the buffer (i.e. if the outer edges of buffered zones meet then it captures the entire area) – see Fig. 1. For example, this incorporates patches of land that are mostly surrounded by urban built-up-areas, such as larger rivers, reservoirs and parks in cities that are otherwise excluded from existing morphology layers.

In order to calculate locations and area of GBI features within the urban extent, we used a combination of satellite data and national mapping products. Land cover was derived from the 25 m CEH Land-cover Data product (Morton et al., 2011). Mapping land use and land cover of finer-scale urban features made use of cadastral data and national survey mapping products, the UK Ordnance Survey MasterMap. OS MasterMap records boundaries and land use, but only records land cover in a highly simplified scheme. For example, areas are defined as either ‘natural surface’ or ‘mixed’ where they include natural features, but additional recording fields completed by surveyors can be used to further differentiate types of natural area. From these data sources we defined green GBI features for woodland, grassland and gardens, as well as blue GBI features including rivers, canals, lakes, ponds and reservoirs.

Woodland was defined as ‘natural surface’ features where trees or woodland were mentioned in the recording fields of OS MasterMap. Woodland polygons $< 200\ \text{m}^2$ were excluded and remaining woodland was separated into two size classes ($<$ and $> 30{,}000\ \text{m}^2$). Grassland was defined as all ‘natural surface’ features described as grassland in surveyor notes of OS MasterMap, which includes areas of open parkland, grassland, playing fields, extensive grass verges, some of which may contain trees. As with woodland, areas $< 200\ \text{m}^2$ were excluded, due to their low importance in providing a cooling service. Gardens in OS MasterMap are recorded as a ‘Mixed Surface’. All areas of Mixed Surface adjacent to buildings were selected, and polygons of contiguous gardens were amalgamated, in order to include composite areas large enough to provide a service. Therefore, only contiguous garden $> 200\ \text{m}^2$ was included for analysis. In several studies 0.1 ha is used as a lower limit of greenspace size, e.g. (Xiao et al., 2023), but here we use a slightly smaller size in order to assess aggregate effects at city level.

For blue GBI features, ‘Natural surface’ features in OS MasterMap identified as ‘water’ were selected. Since cooling effects differ for linear features like rivers and canals compared with larger water bodies, these needed to be differentiated in GIS. Automation of this process was based on the Polsby-Popper test to determine whether a water body was likely to be a lake or a river. The Polsby-Popper test uses the following equation for the relationship between area and perimeter to define mathematical compactness (Eq. 2). Lakes, ponds and reservoirs were features with $PP > 0.25$, while rivers and canals were features where $PP < 0.25$.

$$\text{PP} = 4\text{*PI*area/perimeter\^{}2} \tag{2}$$

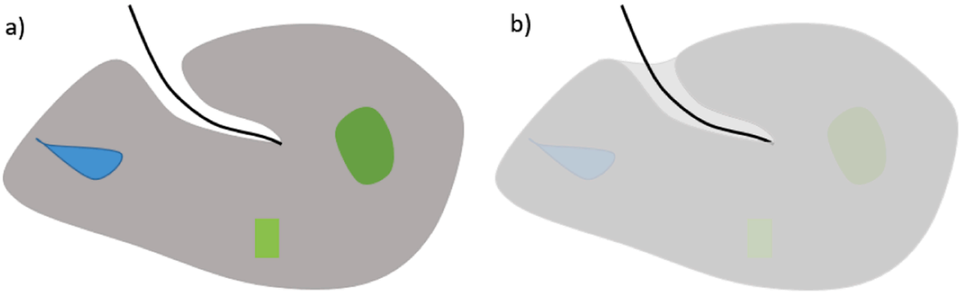

Fig. 1. Illustration of the effect of using a variable buffer to encapsulate areas of GBI within an urban footprint, showing a) before and b) after applying the variable buffer method. The new urban footprint 'captures' a reservoir, area of woodland, sports-ground and a green corridor along a road artery into the city, thus incorporating these into the full urban footprint.

We used a threshold width for rivers and canals of 25 m for inclusion in the analysis. This threshold reflects a balance between evidence that a river of this size can provide a cooling effect, e.g. the River Don in Sheffield, UK which is 22 m wide (Hathway and Sharples, 2012), and challenges in defining linear blue space features in GIS. The threshold was applied as follows – linear blue space features had a negative buffer of 12.5 m applied. If the resulting geometry had an area of zero then the river must be narrower than 25 m. If greater than zero at least some part was > 25 m, and these features were retained for analysis. Lakes, ponds and reservoirs < 700 m^2 were also excluded from analysis due to their low contribution to cooling. For all green and blue GBI features, contiguous areas of the same type were amalgamated prior to analysis to avoid problems when calculating and applying buffer zones.

2.2. Meteorological data on hot-days

The meteorological data used to calculate the number of hot-days, each year over the period 2008–2017, was taken from the UK Met Office Hadley Centre HadUK-Grid, daily maximum temperature 'tasmax' at 1 km resolution. Air temperature was converted to wet bulb globe temperature using the conversion functions in Vecellio et al. (2022) and Stull (2011). For the conversion function, we calculated average relative humidity of 65.9% from daily relative humidity at three urban monitoring locations (London, Birmingham, Manchester) during 3 heatwave events of minimum 10 days duration each in the years 2013, 2018 and 2019. Using this function for example 28 °C WBGT equates to an air temperature of 33.3 °C. For each 1 km grid cell, we calculated the number of days where daily maximum WBGT fell within incremental temperature bands above 28 °C, i.e. number of days in a given year where a grid cell recorded a temperature of 28–29 °C, 29–30 °C etc., truncated above 34 °C, i.e. the highest band included any recorded temperature greater than or equal to 34 °C. This was repeated for each year from 2008 – 2017. Subsequently, the average of number of days within each temperature band was calculated across all grid cells within the urban extent for each of the city regions.

2.3. Cooling factors

Cooling factors for each urban green or blue space type were derived from the literature. Despite the seemingly large literature on this topic, the number of modelling studies or studies based on interpretation of land surface temperature data vastly outweigh primary studies measuring air temperature differentials (Aram et al., 2019), and there remain substantial knowledge gaps around cooling of air temperature provided by many green or blue space types (Jones et al., 2022).

The literature on cooling potential from blue GBI is less comprehensive than for green space, and cooling factors vary. Kleerekoper et al., (2012) report a range of air temperature cooling from 1 – 3 °C. A meta-analysis comprising 27 studies suggested an average of 2.5 °C cooling for blue space relative to the surrounding urban fabric (Völker et al., 2013). For ponds and static water bodies, reported air temperature cooling for small ponds varies from e.g. 1 °C (4x4m) (Robitu et al., 2004), 1.2 °C in Japan (Ishii et al., 1991), and 1.6 °C for a 4 ha pond in Israel (Saaroni and Ziv, 2003) to values up to 3.5 °C for large urban lakes (Völker et al., 2013). A larger number of theoretical or modelling studies suggest cooling factors ranging from 0.4 to > 7 °C (O'malley et al., (2015), Santamouris et al., 2017). For moving water, size matters. Rivers greater than 30 m in width provide a greater cooling of the surrounding LST (Jiang et al., 2021). Cooling of air temperature up to 3–5 °C was measured for the fairly large Ota River in Japan (270 m wide) (Murakawa et al., 1991). In the River Don, Sheffield, UK, Hathway (2012) showed an average cooling of 1 °C when air temperatures were greater than 20 °C, with greater cooling differential observed on hot days in late spring when the temperature differential rose to 2 °C at the river, and 1.5 °C over the river bank. Since cooling factors will vary by climate (Völker et al., 2013), we preferentially focus on UK or similar temperate zone studies. The selected cooling factors for urban blue GBI, and the buffers over which they operate are shown in Table 1. For rivers and canals, we took the summarised cooling value of 1.4 °C from Hathway (2012) and for static water bodies we selected the value of 2.5 °C from Völker (2013) to cover the reported range across surface water features from ponds 1.6 °C up to urban lakes 3.5 °C.

For urban green GBI, there is more literature than for blue GBI (Bowler et al., 2010). Reported cooling effects on day time air temperatures range from < 1 to 6.9 °C (Aram et al., 2019). Studies focusing specifically on trees are fewer than on parks or mixed green space. Modelling studies of shading effects of trees across the US suggests an aggregate cooling effect of 3.06 °C in cities in summer (Wang et al., 2018). In Europe, Larondelle (2013) showed a 3.5 °C cooling in areas with extensive urban tree cover, based on measurements in Leipzig. Urban parks are treated separately from urban trees in this analysis as

Table 1
Width of buffer applied to different green / blue space types, and temperature differential applied for green / blue space and buffers. n/a – not applicable.

	Width of buffer to apply (m)	Temperature differential (°C)	
		Applied to green / blue feature	Applied to buffer
Urban blue space			
Rivers/canals (>25 m wide)	30	-1.4	-0.8
Lakes, ponds, reservoirs (>700 m2)	30	-2.5	-1.425
Urban green space			
Woodland (200 < x < 30,000 m2)	0	-3.5	n/a
Woodland (>30,000 m2)	100	-3.5	-0.52
Open parks & grassland (>200 m2)	0	-0.945	n/a
Contiguous gardens (>200 m2)	0	-0.945	n/a

UK parks typically have greater grass cover than tree cover. Air temperature cooling effects for parks reported in the literature range from 3.8 °C for a medium size park in Tel Aviv (Cohen et al., 2012) to 1–2 °C for a small park in Seoul (Park et al., 2017). Although some individual studies show quite large magnitude of cooling effect, since values reported in the literature vary so widely, for this study we use the robustly established value from a meta-analysis of 0.945 °C for both large and small parks (Bowler et al., 2010). We note this is a conservative estimate. For gardens there is some mixed use of terminology in the literature where the term 'garden' is used to describe both private greenspace as part of a dwelling, which would be described as a domestic garden in a UK context, and small areas of greenspace which are otherwise publicly accessible but not part of or associated with residential buildings. Domestic gardens in the UK have a median size of 96 - 213 m^2 (Loram et al., 2007), with lawns covering around 60% of garden area (Gaston et al., 2005) and tree cover varying between 0.3 – 11% (Whitford et al., 2001). There are few studies in the literature looking at green space of this size. A small green space of 0.24 ha (2400 m^2) in Lisbon showed temperature differentials of 1.6 °C for median air temperature, and up to 6.9 °C for daily maximum temperature (Oliveira et al., 2011). A lush garden in Gabarone, Botswana showed a cooling effect of up to 2 °C (Jonsson, 2004). For gardens we assumed that contiguous garden area was more likely to show a cooling effect. The structure of contiguous garden space fits the urban form of many UK residential areas, where gardens are adjacent to each other for terraced properties and back-back for parallel roads in many housing developments. For this green GBI component, we assumed the same cooling factor as applied to large parks, of 0.945 °C (Bowler et al., 2010) for contiguous gardens of collective area > 200 m^2.

The cooling effects for larger green and blue GBI types extend beyond the immediate boundary of the feature. Despite this, assessment of buffer zones is relatively sparsely in the literature, particularly for blue space features. Hathway (2012) studying a UK river, the Don in Sheffield, report a greater cooling effect at 20 m than at 30 m, but still measurable at the latter distance. While for the Ota River in Japan, the cooling effect extended to 100 m from the banks (Murakawa et al., 1991). Taking a conservative approach for UK rivers, which tend to be relatively narrow compared with others studied in the literature, we use a buffer of 30 m in this analysis, following Hathway (2012), applying the same buffer both for rivers and for static water bodies. Buffer zones for green GBI are frequently calculated in the literature from Land Surface Temperature data, but are also calculated from direct measurements of air temperature. The calculated distance of buffer zones ranges from 40 m to > 1000 m, depending on the size of the green space, the climate and the calculation approach (Lin et al., 2021, Yan et al., 2018, Vaz Monteiro et al., 2016). Studies which have derived air temperature from LST data, suggest a buffer of 200 m is applicable (Bird et al., 2022). Spronken-Smith and Oke (1998) report that the buffer zone of a park is equivalent to the park width (Spronken-Smith and Oke, 1998). Here we apply a cooling factor of 0.52 °C for the buffer area of woodland, large parks and adjacent gardens > 200 m^2, with the buffer area assuming to extend to 100 m (Larondelle and Haase, 2013). This effectively applies the same cooling factor across the entire buffer, although in reality it will be greatest at the boundary of the greenspace and decrease to the outer edge of the buffer. The choice of buffer width and its application only to large parks are both deliberately conservative.

The cooling factors for each green and blue GBI type were applied as follows. We created an alternative scenario of the WBGT temperature dataset where the cooling factor associated with existing GBI did not apply (i.e. temperatures were higher), and re-calculated the number of days above the WBGT threshold of 28 °C, as described in the previous section.

2.4. City Regions and economic data

We selected eleven of the main City Regions in Great Britain (Table 2), purposely defined to include the major cities in England in terms of economic productivity, and at least one city each in Scotland and Wales. Boundaries of City Regions were obtained from UK Office of National Statistics. Remaining rural areas were geographically defined on the basis of the European Nomenclature of territorial units for statistics NUTS1 units (major socio-economic regions). Fig. 2 shows the combined geometry of City Regions, and the remaining NUTS1 areas not including selected city regions. Note some City Regions encompass large urban conglomerations e.g. Greater Manchester City Region, while others include considerable rural area as well e.g. North East City Region. The City Regions are used as the basis of the economic calculations, but note that the cooling effects are calculated only for the urban footprint within those. This is an ongoing challenge when combining socio-economic data only reported at the level of administrative unit with biophysical impact calculations assessed for specific geographies.

Table 2
Major City Regions in Great Britain, showing population (2015) and relative contribution to Gross Value Added (GVA). Data from UK Office of National Statistics.

City Region	Code on map, Fig. 1	Population (2015)	Relative contribution to GB GVA
West of England	20	1119,000	1.93%
Cardiff	11	1505,000	1.48%
Greater Manchester	14	2756,000	3.67%
Liverpool	15	1525,000	1.72%
North East	17	1957,000	2.11%
Sheffield	18	1375,000	1.25%
West Midlands	19	2834,000	3.72%
West Yorkshire	21	2282,000	2.77%
Glasgow	13	1804,000	2.37%
Edinburgh	12	1350,000	1.62%
London	16	8674,000	26.07%

Data on economic productivity for each City Region was collated from the UK Office of National Statistics, for the following ten sectors, summarised in Table 3: Mining and Utilities, Manufacturing, Construction, Wholesale and Retail trade/ repair of motor vehicles, Transportation and storage, Accommodation and food service activities, Information and Communication, Real Estate Activities, Professional, scientific and technical activities, Administrative and Support Service activities.

Productivity losses were calculated from response functions in Costa et al. (2016), which in turn were based on ISO standard 7243:1989 for an average acclimatised worker wearing light clothing, following methods in Kjellstrom et al. (2009). These assume a proportional reduction in productivity with temperature above a WBGT threshold of 28 °C. Different sectors have different response functions, depending on the intensity of the work typically undertaken (Fig. 3). Non-attributable sectors were combined into a category 'Other Services' where productivity losses were applied for wet bulb temperatures greater than or equal to 34 °C.

3. Results

3.1. Urban GBI extent

The total urban area defined by the urban footprint in Great Britain, as calculated in this study was 17,598 km^2, of which the urban area included within the 11 City Regions was 6627 km^2 (Table 4). Overall, woodland greater than 200 m^2 makes up 6% of the City Regions' urban area, grassland/parks greater than 200 m^2 make up 24% and contiguous gardens greater than 200 m^2 make up the largest single category at 26% of urban area. The blue features comprising rivers/canals more than 25 m wide, and lakes/ponds greater than 700 m^2, make up less than 1% of urban area between them. The full area by category and City Region, including buffer areas applied, is shown in Supplementary Material Table S1.

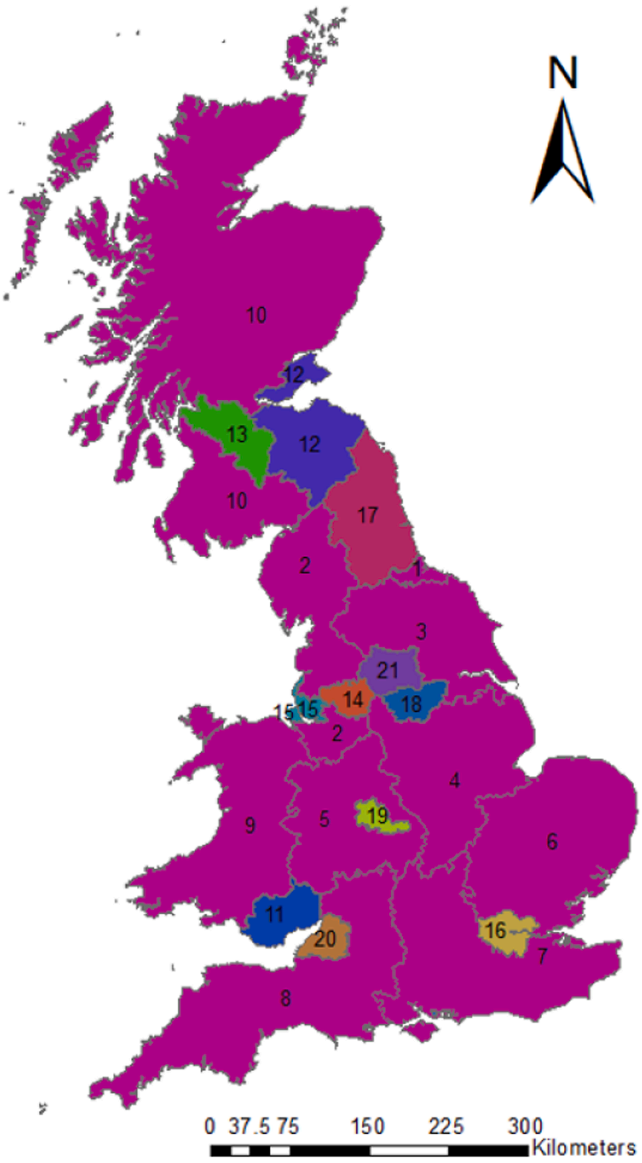

Fig. 2. Boundaries of City Regions and remaining NUTS1 areas (European Nomenclature of territorial units for statistics – major socio-economic regions). Table 2 gives names of City Regions. Remaining codes for NUTS 1 areas are for England: 1 North East, 2 North West, 3 Yorkshire and The Humber, 4 East Midlands, 5 West Midlands, 6 East of England, 7 South East, 8 South West; for Wales: 9 Wales excluding Cardiff; for Scotland: 10 Scotland excluding Edinburgh and Glasgow.

3.2. Calculated cooling factors for each City Region

Calculated cooling factors are shown in Table 5. Domestic gardens provided the greatest cooling in many of the City Regions, but was surpassed by woodland in Edinburgh, Glasgow, London and West Yorkshire. Parks provided the greatest cooling in only one City Region, Greater Manchester. Blue GBI features provided minimal cooling, due to their low overall area. The aggregate cooling at City Region scale from all green and blue GBI varied from 0.64 to 0.89 °C.

The number of hot days exceeding 28 °C WBGT in each City Region is summarised by year in Table S2 in Supplementary Material. 2015 was the hottest year, followed by 2017 and 2019, while in the years 2008–2012, the 28 °C WBGT threshold was not exceeded in any City Region. Fig. 4 illustrates the spatial pattern of WBGT for the hottest year 2015, with highest temperatures concentrated in central and south east England.

Table 3
Economic sectors, and associated work intensity category which defines potential productivity losses.

UK Sector	Most relevant sector in Costa *et al.* (2016)	Average work intensity in Watts (Costa *et al.*, 2016)	Work intensity category (Costa *et al.*, 2016)
Mining and utilities	Other industry	295	Moderate (3)
Manufacturing	Manufacturing	240	Light / moderate (2)
Construction	Construction	355	Moderate / high (4)
Wholesale and retail trade, & Repair of motor vehicles	Wholesale and retail trade	240	Light / moderate (2)
Transportation and storage	Manufacturing	240	Light / moderate (2)
Accommodation and food service activities	Manufacturing	240	Light / moderate (2)
Information and communication	Information and communication	180	Light (1)
Real estate activities	Financial and insurance activities	180	Light (1)
Professional, scientific and technical activities	Financial and insurance activities	180	Light (1)
Administrative and support service activities	Public administration and defence	240	Light / moderate (2)

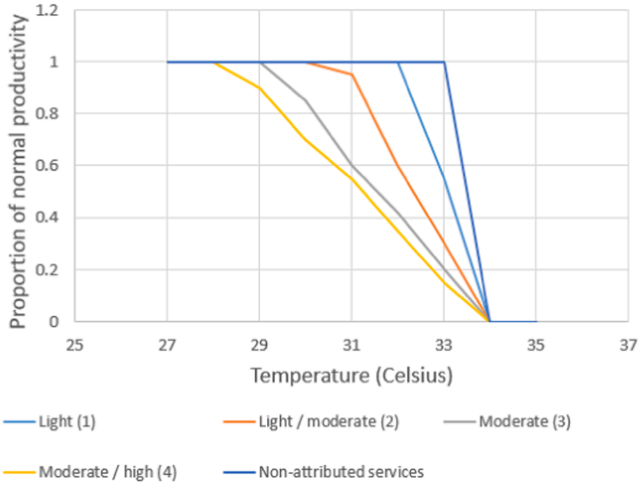

Fig. 3. Loss in productivity with wet bulb globe temperature (°C), by intensity of work (see categories in Table 3). Data from Costa et al. (2016).

The economic value of cooling provided by urban green and blue infrastructure, calculated as avoided loss in productivity totalled £ 24.5 million across the ten years, with an average of £ 2.45 m per year across the 11 City Regions (Fig. 5; Raw data in Table S3 in Supplementary Material). In the hottest year, 2015, the total cooling value was £ 13.97 m. London dominated the cooling benefit, as a result of having the highest temperatures and because it provides the largest contribution to GVA (26%) in Great Britain of any City Region (Table 2). The value of cooling in London was £ 13.74 m in 2015. The value of the cooling service differs considerably from year to year, with the differences driven both by the number of hot days and, to a lesser extent, their spatial distribution across Great Britain. Data by sector (Fig. 6, Table S4 in Supplementary Material) show that overall cooling benefits from urban GBI are greatest for Construction (£5.4 m in 2015), followed by

Table 4
Urban green space and blue space coverage (km^2) in the 11 City Regions, and for full urban area in Great Britain (GB), for comparison.

Urban green or blue space type	11 City Regions	% of urban extent in City Region	Great Britain
All woodland > 200 m^2	416.8	6.3%	984
Small woodland 200 - 30,000 m^2	295.3	4.5%	756
Large woodland > 30,000 m^2	121.5	1.8%	227.5
Grass/parks > 200 m^2	1612	24.3%	4024
Gardens > 200 m^2	1746	26.3%	5395
Rivers/Canals > 25 m	34.7	0.5%	68.1
Lakes/Ponds > 700 m^2	25.5	0.4%	56.5
Total urban footprint	6627		17,598

Mining and Utilities (2.23 m in 2015) and Wholesale and Retail trade/repair of motor vehicles (£2.24 m in 2015).

4. Discussion

This is the first study conducted at national scale which values the cooling benefits of urban green and blue infrastructure on worker productivity. We show that the cooling benefit varies substantially from year to year, depending on the meteorology, with an average total benefit of £ 2.45 m per year across eleven City Regions in Great Britain.

To put this figure into a wider context of economic benefit from green and blue space, this economic value for cooling is currently much lower than the value of £ 136 m for removal of air pollution by urban vegetation in all UK cities (Jones et al., 2019). However, as climate changes and the frequency and intensity of heatwaves increases (Tebaldi et al., 2021), this service is likely to become increasingly important.

For the contribution of different types of GBI to this benefit, the importance of domestic gardens is of interest, exceeding that of woodland in many of the City Regions. Because they are mostly privately owned green space, they are often overlooked in urban assessments, yet gardens made up 26% in our study, typically occupying between 22% and 36% of the total urban area in the UK (Gaston et al., 2005), and more than 50% in Dunedin, New Zealand (Mathieu et al., 2007).

Woodland at 6% is lower than some other UK assessments, e.g. tree cover of 16% in Birmingham, UK (Fletcher et al., 2022). This is partly because green GBI features < 200 m^2 were excluded from this analysis, therefore street trees were not included, and partly because parks were included with grasslands for the purposes of this cooling assessment, since the tree cover in parks is typically low in Great Britain.

A number of improvements are possible which could further develop this approach. The cooling factors used were static for our broad classes of GBI. A number of studies demonstrate size-specific cooling effects of greenspace and the corresponding size of buffers (Aram et al., 2019, Yu et al., 2020). The shape of greenspace features at landscape scale also has an influence on cooling, in addition to size and connectivity (Chen et al., 2014). Cooling efficiency is also reported to vary by temperature (He et al., 2021), both background temperature during the study (Yu et al., 2020) but also the climatic zone in which the park or greenspace is situated (Geng et al., 2022, Wang et al., 2022). Additional climatic factors influence cooling, for example the possible limitations to cooling benefit as a result of reduced evapotranspiration in drought periods. Evapotranspiration also varies with tree size and age (Cornish and Vertessy, 2001). This could be adjusted for urban settings if there are robust cooling factors available for trees of different sizes. Therefore, further consideration of cooling factors according to these properties could be incorporated into further studies. At the same time, economic activity is also variable depending on the weather (Rose and Dolega, 2022). However, this is much harder to factor into an economic analysis at sub-annual timescales. We base the response function for the temperature - productivity relationship on a single study (Costa et al. 2016) which used ISO standards for an average acclimatised worker wearing light clothing. Those relationships are based on underlying physiological studies (e.g. Ramsey, 1995), many of which were conducted some time ago. Therefore, newer studies may be available which reflect updated

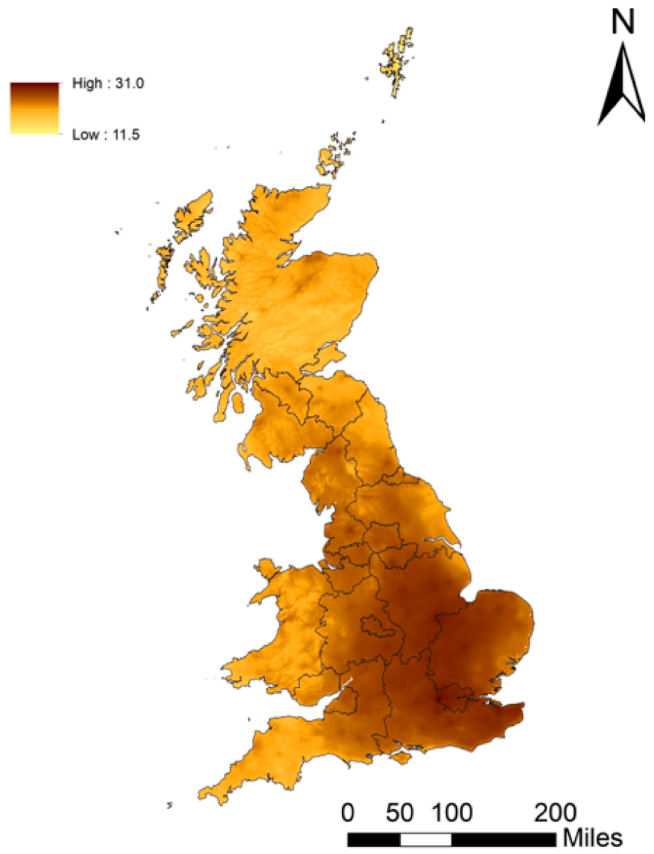

Fig. 4. Spatial distribution of wet bulb globe temperature (°C), showing data from year 2015.

Table 5
Calculated cooling factors by City Region, by green/blue GBI type, and combined (°C).

	Cardiff	**Edinburgh**	**Glasgow**	**Greater Manchester**	**Liverpool**	**London**	**North East**	**Sheffield**	**West Midlands**	**West of England**	**West Yorkshire**
Combined	-0.72	-0.89	-0.81	-0.77	-0.64	-0.75	-0.65	-0.73	-0.73	-0.70	-0.84
Woodland	-0.23	-0.39	-0.32	-0.24	-0.15	-0.25	-0.17	-0.23	-0.21	-0.19	-0.28
Parks / grass	-0.20	-0.24	-0.22	-0.27	-0.19	-0.21	-0.22	-0.20	-0.21	-0.19	-0.32
Gardens	-0.26	-0.24	-0.24	-0.22	-0.27	-0.24	-0.24	-0.29	-0.28	-0.29	-0.22
Rivers / canal	-0.01	-0.01	-0.02	-0.01	-0.01	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01
Lakes / ponds	-0.02	-0.01	-0.01	-0.02	-0.02	-0.03	-0.01	-0.01	-0.02	-0.01	-0.01

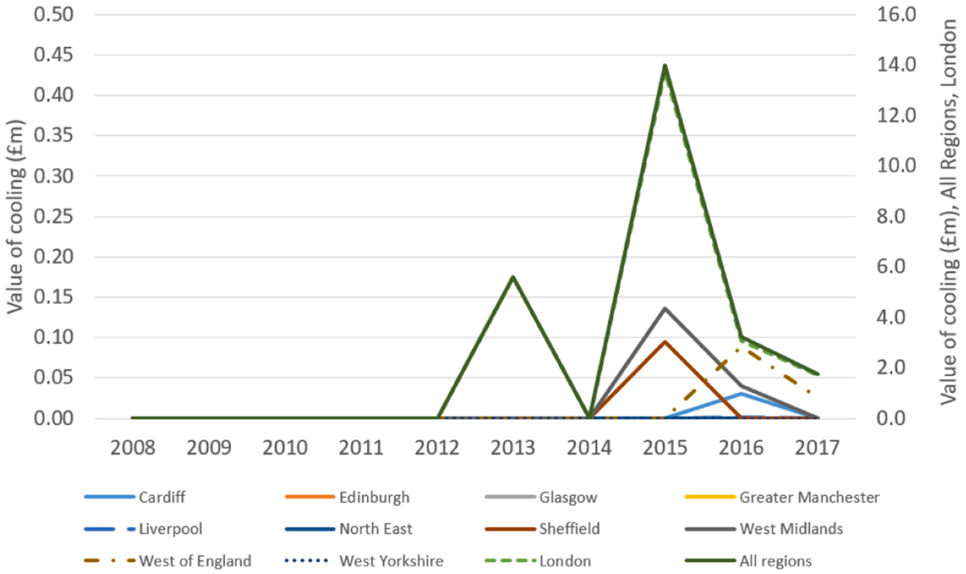

Fig. 5. Value of cooling provided by green and blue infrastructure, calculated as avoided loss of worker productivity, by City Region, by year for the ten year period 2008–2017 (£m). Note London and All Regions total are shown on a different scale on secondary y axis.

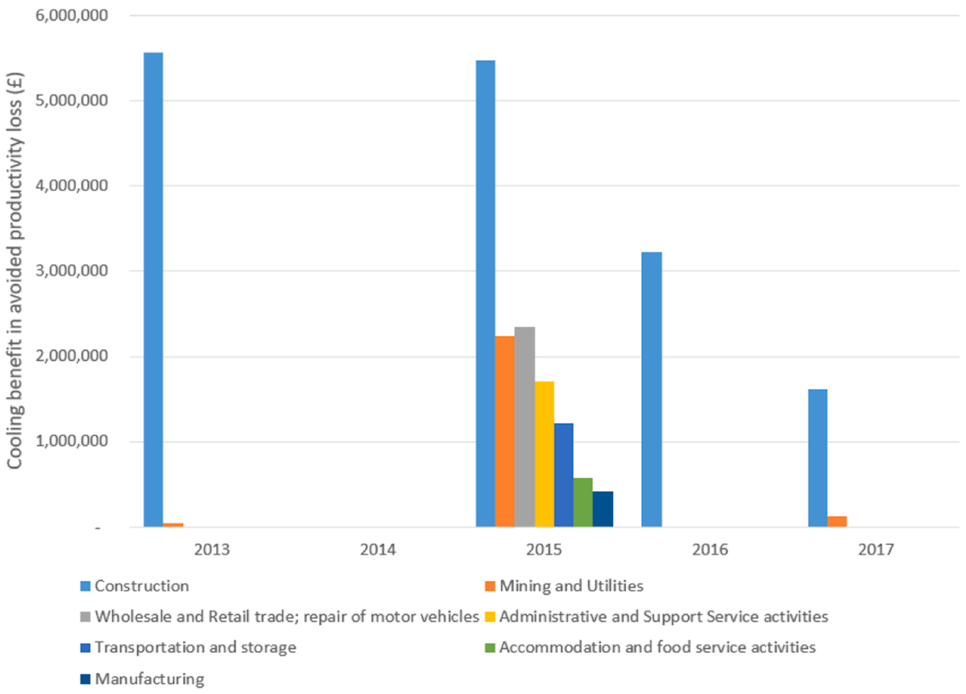

Fig. 6. The economic value of cooling benefit, by sector, showing 2013–2017 only. There were no temperature impacts for the period 2008–2012.

understanding of response functions of worker productivity to high temperatures, and the literature shows that individuals can exhibit a wide variation in their tolerance to high temperatures (Nicol & Roaf, 2017). Since the calculations here are based on threshold temperature values, using a slightly different threshold may result in very different outcomes. For example, in the US the National Institute for Occupational Safety and Health (NIOSH) standards for acclimatised workers define slightly different lower and upper thresholds, which in the most case are around one degree Celsius (WBGT) lower than the ones used here.

The buffer sizes used in this study, particularly for green space, are highly conservative. For example, some estimates for large parks in other parts of the world suggest cooling effects are detectable to at least 1 km away from the boundary (Yan et al., 2018). Different ways of calculating buffer size are used in the literature, and the range of approaches includes using a fixed buffer of 500 m, a function of the square root of park area, and statistical approaches designed to estimate the cooling distance derived from LST data, all discussed in Yu et al. (2020). Notwithstanding differences in climate and scale of parks in these studies compared with Great Britain, which influence cooling capacity (Völker et al., 2013), our conservative approach here means that, with respect to both park size effects and buffer sizes, the cooling benefits presented are likely to be an under-estimate.

We assessed GBI cooling effects for hot days in summer. However, GBI can have differential impacts in winter, potentially leading to some adverse effects where trees block summer sunlight to buildings (Hamada and Ohta, 2010), or contribute to higher night time temperatures in summer. Future assessments could take these effects into account to generate a full-year assessment of positive and negative impacts on urban temperature. Such estimates can be improved with the use of city-scale urban meteorology models, although the representation of vegetation exchanges with the atmosphere in some models may be limited (Garuma, 2018). There is a degree of acclimation in human physiological responses to high temperatures in different climates (Guo et al., 2014). This means that in hot countries, the temperature threshold at which worker productivity starts to decline is likely to be higher. Conversely, it may be lower in high latitude countries. Application of this approach in other countries should consider altering the temperature threshold where there is sufficient information to do so. In addition, there are a range of technological adaptation responses such as improving thermal insulation in buildings, or installing air conditioning (Hatvani-Kovacs et al., 2016) that can reduce these impacts for indoor workers, although they will not apply for outdoor sectors.

The cooling factors we report here of 0.64 – 0.89 °C for all urban green and blue space types, depending on the City Region characteristics, are broadly in line with an estimated cooling of 0.4 C with increase in urban tree cover to 30% reported by Iungman (2023), and are similar to ranges reported for cities in different continents (Fletcher et al., 2021).

Overall, the conservative choice of buffer size and cooling factors applied by GBI type for hot days used in this study may lead to an underestimate of benefit. Our assessments of economic impact do not take into account infrastructure such as air conditioning which in many of the sectors assessed will reduce the effect of hot days. There are many complex interacting factors contributing to this analysis, and the extent to which these factors together affect the estimate of benefit requires further exploration through a more detailed sensitivity analysis.

5. Conclusions

The calculated economic benefit from cooling provided by GBI illustrates a so-far overlooked aspect of urban green and blue infrastructure, that it has direct economic benefits through improved worker productivity on hot days. The economic value estimated for this service in terms of worker productivity is lower than estimates calculated for other services such as air pollution removal, but is likely to increase substantially under climate change. When combined with valuation of multiple ecosystem services, each additional non-market benefit that can be valued adds to our understanding of the multi-functional nature of such green and blue infrastructure types, and their importance in making our cities more liveable spaces.

The findings of this study highlight the importance of maintaining or enhancing the existing greenspace in cities to provide cooling on hot days. This is particularly important in the context of increasing frequency and intensity of such events under a changing climate. This study also shows that these benefits are not just a function provided by certain types of greenspace such as parks, which are a common focus of urban greening studies. It highlights the important role of domestic gardens in cooling cities, with the implication that policies on green space should consider measures to encourage private land owners to maintain and enhance greenery on their properties, as well as measures for land managed by public and municipal bodies.

Under the ongoing threat of climate change, societies will increase the use of technical solutions to adapt to climate, such as air conditioning and improved thermal insulation or building materials. These adaptation measures take time to implement, and can be costly. Implementation of technical measures often leaves poorer or disadvantaged communities behind. Natural solutions therefore represent both an efficient and an equitable option for adaptation to heat-related climate pressures, as well as providing a wide array of co-benefits which help make our cities more liveable.

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.

Acknowledgements

The authors declare no financial and personal relationships with other people or organizations that have influenced the submitted work.

Authors of this work received funding from the following sources: The Department of the Environment, Farming and Rural Affairs (England), UK. The DeSCIPHER project under the Sustainable and Liveable Cities and Urban Areas programme jointly co-ordinated by the Joint Programme Initiative (JPI) Urban Europe and National Natural Science Foundation of China (NSFC); projects funded under both the Sustainable and Liveable Cities and Urban Areas and all the other JPI Urban Europe programmes (e.g. ENSUF) have received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 857160, with the DeSCIPHER project also receiving UK Economic and Social Science Research Council (ESRC) funding under grant ES/T000244/1.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128212.

References

An Der Heiden, M., Muthers, S., Niemann, H., Buchholz, U., Grabenhenrich, L., Matzarakis, A., 2020. Heat-related mortality: an analysis of the impact of heatwaves in Germany between 1992 and 2017. Dtsch. Ärzteblatt Int. 117, 603.

Aram, F., Higueras García, E., Solgi, E., Mansournia, S., 2019. Urban green space cooling effect in cities. Heliyon 5, e01339.

Barboza, E.P., Cirach, M., Khomenko, S., Iungman, T., Mueller, N., Barrera-Gómez, J., Rojas-Rueda, D., Kondo, M., Nieuwenhuijsen, M., 2021. Green space and mortality in European cities: a health impact assessment study. Lancet Planet. Health 5, e718–e730.

Berland, A., Shiflett, S.A., Shuster, W.D., Garmestani, A.S., Goddard, H.C., Herrmann, D. L., Hopton, M.E., 2017. The role of trees in urban stormwater management. Landsc. Urban Plan. 162, 167–177.

Bird, D.N., Banzhaf, E., Knopp, J., Wu, W., Jones, L., 2022. Combining spatial and temporal data to create a fine-resolution daily urban air temperature product from remote sensing land surface temperature (LST) data. Atmosphere 13, 1152.

Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landsc. Urban Plan. 97, 147–155.

Chen, A., Yao, X.A., Sun, R., Chen, L., 2014. Effect of urban green patterns on surface urban cool islands and its seasonal variations. Urban For. Urban Green. 13, 646–654.

Cohen, P., Potchter, O., Matzarakis, A., 2012. Daily and seasonal climatic conditions of green urban open spaces in the Mediterranean climate and their impact on human comfort. Build. Environ. 51, 285–295.

Cornish, P.M., Vertessy, R.A., 2001. Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest. J. Hydrol. 242, 43–63.

Costa, H., Floater, G., Hooyberghs, H., Verbeke, S., De Ridder, K., 2016. Climate change, heat stress and labour productivity: a cost methodology for city economies. Centre For Climate Change Economics And Policy London, UK.

Fletcher, D.H., Likongwe, P.J., Chiotha, S., Nduwayezu, G., Mallick, D., Uddin Md, N., Rahman, A., Golovatina, P., Lotero, L., Bricker, S., Tsirizeni, M., Fitch, A., Panagi, M., Ruiz Villena, C., Arnhardt, C., Vande Hey, J., Gornall, R., Jones, L., 2021. Using demand mapping to assess the benefits of urban green and blue space in cities from four continents. Sci. Total Environ., 147238

Fletcher, D.H., Garrett, J.K., Thomas, A., Fitch, A., Cryle, P., Shilton, S., Jones, L., 2022. Location, location, location: modelling of noise mitigation by urban woodland shows the benefit of targeted tree planting in cities. Sustainability 14, 7079.

Garuma, G.F., 2018. Review of urban surface parameterizations for numerical climate models. Urban Clim. 24, 830–851.

Gaston, K.J., Warren, P.H., Thompson, K., Smith, R.M., 2005. Urban domestic gardens (IV): the extent of the resource and its associated features. Biodivers. Conserv. 14, 3327–3349.

Geng, X., Yu, Z., Zhang, D., Li, C., Yuan, Y., Wang, X., 2022. The influence of local background climate on the dominant factors and threshold-size of the cooling effect of urban parks. Sci. Total Environ. 823, 153806.

Gunawardena, K.R., Wells, M.J., Kershaw, T., 2017. Utilising green and bluespace to mitigate urban heat island intensity. Sci. Total Environ. 584, 1040–1055.

Guo, G., Wu, Z., Cao, Z., Chen, Y., Zheng, Z., 2021. Location of greenspace matters: a new approach to investigating the effect of the greenspace spatial pattern on urban heat environment. Landsc. Ecol. 36, 1533–1548.

Guo, Y., Gasparrini, A., Armstrong, B., Li, S., Tawatsupa, B., Tobias, A., Lavigne, E., De Sousa Zanotti Stagliorio Coelho, M., Leone, M., Pan, X., Tong, S., Tian, L., Kim, H., Hashizume, M., Honda, Y., Guo, Y.-L.L., Wu, C.-F., Punnasiri, K., Yi, S.-M., Michelozzi, P., Saldiva, P.H.N., Williams, G., 2014. Global variation in the effects of ambient temperature on mortality: a systematic evaluation. Epidemiology 25, 781–789.

Hamada, S., Ohta, T., 2010. Seasonal variations in the cooling effect of urban green areas on surrounding urban areas. Urban For. Urban Green. 9, 15–24.

Hathway, E.A., Sharples, S., 2012. The interaction of rivers and urban form in mitigating the Urban Heat Island effect: a UK case study. Build. Environ. 58, 14–22.

Hatvani-Kovacs, G., Belusko, M., Pockett, J., Boland, J., 2016. Assessment of Heatwave Impacts. Procedia Eng., 169, 316–323.

He, C., Zhou, L., Yao, Y., Ma, W., Kinney, P.L., 2021. Cooling effect of urban trees and its spatiotemporal characteristics: a comparative study. Build. Environ. 204, 108103.

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D.J., Muir-Wood, R., Wilson, P., Oppenheimer, M., Larsen, K., Houser, T., 2017. Estimating economic damage from climate change in the United States. Science 356, 1362–1369.

Ishii, A., Iwamoto, S., Katayama, T., Hayashi, T., Shiotsuki, Y., Kitayama, H., Tsutsumi, J.-I., Nishida, M., 1991. A comparison of field surveys on the thermal environment in urban areas surroundings a large pond: when filled and when drained. Energy Build. 16, 965–971.

Iungman, T., Cirach, M., Marando, F., Pereira Barboza, E., Khomenko, S., Masselot, P., Quijal-Zamorano, M., Mueller, N., Gasparrini, A., Urquiza, J., Heris, M., Thondoo, M., Nieuwenhuijsen, M., 2023. Cooling cities through urban green infrastructure: a health impact assessment of European cities. Lancet 401, 577–589.

Jiang, Y., Huang, J., Shi, T., Wang, H., 2021. Interaction of urban rivers and green space morphology to mitigate the urban heat island effect: case-based comparative analysis. Int. J. Environ. Res. Public Health 18, 11404.

Jones, L., Vieno, M., Fitch, A., Carnell, E., Steadman, C., Cryle, P., Holland, M., Nemitz, E., Morton, D., Hall, J., Mills, G., Dickie, I., Reis, S., 2019. Urban natural capital accounts: developing a novel approach to quantify air pollution removal by vegetation. J. Environ. Econ. Policy 8, 413–428.

Jones, L., Anderson, S., Læssøe, J., Banzhaf, E., Jensen, A., Bird, D.N., Miller, J., Hutchins, M.G., Yang, J., Garrett, J., Taylor, T., Wheeler, B.W., Lovell, R., Fletcher, D., Qu, Y., Vieno, M., Zandersen, M., 2022. A typology for urban Green Infrastructure to guide multifunctional planning of nature-based solutions. Nat. -Based Solut. 2, 100041.

Jonsson, P., 2004. Vegetation as an urban climate control in the subtropical city of Gaborone, Botswana. Int. J. Climatol. 24, 1307–1322.

Kim, S.W., Brown, R.D., 2021. Urban heat island (UHI) intensity and magnitude estimations: a systematic literature review. Sci. Total Environ. 779, 146389.

Kjellstrom, T., Holmer, I., Lemke, B., 2009. Workplace heat stress, health and productivity–an increasing challenge for low and middle-income countries during climate change. Glob. Health Action 2 (1), 2047.

Kleerekoper, L., Van Esch, M., Salcedo, T.B., 2012. How to make a city climate-proof, addressing the urban heat island effect. Resour., Conserv. Recycl. 64, 30–38.

Larondelle, N., Haase, D., 2013. Urban ecosystem services assessment along a rural–urban gradient: a cross-analysis of European cities. Ecol. Indic. 29, 179–190.

Lin, M., Dong, J., Jones, L., Liu, J., Lin, T., Zuo, J., Ye, H., Zhang, G., Zhou, T., 2021. Modeling green roofs' cooling effect in high-density urban areas based on law of diminishing marginal utility of the cooling efficiency: A case study of Xiamen Island, China. J. Clean. Prod. 316, 128277.

Livesley, S., Mcpherson, E.G., Calfapietra, C., 2016. The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. J. Environ. Qual. 45, 119–124.

Loram, A., Tratalos, J., Warren, P.H., Gaston, K.J., 2007. Urban domestic gardens (X): the extent & structure of the resource in five major cities. Landsc. Ecol. 22, 601–615.

Manteghi, G., Bin Limit, H., Remaz, D., 2015. Water bodies an urban microclimate: a review. Mod. Appl. Sci. 9, 1.

Marando, F., Salvatori, E., Sebastiani, A., Fusaro, L., Manes, F., 2019. Regulating Ecosystem Services and Green Infrastructure: assessment of Urban Heat Island effect mitigation in the municipality of Rome, Italy. Ecol. Model. 392, 92–102.

Mathieu, R., Freeman, C., Aryal, J., 2007. Mapping private gardens in urban areas using object-oriented techniques and very high-resolution satellite imagery. Landsc. Urban Plan. 81, 179–192.

Morton, D., Rowland, C., Wood, C., Meek, L., Marston, C., Smith, G., Wadsworth, R. & Simpson, I. 2011. Final Report for LCM2007-the new UK land cover map. Countryside Survey Technical Report No 11/07.

Murakawa, S., Sekine, T., Narita, K.-I., Nishina, D., 1991. Study of the effects of a river on the thermal environment in an urban area. Energy Build. 16, 993–1001.

Nicol, J.F., Roaf, S., 2017. Rethinking thermal comfort. Build. Res. Inf. 45 (7), 711–716.

Nowak, D.J., Hirabayashi, S., Bodine, A., Greenfield, E., 2014. Tree and forest effects on air quality and human health in the United States. Environ. Pollut. 193, 119–129.

O'malley, C., Piroozfar, P., Farr, E.R.P., Pomponi, F., 2015. Urban Heat Island (UHI) mitigating strategies: a case-based comparative analysis. Sustain. Cities Soc. 19, 222–235.

Oliveira, S., Andrade, H., Vaz, T., 2011. The cooling effect of green spaces as a contribution to the mitigation of urban heat: a case study in Lisbon. Build. Environ. 46, 2186–2194.

Palme, M., Inostroza, L., Salvati, A., 2018. Technomass and cooling demand in South America: a superlinear relationship. *Build. Res. Inf.,* 46, 864–880.

Park, J., Kim, J.-H., Lee, D.K., Park, C.Y., Jeong, S.G., 2017. The influence of small green space type and structure at the street level on urban heat island mitigation. Urban For. Urban Green. 21, 203–212.

Perkins-Kirkpatrick, S.E., Lewis, S.C., 2020. Increasing trends in regional heatwaves. Nat. Commun. 11, 3357.

Pirard, P., Vandentorren, S., Pascal, M., Laaidi, K., Le Tertre, A., Cassadou, S., Ledrans, M., 2005. Summary of the mortality impact assessment of the 2003 heat wave in France. Eurosurveillance 10, 7–8.

Ramsey, J.D., 1995. Task performance in heat: a review. Ergonomics 38 (1), 154–165.

Ren, Z., He, X., Pu, R., Zheng, H., 2018. The impact of urban forest structure and its spatial location on urban cool island intensity. Urban Ecosyst. 21, 863–874.

Ren, Z., Fu, Y., Dong, Y., Zhang, P., He, X., 2022. Rapid urbanization and climate change significantly contribute to worsening urban human thermal comfort: a national 183-city, 26-year study in China. Urban Clim. 43, 101154.

Robitu, M., Inard, C., Groleau, D., Musy, M., 2004. Energy balance study of water ponds and its influence on building energy consumption. Build. Serv. Eng. Res. Technol. 25, 171–182.

Rose, N., Dolega, L., 2022. It's the weather: quantifying the impact of weather on retail sales. Appl. Spat. Anal. Policy 15, 189–214.

Saaroni, H., Ziv, B., 2003. The impact of a small lake on heat stress in a Mediterranean urban park: the case of Tel Aviv, Israel. Int. J. Biometeorol. 47, 156–165.

Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., Prasad, D., Synnefa, A., 2017. Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. Sol. Energy 154, 14–33.

Spronken-Smith, R.A., Oke, T.R., 1998. The thermal regime of urban parks in two cities with different summer climates. Int. J. Remote Sens. 19, 2085–2104.

Stull, R., 2011. Wet-bulb temperature from relative humidity and air temperature. J. Appl. Meteorol. Climatol. 50 (11), 2267–2269.

Tebaldi, C., Debeire, K., Eyring, V., Fischer, E., Fyfe, J., Friedlingstein, P., Knutti, R., Lowe, J., O'neill, B., Sanderson, B., Van Vuuren, D., Riahi, K., Meinshausen, M., Nicholls, Z., Tokarska, K.B., Hurtt, G., Kriegler, E., Lamarque, J.F., Meehl, G., Moss, R., Bauer, S.E., Boucher, O., Brovkin, V., Byun, Y.H., Dix, M., Gualdi, S., Guo, H., John, J.G., Kharin, S., Kim, Y., Koshiro, T., Ma, L., Olivié, D., Panickal, S., Qiao, F., Rong, X., Rosenbloom, N., Schupfner, M., Séférian, R., Sellar, A., Semmler, T., Shi, X., Song, Z., Steger, C., Stouffer, R., Swart, N., Tachiiri, K., Tang, Q., Tatebe, H., Voldoire, A., Volodin, E., Wyser, K., Xin, X., Yang, S., Yu, Y., Ziehn, T., 2021. Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. Earth Syst. Dynam 12, 253–293.

Tiwari, A., Kumar, P., Baldauf, R., Zhang, K.M., Pilla, F., Di Sabatino, S., Brattich, E., Pulvirenti, B., 2019. Considerations for evaluating green infrastructure impacts in microscale and macroscale air pollution dispersion models. Sci. Total Environ. 672, 410–426.

Van Renterghem, T., Botteldooren, D., Verheyen, K., 2012. Road traffic noise shielding by vegetation belts of limited depth. J. Sound Vib. 331, 2404–2425.

Vaz Monteiro, M., Doick, K.J., Handley, P., Peace, A., 2016. The impact of greenspace size on the extent of local nocturnal air temperature cooling in London. Urban For. Urban Green. 16, 160–169.

Vecellio, D.J., Wolf, S.T., Cottle, R.M., Kenney, W.L., 2022. Evaluating the 35C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT Project). J. Appl. Physiol. 132 (2), 340–345.

Völker, S., Baumeister, H., Claßen, T., Hornberg, C., Kistemann, T., 2013. Evidence for the temperature-mitigating capacity of urban blue space — a health geographic perspective. Erdkunde 67, 355–371.

Wang, C., Wang, Z.-H., Yang, J., 2018. Cooling effect of urban trees on the built environment of contiguous United States. Earth'S. Future 6, 1066–1081.

Wang, C., Ren, Z., Dong, Y., Zhang, P., Guo, Y., Wang, W., Bao, G., 2022. Efficient cooling of cities at global scale using urban green space to mitigate urban heat island effects in different climatic regions. Urban For. Urban Green. 74, 127635.

Whitford, V., Ennos, A.R., Handley, J.F., 2001. "City form and natural process"—indicators for the ecological performance of urban areas and their application to Merseyside, UK. Landsc. Urban Plan. 57, 91–103.

Xiao, Y., Piao, Y., Pan, C., Lee, D., Zhao, B., 2023. Using buffer analysis to determine urban park cooling intensity: five estimation methods for Nanjing, China. Sci. Total Environ. 868, 161463.

Yan, H., Wu, F., Dong, L., 2018. Influence of a large urban park on the local urban thermal environment. Sci. Total Environ. 622-623, 882–891.

Yang, J., Yin, P., Sun, J., Wang, B., Zhou, M., Li, M., Tong, S., Meng, B., Guo, Y., Liu, Q., 2019. Heatwave and mortality in 31 major Chinese cities: definition, vulnerability and implications. Sci. Total Environ. 649, 695–702.

Yu, Z., Yang, G., Zuo, S., Jørgensen, G., Koga, M., Vejre, H., 2020. Critical review on the cooling effect of urban blue-green space: a threshold-size perspective. Urban For. Urban Green. 49, 126630.

Zhao, L., Oleson, K., Bou-Zeid, E., Krayenhoff, E.S., Bray, A., Zhu, Q., Zheng, Z., Chen, C., Oppenheimer, M., 2021. Global multi-model projections of local urban climates. Nat. Clim. Change 11, 152–157.