Urban Climate 51 (2023) 101606

Contents lists available at ScienceDirect

Urban Climate

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

High summer land surface temperatures in a temperate city are mitigated by tree canopy cover

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ARTICLE INFO

Keywords:
Surface urban heat island
Cooling effect
Greenspace
Canopy coverage
Land surface temperature

ABSTRACT

As climate warms, the impact of existing urban heat islands on the health of residents in towns and cities will worsen. A reduction in impervious in cities may help to reduce temperatures, but the relationship between tree canopy coverage and land surface temperature (LST) is not well characterised. Here, we quantified the summer LST of the temperate city of Leeds, UK using Landsat 8 TIRS remote sensing image and explored the spatial relationships between LST and impervious land cover, greenspace coverage, type of greenspace and canopy cover. We found a strong relationship between LST and canopy coverage across the built-up region of Leeds and use this relationship to project the impact of future canopy cover expansion. We found that of the nine main types of greenspaces in Leeds, private gardens occupied the greatest fraction of the total greenspace area and offered most potential for canopy cover expansion. Results suggest that a doubling of canopy coverage across the city, could reduce the mean LST by around 2.5 °C during the warmest summer months. Such a temperature reduction adds further weight to efforts by cities and countries globally to increase tree cover to both mitigate for and adapt to climate change.

1. Introduction

Globally, the frequency, intensity and duration of heatwaves have increased since 1950, with the trends projected to worsen under climate change (Perkins-Kirkpatrick and Lewis, 2020). Exposure to extremely high temperatures and high relative humidity raise human morbidity and mortality rates (Matthews et al., 2017). Heatwaves and high temperatures also have adverse impacts on agricultural yields and wildfire frequency and intensity (Deryng et al., 2014; Sun et al., 2019). Even if climate warming is limited to 2 °C above pre-industrial temperatures, substantial increases in the frequency of heatwaves are projected, and >350 million megacity inhabitants could be affected by mid-century (Matthews et al., 2017). Urban citizens may face greater risks from heatwaves due to the Urban Heat Island (UHI) effect (Yang et al., 2020; Mahmoud and Gan, 2018; Ahmed, 2018). In recent decades, there have been many studies using "surface urban heat island (SUHI)", which refers to the differences in land surface temperature between urban and rural areas (Geletič et al., 2019; Peng et al., 2012; Shi and Zhang, 2018; Sekliziotis, 1980). Land surface temperature is a key variable in

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https://doi.org/10.1016/j.uclim.2023.101606
Received 27 June 2022; Received in revised form 21 April 2023; Accepted 8 July 2023
Available online 11 September 2023
2212-0955/

urban climate studies and it plays a role in the exchange of energy between the atmosphere and the urban surface (Benas et al., 2017). SUHI also contributes to temperature based UHI effects (Schwarz et al., 2012; Majkowska et al., 2017). In the UK, urban land surface temperatures are typically 1–2 °C higher than the surrounding rural areas (Manoli et al., 2019), whereas in the USA, which has a greater range of climatic conditions, the UHI intensity measured by air temperature ranges from 1.23 to 4.35 °C (Kim et al., 2018). In the tropical areas of India, SUHI effect is 1–5 °C (Kumar et al., 2017), while in warm temperate regions of China the SUHI effect can be as much as 9.4 °C (Xue et al., 2012). The SUHI effect occurs due to the prevalence of low albedo and darker coloured, impervious urban surfaces such as roofs, walls and roads, which reflect less solar radiation, store more heat and absorb less moisture than vegetated surfaces (Morini et al., 2016). By using the remote sensing images, the land surface temperature is more suitable for evaluating thermal environments at a broad scale, compared with air temperature (Yang et al., 2019).

Many studies indicate that greenspaces help to improve urban thermal comfort in warm and dry climatic regions by decreasing air temperature and increasing the relative humidity (Zhang et al., 2013; Yu et al., 2017; Yang et al., 2020). More specifically, high urban tree canopy coverage has been linked to lower heat-related morbidity (Petri et al., 2019; Graham et al., 2016). Tree canopies can intercept incoming solar radiation and shade surfaces, in addition to reducing ambient temperature through evapotranspiration (Moss et al., 2019; Dimoudi and Nikolopoulou, 2003; Liu et al., 2017). Many cities plan to mitigate the UHI effect by increasing tree canopy in built-up areas, but the relationship between tree canopy coverage and land surface temperature is still poorly characterised (Zhao et al., 2020; Godinho et al., 2016; Feyisa et al., 2014; Morabito et al., 2021; Hua and Qinhuo, 2008). For instance, canopy cover and land surface temperature can linearly and negatively related(Feyisa et al., 2014; Yan and Dong, 2015; Wetherley et al., 2018), as can, vegetation cover and air temperature (Ibsen et al., 2021). Further, at small spatial scales, canopy cover and air temperature can be exhibit non-linear relationship (Ziter et al., 2019). Trees have a greater cooling effect than other vegetation, such as grasses, because trees provide shade and their deep roots facilitate more evapotranspiration from the land surface. The amount of shade provided by trees is influenced by structure, height and canopy density (Shashua-Bar and Hoffman, 2000), leaf albedo (Beringer et al., 2005; Richardson et al., 2013), crown width, and leaf area (Speak et al., 2020; Rahman et al., 2020).

Continued urbanization limits the amount of space available for greenspace and tree cover (Lin et al., 2015). Urban land ownership is complex (Dixon, 2009); finding available space to increase canopy coverage therefore presents a major challenge in many cities. Existing canopy coverage, and the potential to increase it, can vary widely between different greenspace types (Hall et al., 2012). The ownership of greenspaces can be divided into public greenspaces, such as public parks or gardens, school grounds and sport facilities, and private greenspaces such as private lawns and gardens (Hatton MacDonald et al., 2010; Landry and Pu, 2010; Coolen and Meesters, 2012). In many cities, privately owned greenspaces could provide more available space for trees as they make up a large proportion of the total greenspace area. In Sydney, Australia, private gardens are the single largest contribution to greenspace area (Lin et al., 2015). Private gardens cover 36.4% of Paris, France (Mimet et al., 2020; Masoudi and Tan, 2019), and 30% of Glasgow, UK (Greenspace Scoland, 2018). Canopy coverage in private gardens was strongly dependent on socioeconomic factors; richer areas have more canopy cover than poor areas (Landry and Pu, 2010; Heynen et al., 2006). The potential canopy cover is defined as the percentage of total land area that is pervious and without tree canopy cover (Wu et al., 2008). Some research reveals that the potential for extra tree cover was 3.7% in Manchester, UK (Hall et al., 2012), and 8.4% in Los Angeles, USA (Wu et al., 2008). However, the fragmented nature of ownership of private gardens may prevent widespread tree planting. Little is known about the extent to which different types of urban greenspace may be able to contribute to increased canopy coverage, and therefore urban cooling.

In line with the Paris Agreement on Climate Change, the UK has committed to reaching net-zero greenhouse gas emissions by 2050. To deliver on this national ambition, local and regional authorities are making their own commitments to reduce emissions. Leeds, UK, has a current tree canopy cover of 17% and the local authority has ambitions to double this by 2050 to sequester carbon and deliver a range of other benefits including flood risk reduction and habitat creation (Leeds City Council, 2020). Here, we use high resolution datasets to interrogate the relationship between existing tree canopy coverage and urban land surface temperatures, to explore potential impacts (beyond carbon sequestration) of a future increase in tree canopy cover. Using the temperate city of Leeds, UK as a case study, we (1) demonstrate the relationship between land surface temperature and tree canopy coverage, (2) explore the potential opportunities to increase canopy cover, (3) quantify the role in urban cooling of different types of greenspaces, and (4) project changes to land surface temperature under scenarios of increased tree canopy coverage.

2. Materials and methods

2.1. Study area

Leeds is located in central north England (53° 47′N, 1° 32′W), with a population of 793,139 in 2019 (Leeds Observatory, 2020). Temperatures peak during the northern hemisphere summertime, in July and August. For instance the air temperature reached 35 °C in July 2019 (National Centre for Atmospheric Science, 2021a, 2021b). Estimates of greenspace coverage vary depending on definitions used for the extent of the city itself. Greenspace coverage within the city was estimated as 41% in Heynen et al., 2006 (Dallimer et al., 2011), whereas using i-Tree Canopy, the tree canopy coverage of the wider Leeds local authority region was 17.4 (±1.2)% in 2016 (Doick et al., 2019). As with many cities, the boundaries of any administrative region do not tend to coincide with the extent of the built up area. As our study is focussed on urban greenspaces, we first needed to define the extent of the built-up area of the city. We applied the rural-urban classification developed by the Office for National Statistics and Defra (Office for National Statistics, 2016), in which urban areas are the built-up areas identified by Ordnance Survey mapping that have resident populations above 10,000 people based on the 2011 Census. Rural areas are those areas that are not urban, i.e. consisting of settlements below 10,000 people or are open countryside. Under this definition, the built-up area of Leeds is 154.98 km^2, and we take this as our research area (Fig. 1).

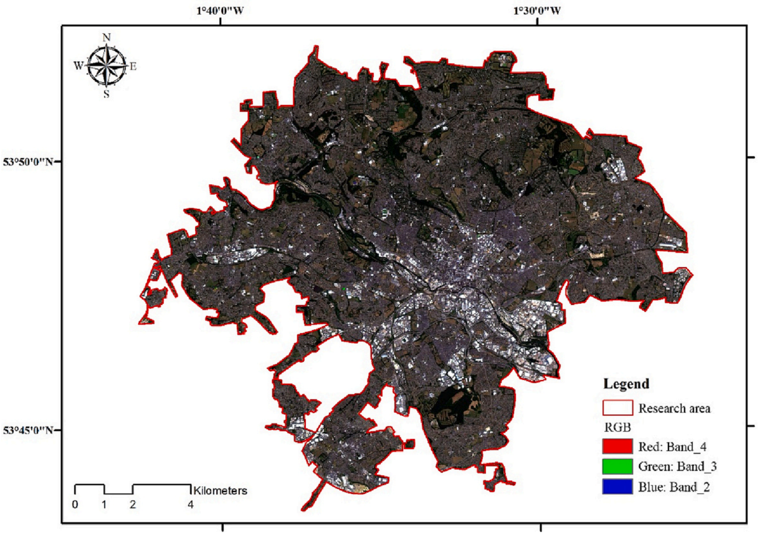

Fig. 1. The built up area of the city of Leeds, UK (research area). The background image is the remote sensing data from Landsat 8 TIRS at 27 June 2018.

2.2. Data sources and land surface temperature

Land surface temperatures from remote sensing thermal infrared images are positively and significantly correlated with air temperatures (Ren et al., 2016; Schwarz et al., 2012; Feyisa et al., 2014). We used Landsat TIRS images to determine land surface temperature in summer 2018. One cloudless remote image was selected from Landsat 8 TIRS (27 June 2018, GMT: 11:03:22), was downloaded from https://glovis.usgs.gov/. The air temperature corresponding to the remote sensing image was 18 °C (National Centre for Atmospheric Science Ibsen et al., 2021). Land surface temperature was estimated by the previously validated radiative transfer equation (Du et al., 2017; Masoudi and Tan, 2019; Qiu and Jia, 2020), which has the higher accuracy when compared to other algorithms, such as the mono-windows algorithm and the generalized single-channel algorithm (Yu et al., 2014). Land surface emissivity (ε) is an essential parameter for retrieving LST from thermal infrared remote sensing data. Land surface emissivity (ε) is estimated by using the values of NDVI and green cover ratio (P_v):

$$P_v = (\mathrm{NDVI} - \mathrm{NDVI}_{soil}) / (\mathrm{NDVI}_{veg} - \mathrm{NDVI}_{soil}) \quad (1)$$

$$NDVI = (\rho_{NIR} - \rho_{RED}) / (\rho_{NIR} + \rho_{RED}) \quad (2)$$

The land surface can be viewed as composed of three land cover types: vegetation, bare soil and water (Qin et al., 2004). In formula (1), NDVI is the normalized difference vegetation index, NDVI_{soil} and NDVI_{veg} are NDVI in bare land and vegetation area, set as 0.05 and 0.7, respectively. In formula (2), ρ_{NIR} is the near-infrared band, ρ_{RED} is the red band, which is band 5 and band 4 respectively in Landsat 8 data.

$$\varepsilon_{vegetation} = 0.9625 + 0.0614P_v - 0.0461{P_v}^2 \quad (3)$$

$$\varepsilon_{building} = 0.9589 + 0.086P_v - 0.0671{P_v}^2 \quad (4)$$

Based on the land surface cover types, ε_{water} (the land surface emissivity of water) is 0.995. Where $\varepsilon_{vegetation}$ is the emissivity of the natural surface, $\varepsilon_{building}$ is the emissivity of the built-up surface (Shi and Zhang, 2018; Qin et al., 2004).

$$B(T_s) = [L_\lambda - L^\uparrow - \tau(1-\varepsilon)L^\downarrow]/\tau\varepsilon \quad (5)$$

L_λ is the radiance registered by the sensor, B is the blackbody radiance related to the surface temperature by Planck's law, $L^\uparrow$ and $L_\downarrow$ are the upward and downward atmospheric radiance, respectively, τ is the atmospheric transmission.

$$T_s = K_2 / ln[K_1 / B(T_s) + 1] \quad (6)$$

In formula (6), T_s is the land surface temperature, calculated by Planck formula, for band 10 of TIRS, $K_1 = 774.89$ W/(m^2•μm•sr), $K_2 = 1321.08$ K. Atmospheric profile parameters ($L^\uparrow$, $L_\downarrow$, and τ) can be obtained by entering the imaging time and the centre coordinate by latitude: 53.778, longitude: −1.360 on the website provided by NASA (http://atmcorr.gsfc.nasa.gov/). These data allow us to calculate the land surface temperature for the urban area of Leeds, UK.

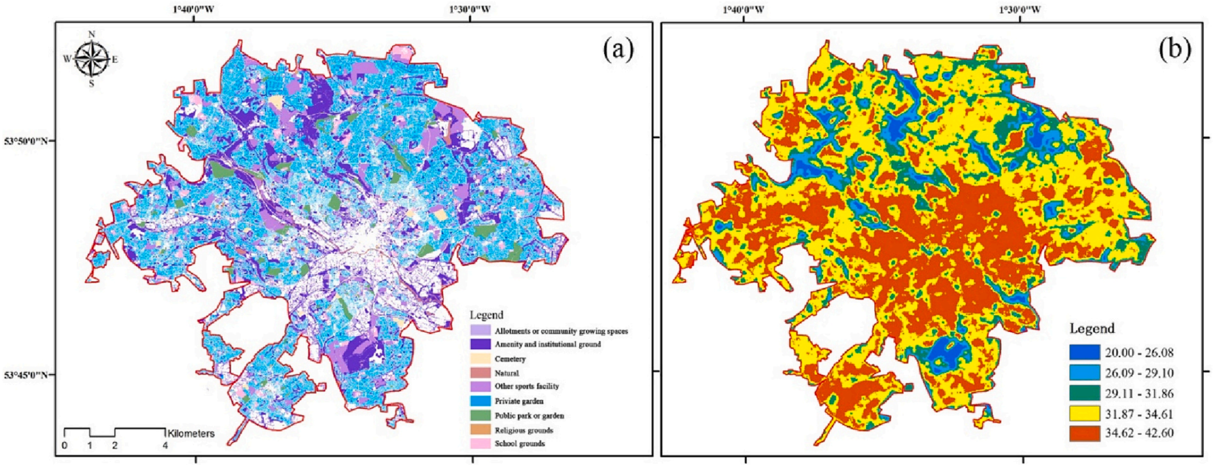

Fig. 2. (a) The distribution of nine greenspace types in Leeds utilising OS MasterMap Greenspace Layer data (DIGIMAP, 2021), (b) the land surface temperature (°C) of research area (27 June 2018, GMT: 11:03:22).

2.3. Greenspace types and canopy coverage data

Greenspace types were derived from the OS MasterMap® Greenspace Layer, in which greenspaces are classified as one of 18 types. We combined some greenspace types with similar characteristics to reduce the number of types to nine. Firstly, *bowling green, golf course*, *other sport facility*, *play space*, *playing field* and *tennis court* are all types of sports facility, therefore these six greenspace types were combined into *other sport facility*. Secondly, *amenity-residential or business*, *amenity-transport* and *institutional grounds* were combined into an *amenity and institutional ground* greenspace type. *Land use changing* was moved from greenspaces to built-up land because it was land that is currently under development or awaiting redevelopment (Table 3, Fig. 2(a)).

Canopy coverage was determined from Bluesky's National Tree Map™ (NTM™) of 2018 (https://www.bluesky-world.com/ntm). NTM™ is created from high resolution aerial photography, terrain, surface data and colour infrared imagery, and is widely used in planning and environmental management (National Tree Map, 2021). It is the most detailed dataset available in the UK and provides location, height and crown canopy area for every tree that is visible from above, and >3 m in height. To assess the canopy coverage within the boundary of greenspaces, the NTM™ data were overlaid with the nine greenspace type data; canopy coverage within the boundary of each greenspace type was then extracted and analysed using ArcMap 10.6.

2.4. Statistical modeling of temperature

To explore the relationship between temperature and greenspace types, the urban area of Leeds was divided into 209 1 km × 1 km units. For each we determined the proportion that was covered by built-up features, greenspace, tree canopy and grass/shrubs (Appendix 1). Grass/shrub coverage was calculated by subtracting canopy coverage from greenspace coverage. We used Spearman's correlations to explore associations between variables, as not all data were normally distributed (Appendix 1). We further modelled the relationships between land surface temperature and land cover types using multiple regression. Variance inflation factors (VIF) were used to measure possible multicollinearity among the predictor or explanatory variables (Robinson and Schumacker, 2009), with VIF > 10 taken to indicate multicollinearity (Salmerón et al., 2013), and when the explanatory variable is orthogonal to the remaining variables, its VIF will be 1 (Robinson and Schumacker, 2009).

2.5. Projecting the impact of double canopy coverage on land surface temperature

Land surface temperatures in Leeds will be affected by newly planted trees. Here, we use the relationship between current tree canopy cover and land surface temperature to project the potential impact of doubling existing canopy cover. We increased the canopy coverage of each gridcell by 1/3 of its present value, by 2/3 of its present value, and finally we doubled the present canopy coverage. For gridcells with current canopy coverage >50%, final canopy was capped at 100%.

3. Results

3.1. Impact of land cover on temperature

Land surface temperature was positively correlated with built-up coverage, negatively correlated with canopy coverage and greenspaces coverage, and had no correlation with grass/shrub coverage (Table 1).

Based on the Spearman correlation analysis, we used the multiple regression to quantify the relationship between canopy coverage,

Table 1
Spearman correlations between land surface temperature and land cover, **Significant at P<0.01.

	LST	canopy coverage	built-up coverage	greenspaces coverage	grass/shrub coverage
LST	1	−0.727**	0.525**	−0.525**	−0.046
canopy coverage		1	−0.617**	0.586**	−0.052
built-up coverage			1	−0.987**	−0.660**
greenspaces coverage				1	0.701**

Table 2
Three models (M_1, M_2, M_3) that represent the relationship between land surface temperature and land cover.

	canopy coverage	built-up coverage	greenspaces coverage	Constant	Adj. R^2	VIF
M_1	−0.14	0.01		35.41	0.60	1.55
M_2		0.02	−0.04	34.88	0.25	22.75
M_3	−0.14			35.78	0.60	1.00

built-up coverage and greenspace coverage with land surface temperature. We selected the final model of land surface temperature by the adjusted R^2 and VIF value, and used M_1, M_2, and M_3 as the statistical models to represent them (Table 2). M_2 has a lower R^2 value and VIF > 10, this indicated that multicollinearity exists within the model. M_1 and M_3 have almost same adjusted R^2. VIF value of M_3 is lower than M_1, so based on the value of R^2 and VIF, $M_3$was selected to predict the land surface temperature of Leeds. The model explains 60% of the variance in land surface temperature. Applying M_3 to a canopy coverage increase of 10%, projects a land surface temperature decrease of 1.4 °C.

3.2. Exploring the role of different greenspace types

Within the built-up area of Leeds (Fig. 1) there were 89.81 km^2 of greenspace, representing 57.95% of the total. The area covered by the nine greenspace types varied considerably (Fig. 2a and Table 3). Private gardens occupied 39.18 km^2, or 43.63% of the total greenspaces area. Tree canopy coverage within private gardens was 6.89 km^2 (17.59%). The area occupied by amenity and institutional grounds was 29.12 km^2 (32.42% of total greenspace); the tree canopy area was 13.27 km^2 (45.57%). Private gardens occupy the greatest fraction of greenspace within the built-up area of Leeds; in total private gardens and amenity and institutional grounds account for 76.00% of the total greenspace coverage. Religious grounds and allotments or community growing spaces each account for <1% of the total greenspace area. Based on the definition of potential canopy cover, private gardens in Leeds hold the greatest potential for canopy cover expansion, and the religious grounds the least (Table 3).

Table 3
Area occupied by, canopy coverage within, and land surface temperature of, nine greenspace types.

	Greenspace type	Greenspace area (km^2)	Greenspace coverage (%)	Canopy area (km^2)	Canopy coverage (%)	Potential canopy cover (km^2)	Mean LST of greenspace (°C)	Mean LST of tree canopy (°C)	ΔLST (°C)
1	Allotments Or Community Growing Spaces	0.73	0.81	0.1	13.70	0.63	32.84	31.87	0.97
2	Amenity And Institutional Ground	29.12	32.42	13.27	45.57	15.85	31.69	30.08	1.61
3	Cemetery	0.99	1.10	0.31	31.31	0.68	32.48	31.28	1.20
4	Natural	1.77	1.97	0.74	41.81	1.03	28.80	28.54	0.26
5	Sports Facility	8.86	9.87	1.65	18.62	7.21	33.28	31.25	2.03
6	Private Garden	39.18	43.63	6.89	17.59	32.29	33.55	32.83	0.72
7	Public Park Or Garden	4.43	4.93	2.00	45.15	2.43	31.12	29.15	1.97
8	Religious Grounds	0.52	0.58	0.15	28.85	0.37	33.60	32.83	0.77
9	School Grounds	4.21	4.69	0.65	15.44	3.56	34.55	33.72	0.83
	Total	89.81		25.76					

Greenspaces coverage (%) is the area of each greenspace type divided by the total area of greenspaces. Canopy coverage (%) is the canopy area within a greenspace type divided by the area of that greenspaces type; ΔLST is LST difference between canopy and greenspaces.

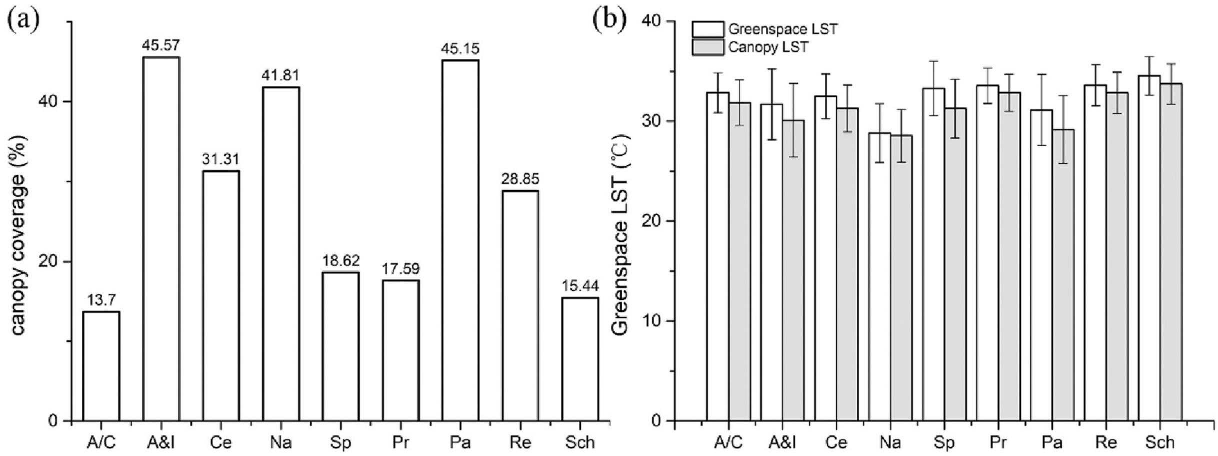

Fig. 3. (a) the canopy coverage of each greenspace type (b) the mean land surface temperature of each greenspace type and canopy, error bar is standard deviation. Letters give abbreviated greenspace type names: A/C = allotments or community growing spaces, A&I = amenity and institutional ground, Ce = cemetery, Na = natural, Sp = sports facility, Pr = private garden, Pa = public park or garden, Re = religious grounds, Sch = school grounds.

The mean land surface temperature of each greenspace type varied. Greenspace types with lower tree canopy coverage had higher land surface temperature (Table 3). School grounds had the highest land surface temperature (34.55 °C). In contrast natural areas which are characterised by high tree canopy coverage had the lowest temperatures at 29.96 °C (Table 3, Fig. 2 (b)).

Canopy coverage is unevenly distributed across the different greenspace types (Table 3 and Fig. 3a). Canopy coverage was 29.29 km^2 (18.9% of the total area). Of this, 25.76 km^2 was within and 3.53 km^2 outside of urban greenspaces. Canopy area varied across greenspace types (Fig. 3a). Although private gardens had the highest area, canopy coverage was low (17.59%). The highest canopy coverage was in amenity and institutional ground (45.57%), followed by public park or garden (45.15%).

The average land surface temperature of areas covered by canopy was lower than that of the remaining greenspace (Fig. 3b). The largest difference in temperatures between areas covered by canopies and elsewhere in a greenspace was 2.03 °C for sports facilities, and the smallest was 0.26 °C for natural greenspaces. Private gardens, that account for 43.63% of the urban area of Leeds, have a low canopy coverage, and therefore, a relatively high land surface temperature of 33.55 °C. In contrast, natural areas cover a small proportion of the city, have high canopy coverage and, therefore low land surface temperature of 28.80 °C. Some greenspace types that cover large areas, such as amenity and institutional grounds also have high canopy coverage and relatively lower land surface temperatures.

3.3. Projecting land surface temperature change with increasing tree canopy coverage

We used the tree canopy and land surface temperature model (M_3) to project the potential land surface temperature change associated with doubling canopy coverage. Fig. 4 (a) illustrates the situation in 2018, the mean canopy coverage across the built-up Leeds region was 18.9% but this coverage is unevenly distributed. In the very centre of the city, there are large built-up areas. These neighbourhoods have lower current canopy coverage and higher land surface temperatures compared to the north of Leeds.

We increased the canopy coverage of each gridcell by 1/3 of its present value (Fig. 4 (b)), by 2/3 of its present value (Fig. 4 (c)), and finally we doubled the present canopy coverage (Fig. 4 (d)). The final scenario saw canopy coverage increase from 18.90% (present) to 37.80% (doubling). With present-day canopy coverage, the mean land surface temperature of our research area was 33.15 °C; the change in land surface temperature in each gridcell, under each scenario, was determined using M_3. When canopy cover was increased by 1/3 the mean temperature reduced to 32.32 °C, when canopy cover was increased by 2/3 the mean temperature reduced to 31.44 °C and when canopy cover was doubled the mean temperature reduced to 30.59 °C.

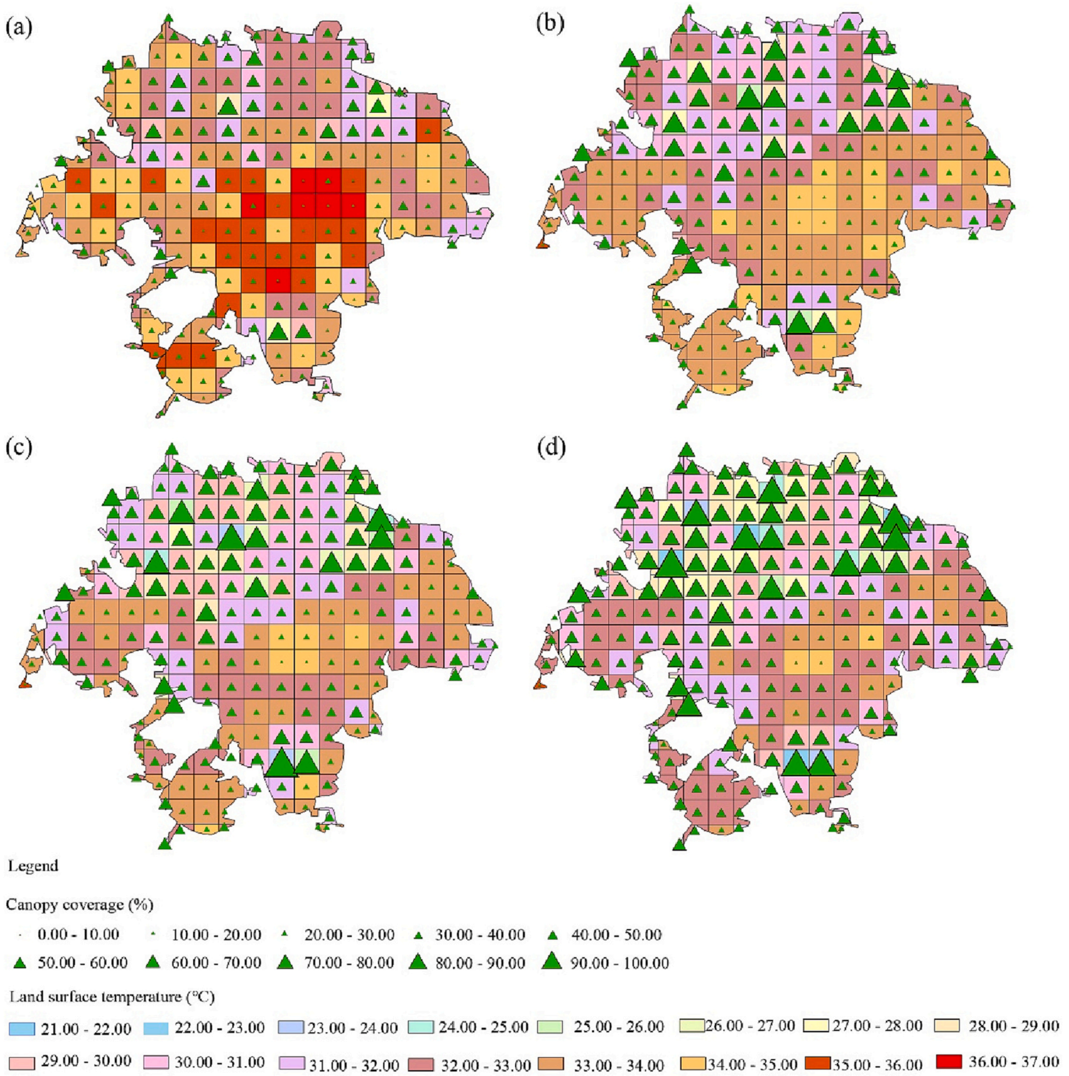

Fig. 4. (a) tree canopy coverage (green triangles) and land surface temperature (coloured shading) for each gridcell in 2018. (b), (c) and (d) illustrate changes to land surface temperature for a 1/3 increase, 2/3 increase and doubling of tree canopy cover respectively.

4. Discussion

4.1. Projecting land surface temperature changes with increasing tree canopy coverage

We found that land surface temperature was strongly correlated with canopy coverage in the city of Leeds, UK; this result concurs with the results of previous studies in other climate regions (Feyisa et al., 2014; Godinho et al., 2016). We found that land surface temperature decreased by 1.4 °C for every 10% increase in canopy coverage. In the Mediterranean land surface temperature has been shown to decrease by 0.64 °C when the canopy coverage increases by 10% (Godinho et al., 2016). In the largest city of Ethiopia, Addis Ababa, the temperature decreased by 0.2 °C for every 10% increase in tree canopy cover (Feyisa et al., 2014). In Italian cities, for every 10% increase in highly impervious surface and low tree cover region, land surface temperature increased by 4 °C (Morabito et al., 2021). In Phoenix, Arizona in the United States, every 10% increase in impervious area increased temperature by 3.2 °C (Connors et al., 2013). In our research every 10% increase in built-up area increased land surface temperature by 0.6 °C. We did not find a correlation between grass/shrub and land surface temperature, which differs from previous research in Phoenix, Arizona in the United States, where a 10% increase in grass decreased land surface temperature by 3.4 °C (Connors et al., 2013).

Expanding tree canopy cover has long been considered as an effective means to decrease the land surface temperature in urban areas. Trees could increase latent heat flux by transpiration, which could reduce the land surface temperature, as the heat energy is spent into evaporation resulting in a lower surface temperature (Ibsen et al., 2022). Soil moisture can also potentially affect ground lever air temperature due to latent heat flux (Gómez-Navarro et al., 2021), which influence ground level vegetation temperature. When canopy cover increase in urban area, trees shade ground surface from radiation, and thus lower the surface temperature. Here, initial canopy coverage varied across our study region (Fig. 4a) and projected temperature changes were proportional to that existing canopy coverage. For instance, when the canopy coverage of Leeds doubled from the present situation, the mean land surface temperature is projected to decrease by 2.56 °C.

Potential increases in urban tree canopy coverage are driven, in part, by local, regional and national biodiversity and net-zero targets. As part of its Environment Improvement Plan, the UK government aims to increase woodland and tree coverage in England from 14.5 to 16.5% by 2050. In China, among the new climate action targets proposed in 2020, the goal of increasing forest stock by 2030 from 4.5 billion cubic meters to 6 billion cubic meters over 2005 has been established (Renmingwang, 2021). The role of urban tree canopy cover in contributing to these targets is not yet clear but, using Leeds as a case study, our work demonstrates the potential for canopy cover increase to help decrease high land surface temperature in urban area, in addition to delivering on other climate change related targets. Canopy cover increases can potentially mitigate high land surface temperatures in cities as well as providing other co-benefits, which can include reducing the demand for air conditioning, sequestering carbon, improving air quality, providing habitat for biodiversity, and ameliorating human health and wellbeing (Akbari et al., 2001; Anguluri and Narayanan, 2017; Shackleton et al., 2015).

4.2. The potential to increase canopy coverage across different greenspace types

If cities wish to increase canopy cover as an approach to mitigate the impacts of higher temperatures associated with urbanization and climate change, land will be required for tree planting. However, land availability is limited in cities as urbanization decreases and fragments greenspace (Lin et al., 2015; Yokohari et al., 2000). Cities will, therefore, have to make use of existing greenspaces and consider how these might be used to increase canopy cover to reduce temperatures (Ziter et al., 2019). Here we show that there is huge potential to increase canopy cover in private gardens, as they cover the largest areas of greenspaces in many cities (in Leeds 43.63% of the total greenspace area) (Lin et al., 2015; Mimet et al., 2020; Goddard et al., 2013; Wu et al., 2008). In contrast with public parks, or amenity and institutional grounds, private gardens tend to be widely distributed across cities, offering scope to increase canopy cover and reduce temperatures across wide spatial extents. However, ownership of private gardens is held by thousands of different individuals, and gardens are used for many different purposes (Holland, 2004), not all of which are compatible with planting trees. Further, the potential for trees to cause damage to residential buildings, such as via subsidence (Gill et al., 2007), or be a nuisance to owners, such as via shading or costs associated with clearing up leaf fall, is often a major barrier to the presence of large trees in gardens (Conway, 2016). Amenity and institutional grounds, public park or garden also cover large areas of cities (in Leeds these areas take 37.35% of the total greenspace areas); although in Leeds canopy cover was already high in these greenspace types, the fact that there are fewer owners may mean that it is easier to expand canopy coverage on these greenspaces. While this may help cities to reach tree planting and canopy coverage targets, the benefits for residents in terms of reduced temperatures is likely to be restricted to fewer residents who live near these greenspaces.

4.3. Study limitations

The quality of spatial resolution of remote sensing image might prevent very accurate analyses. Landsat 8 TIRS remote sensing image was used to retrieve land surface temperature in Leeds, UK, the 100 m spatial resolution of the thermal imagery will record a land surface temperature value for areas larger than some greenspace patches. Consequently, the land surface temperature of smaller greenspaces, such as private gardens, will be high because of the low spatial resolution of Landsat 8 thermal band. Installing thermal imagers on airborne platforms can improve spatial resolution, while it may require collection over multiple days with varying conditions for a city, and it is expensive. Higher spatial resolution from a thermal imager mounted on an airborne platform would not completely address the issue of microscale temperature variability, as a remote sensor above the canopy would not be able to see all surfaces shaded by the canopy. To explore the cooling capacity of private gardens and other small patched greenspaces, measuring air temperature is more feasible for further research.

5. Conclusion

City planners and local authorities need to consider the effect of climate warming on the future of urban areas. An efficient way to reduce land surface temperature is to increase canopy coverage, and decrease impervious built-up surface coverage. Finding available space for additional trees in cities is a major challenge when attempting to increase urban canopy coverage. Among the different greenspace types, private gardens offer the greatest potential opportunity for increasing canopy coverage due to the area they occupy but also present challenges associated with multiple individual ownerships. Our projections suggest that if the canopy coverage of Leeds doubled, the mean land surface temperature would decrease by 2.56 °C. Whilst it is challenging to turn impervious surfaces into greenspaces, canopy coverage may still be increased through careful siting of street trees that are able to achieve large canopy sizes.

Funding

The research was supported by Chunhui Project Foundation of the International Education Department of China and Natural Environment Research Council (grant NE/S015396/1).

CRediT authorship contribution statement

Xinjun Wang: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Catherine E. Scott:** Methodology, Writing – review & editing, Supervision. **Martin Dallimer:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

Research data was added as an supplement file in Attach Files.

Acknowledgments

The authors would like to express the sincere thanks to Anna Gugan at the United Bank of Carbon (UBoC) and University of Leeds for assistance with data processing. We would also like to acknowledge Leeds City Council and the White Rose Forest for providing access to Bluesky's National Tree Map™ (NTM™) as part of the development of the White Rose Forest Action Plan. We would also like to acknowledge © Crown copyright and database rights 2022 Ordnance Survey (100025252) for providing greenspace types of Leeds.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2023.101606.

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