Heliyon 10 (2024) e24912

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Comparative study and effects of urban green scape on the land surface temperature of a large metropolis and green city

Muhammad Sadiq Khan[a,b,c,*], Yuelin Li[a,b,c,d,*]

[a] Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China National Botanical Garden, Chinese Academy of Sciences, 723 Xingke Road, Guangzhou 510650, China
[b] Guangdong Provincial Key Laboratory of Applied Botany, South China National Botanical Garden, Chinese Academy of Sciences, 723 Xingke Road, Tianhe District, Guangzhou 510650, China
[c] South China National Botanical Garden, Chinese Academy of Sciences, 723 Xingke Road, Guangzhou, 510650, China
[d] University of Chinese Academy of Sciences, Beijing, 100049, China

ARTICLE INFO

Keywords:
Urban environment
Vegetation composition
Vegetation configuration
Buffer analysis
Sustainable green cities

ABSTRACT

Previous studies have provided valuable insights into the impact of green space (GS) on land surface temperature (LST). However, there is a need for in-depth comparative research on changing landscape patterns in cities and their effects on the urban thermal environment. This study investigates the spatial arrangement of GS and the influence of impervious surfaces on LST in urban areas, examining their cooling and warming effects in the urban landscapes of Beijing and Islamabad. The study aims to assess the impact of the spatial arrangement of GS on LST using a moving window of 1 km^2 to analyze the overall effect of landscape patterns on the urban environment. Using Gaofen (GF–2) and Landsat–8 satellite data, we examined the biophysical surface properties of core urban areas. The results indicate a significant difference in the mean LST of 5.44 °C and 3.31 °C between impervious surfaces and GS in Beijing and Islamabad, respectively. The barren land and GS in Islamabad experience a higher LST of 3.39 °C compared to Beijing, which accounts for 1.39 °C. In Beijing, configuration metrics show no significant effect on urban LST, while edge density (ED) exhibits a slightly negative trend. In contrast, in the city of Islamabad, the landscape shape index (LSI), patch density (PD), and number of patches (NP) metrics have a significant influence on LST. The cooling effect of GS patches (0.1–0.5 ha) is more pronounced, while that of GS patches of 15–20 ha shows no significant effect on LST. The temperature difference (TD) of 5.01 °C was observed from the edge of GS in Beijing and 3.3 °C in Islamabad. Considering Islamabad's lush green scape compared to Beijing, this study suggests that Islamabad may experience an increase in LST in the future due to urbanization. This study's findings may assist urban policy-makers in designing sustainable green city layouts that effectively address future planning considerations.

1. Introduction

Increasing surface temperatures in urban areas have become a critical issue in the 21st century, leading to various problems that

* Corresponding authors. Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, 723 Xingke Road, Guangzhou, China.

E-mail addresses: khan_eco@scbg.ac.cn (M.S. Khan), yuelin@scib.ac.cn, yuelin.li@uni-bayreuth.de (Y. Li).

https://doi.org/10.1016/j.heliyon.2024.e24912
Received 8 June 2023; Received in revised form 20 December 2023; Accepted 17 January 2024
Available online 23 January 2024
2405-8440/

affect biodiversity, human life, and economic activities. Urbanization has resulted in the emergence of the surface urban heat island (SUHI) phenomenon [1], where urban areas experience higher temperatures than surrounding rural areas [2]. Land surface temperature (LST) in urban areas is a significant environmental concern due to its associated negative impacts, such as greenhouse gas emissions, vehicular and industrial pollution, concrete surfaces, and less vegetation cover. Such factors have implications for biodiversity [3], energy expenditure [4], and thermal comfort for urban dwellers [5]. LST is mainly influenced by urbanization and global warming [6], and research has been conducted to develop effective strategies and policies to mitigate its effects.

Urban green space (GS) refers to the vegetation within cities, including parks, street vegetation, green roofs, and wood lots, which play an important role in maintaining a cooler urban thermal environment [7,8]. Studies have examined the cooling effect of GS in cities and emphasized the importance of vegetation types, abundance, and spatial arrangement in improving urban ecological environments [9–12]. However, limited research has focused on how adjacent landscapes, particularly GS with impervious surfaces, affect the urban thermal environment in different climatic backgrounds. Some studies found that the relationship between GS and LST was nonlinear, with different cooling intensities of different GS patches. The spatial arrangement, composition, and configuration of the urban landscape influence the cooling effect of GS.

The composition of GS refers to the variety and abundance of landscape elements, while landscape configuration refers to the distribution and spatial arrangement of land cover features [13,14]. Previous studies have shown a negative correlation between GS composition, configuration, and LST. In populated cities, increasing GS can be challenging, but the spatial arrangement of GS can contribute to maintaining a cooler urban environment [8]. However, there is a need to compare the spatial arrangement of GS and their cooling effects in different urban contexts, considering factors such as connectivity, perimeter density, fragmentation, and shape complexity.

To better understand the urban landscape, this study aims to explore the relationship between urban GS and LST, particularly the spatial arrangements of GS in the large city of Beijing and the sprawling green city of Islamabad. By analyzing GS and impervious surface samples using buffer analysis, the study investigates the effects of adjacent landscapes on LST in different urban climates. This study employs landscape metrics, such as the largest patch index (LPI), percentage of landscape (PLAND), patch density (PD), edge density (ED), landscape shape index (LSI), and number of patches (NP), to assess the relationship between GS configuration and LST fluctuation.

Beijing and Islamabad are Asian capital cities experiencing increasing LST and facing challenges related to their urbanization rate [15]. Islamabad, known for its abundant GS, offers insights into sustainable green city planning. Comparing the two cities' landscapes will exchange ideas for landscape planners to develop sustainable layouts that combat the impacts of LST. The study will utilize high–resolution satellite imagery to analyze GS samples to (a) explain the relationship between land use/land cover (LULC) and LST in urban environments, (b) explore the relationship between the spatial arrangement of GS and LST, and (c) assess the warming and

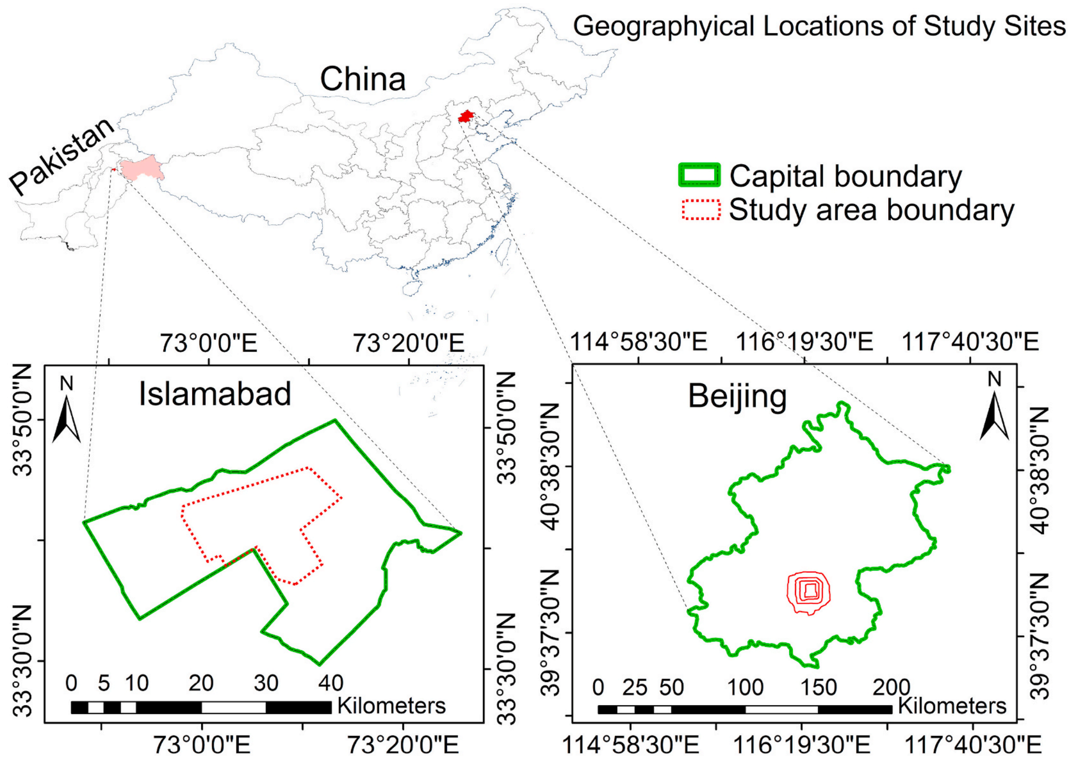

Fig. 1. Geographical position of the cities, i.e., Islamabad and Beijing, and urban areas.

cooling contributions of adjacent landscapes and their extent in urban areas. Overall, this study seeks to contribute to understanding the effects of urban GS on LST and will provide in-depth insights into increasing surface temperatures for future urban planning and management.

2. Materials and methods

2.1. Study area

This study selected two tenanted cities i.e., Beijing (China) and Islamabad (Pakistan), to evaluate the spatial arrangement of the GS effect on LST (Fig. 1). The city of Beijing is located at latitudes 39° 26′ to 41° 30′ N and longitudes 115° 25′ to 117° 30′ E and covers an area of approximately 16,000 km^2 at an elevation of 200 m from sea level. Beijing's urban landscape is studied in different dimensions [16–18]. The city is a large metropolis compared to Islamabad, and its population is lower than that of Beijing. The urban area is expanding rapidly due to urbanization and may face SUHI problems in the near future [19]. The latter lacks much research on the spatial arrangement of GS to find solutions for human-induced climate calamities.

Beijing's topography is moderate and smooth, between 20 and 60 m elevation ranges. The city experiences four seasons under a sub-humid continental warm temperate monsoon climate, with rainy summers, cold–dry winters, and short spring and autumn seasons. Urban climatic conditions inside the metropolitan area remain the same, and elevation does not influence the SUHI [2,20]. This study focused on the landscape within the Fifth Ring Road, a core urban area with intense human activity. The current population is approximately 21.54 million people permanently residing in the city.

Islamabad is positioned between 33° 28′ N latitude and 72° 48′ E longitude. The city's surface area comprises approximately 906 km^2 with an altitude of 400–650 m from sea level. In this region, the climate is humid-subtropical with five distinct seasons, namely, spring (March–April), summer (May–June), monsoon (July–August), autumn (September–October), and winter (November–February) [15,21,22]. The highest summer temperature in Islamabad was recorded at 46.5 °C in 2005. The city had a growth rate of 0.00 % in 1950, increased by 5.70 % in 1995, declined to 3.53 % in 2005, 3.14 % in 2017, and 3.12 % in 2020, and is predicted to be 2.51 % in 2035 [23]. The city population was approximately 0.04 million in 1950, 0.678 million in 2005, and about 1.2 million in 2023. These estimates of city growth are characteristics of urban agglomeration. The city is an exceptional case "planned for the future and built for the present", entirely enduring future planning [24]. In the late 1950s, the prominent city planners Constantinos A. Doxiadis and Doxiadis associates designed and planned the city, which is currently sprawling.

2.2. LULC types classification

Gao-fen satellite data (GF-2) were utilized to map LULC in both cities. Using R statistical software, we classified the urban areas into forestland, impervious surfaces, water bodies, barren land, and grass/agricultural land through the random forest classifier algorithm. The classification producer and user accuracies were satisfactory for land cover type using the Kappa statistics (K) [25] using Equation [1].

$$K = \frac{observed - expected}{1 - expected} \quad [1]$$

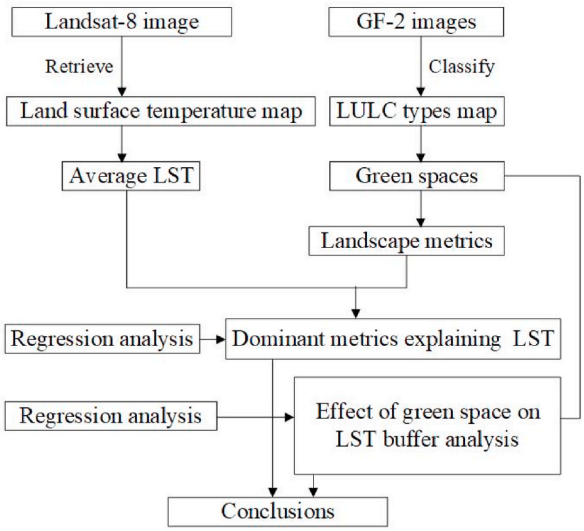

Fig. 2. Pathways of the data analysis and processing of satellite data.

For quantitative landscape structure analysis, six landscape metrics (i.e., PLAND, LPI, PD, ED, NP, and LSI) were derived using spatial analysis software (Fragstats 4.2). The selected metrics represent the number and shape of green patches widely used for landscape interpretation. The details are illustrated in Fig. 2.

To investigate the spatial arrangements of GS, landscape metrics could describe urban GS composition and configuration [26,27]. In the city landscape, six metrics usually represent the relationship between GS and LST [17], as given in Table 1. Among these, the LPI and PLAND represent the abundance and distribution of large GS patches. In contrast, NP, PD, ED, and LSI are the configuration metrics that quantify GS distribution and spatial arrangements. These metrics provide reliable information about vegetation composition and configuration based on the principle, are easy to calculate and interpret, are theoretically and practically important, and have a slight lay-off [28]. A moving window of 1 km^2 was analyzed in Fragstat software as a sampling strategy to create new grids over the greenscape in urban areas.

2.3. LST retrieval

The thermal infrared band (TR-10) of Landsat–8 was used to retrieve LST. Cloud–free Landsat-8 images were acquired to avoid any bias in the extraction of the temperature data using Equation [2]. A radiative transfer model based on the single channel method was used to estimate the LST, as suggested in the literature [30,31].

$$LST_{RTEBi} < -EiTi + ((1 - Ei)\text{Downwelling}) + \text{Upwelling} \quad [2]$$

Ei: surface emissivity of band i.
Ti: spectral radiance.
Downwelling: downwelling path radiance.
Upwelling: upwelling path radiance.
According to Plank's law, ground radiance (Ti) can be expressed using Equation [3].

$$Ti < -\frac{C_1}{Wavelength_{Bi}{}^{5}\left(\exp\left(\frac{C_2}{Wavelength_{Bi}}Ts\right) - 1\right)} \quad [3]$$

Where C1 and C2 are Plank's radiation constant (C_1 is 1.19104 * 108 Wμm4 m-2 sr-1 and C_2 is 14387.7 μm k), the wavelength of the TIRS band 10 = 10.602 and Ts is the surface temperature derived by using Equation [4].

$$Ts_{Bi} < -\frac{K2_{Bi}}{\log\left(\left(\frac{K1_{Bi}}{Li}\right) + 1\right)} - 273.15 \quad [4]$$

For detailed interpretation, we selected 16 and 20 samples from GS patches, impervious surfaces, and fragmented GS from Islamabad and Beijing, respectively. For further analysis, we buffered the samples and investigated the cooling-warming effect consequent to LST in city natural backgrounds. Within the equidistance buffers (10 m), we observed the maximum drop/increase in LST from the edge of samples to a certain distance from the equilibrium state. Furthermore, the temperature difference (TD), temperature gradient (TG), and green space range (GR) were quantified as previously suggested [32]. We performed correlation and regression analysis between dependent (LST) and independent (green space/impervious) variables to better understand their relationship using Origin 2022, a statistical and graphical software. Pearson's correlation between green scape (metrics) and LST, such as LPI and PLAND (compositional metrics), was significant in urban green scape in both cities. In Islamabad, the PD and ED (configuration metrics) show a robust trend with LST in the urban area of Islamabad.

3. Results

3.1. LULC contribution to LST

As shown in Fig. 3, the landscape of Beijing and Islamabad urban areas was classified into five distinct LULC types: forestland, impervious surface, waterbodies, barren Land, and agricultural/grasslands. The percent covered of LULC types in both cities is

Table 1
Important landscape metrics that significantly describe the spatial arrangement of GS [29].

Class metrics (abbreviation)	Description	Unit
Percent of landscape (PLAND)	The highest percentage of a dominant specified type of landscape in a patch	Percent
Largest patch index (LPI)	A measure of the dominated area by a big patch of a specified patch type divided by the landscape's total area.	Percent
Number of Patches (NP.)	Fragmentation numbers are measured as the number of patches of a given patch type.	Number
Patch density (PD.)	Counts of patches per unit area of a specific feature type.	n/100ha
Edge density (ED.)	The total edge length of a given patch per unit area (hectare), overall shape complexity measurement.	meter/ha
Landscape shape index (LSI)	The complex shape measurement of patches; an improved perimeter to area proportion.	number

illustrated in Fig. 4a and b. In Beijing, approximately 63.08 % of the surface area comprised impervious surfaces and 24.01 % by GS within the fifth ring road. In Islamabad, about 49.62 % comprised GS, and 29.45 % comprised of impervious surfaces. The impervious surface/built-up environment in Beijing was found to be two times higher than that in Islamabad. Similarly, along with vegetation, the grassland area in Islamabad was slightly higher than that in urban Beijing. Comparatively, grassland cover was estimated to be lower than the expected areas in both cities (Figs. 3 and 4).

We assessed classification accuracy by randomly selecting validation points in LULC types in urban areas. The LULC sample points were taken from the pixel's center of classified maps, achieving an accuracy of 91 % with a kappa coefficient of 0.85 for Islamabad. On the other hand, Beijing's classification accuracy was 89 % with a 0.83 kappa coefficient. Nevertheless, we cross-checked and verified the maps with referenced high-resolution data from Google Earth. The LULC and associated LST were found to be higher in the city of Beijing than in Islamabad (Fig. 5). The high LST values in Beijing due to the more impervious cover, tall buildings, and accelerated human activities, while less GS cover was observed in the urban area (Fig. 5a). Overall, the mean LST pattern of Islamabad was ranked as follows: barren land > built-up area > grass/agricultural land > forestland > water bodies, while that of Beijing was ranked as follows: built-up area > barren Land > grass/agricultural land > forestland > water bodies (Fig. 5b). In Islamabad, the built-up pattern is scattered with low-height buildings surrounded by GS, which mitigates the soaring LST. Barren lands in Islamabad showed the highest mean LST of 36.35 °C compared to other LULCs. Consequent to the LULC types, the higher mean LST of 39.75 °C was investigated in the built-up area and 34.31 °C in the GS in Beijing, and that of Islamabad was 29.66 °C. The LULC LSTs varied due to the biophysical characteristics of the urban surfaces, which were notably higher in the dense infrastructure in the city of Beijing. The difference in mean LST of 5.44 °C and 3.31 °C was noticed between the impervious surface and GS in Beijing and Islamabad entirely. In contrast, between barren Land and GS, Islamabad's mean LST soared by 3.39 °C compared to Beijing, which accounted for 1.39 °C. The LST details in both cities are given in Table 2.

3.2. Correlation between GS and LST

The relationship between GS and LST in Beijing is shown in Fig. 6. The scatter plots show that the LPI and PLAND have a slight negative trend ($R^2 = 0.28$) in Beijing (Fig. 6a and b). At the same time, the configuration metrics LSI, PD, and NP had no significant effect on the urban thermal environment (Fig. 6c, d, 6e). The ED has a slight negative trend (negligible, $R^2 = -0.08$) with the LST in the city of Beijing (Fig. 6f). On the other hand, in Islamabad, the relationship between the GS and LST was robust for PLAND and LPI, with a significant negative trend ($R^2 = 0.55$). The relationships between GS and LST's spatial arrangement seem statistically more critical in Islamabad due to abundant vegetation cover, and the PLAND and LPI explained significant negative relationship between GS and LST ($R^2 = 0.5$) (Fig. 7a and b). Among the metrics, LSI, PD, and NP for Islamabad, except for ED, showed a moderately significant effect on

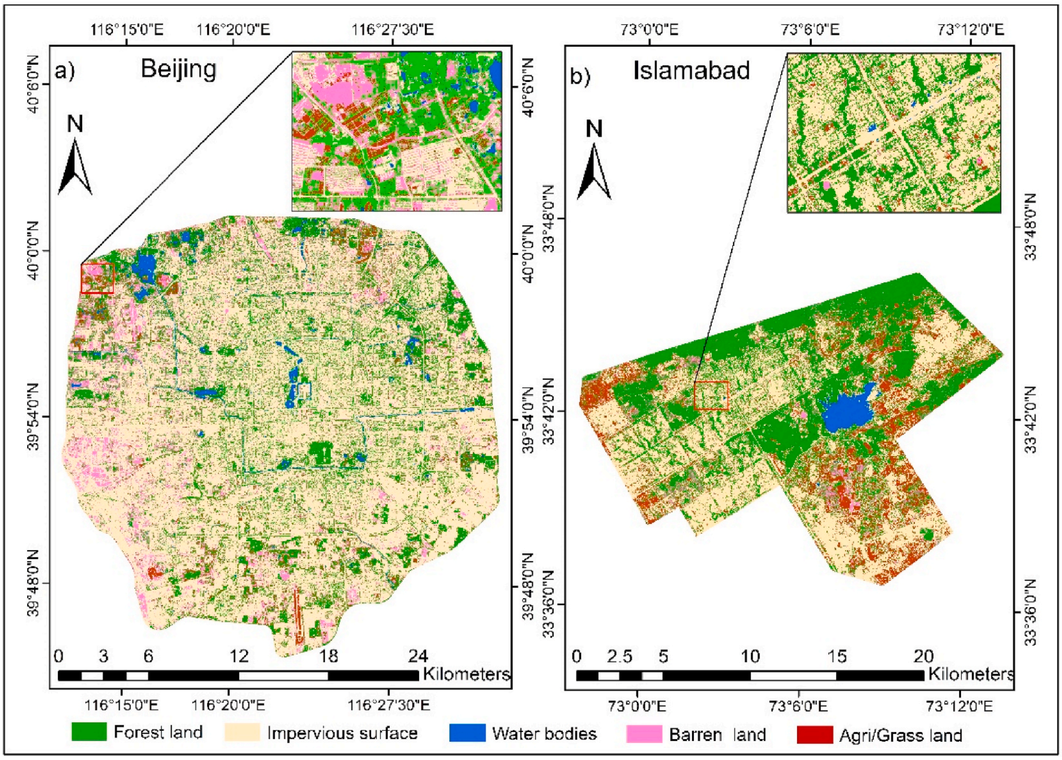

Fig. 3. Land use and land change (LULC) types (**a**) Beijing and, (**b**) Islamabad.

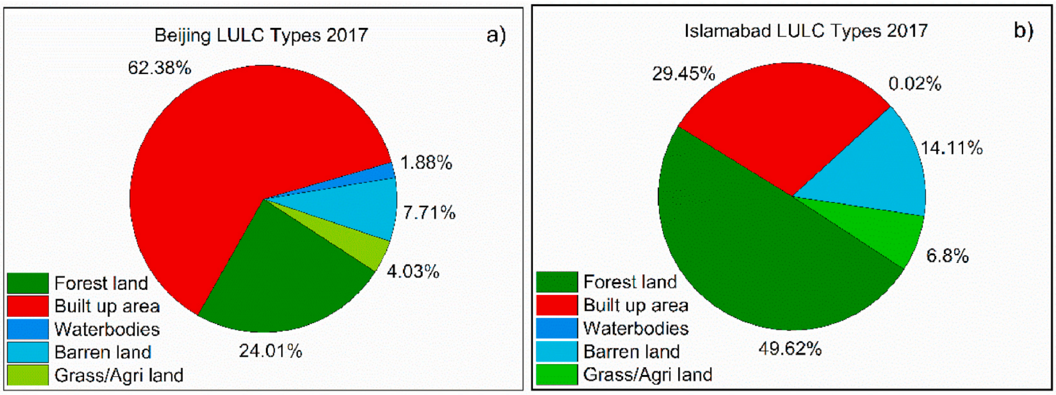

Fig. 4. Descriptive statistics of LULC types (**a**) Beijing LULC and (**b**) Islamabad LULC.

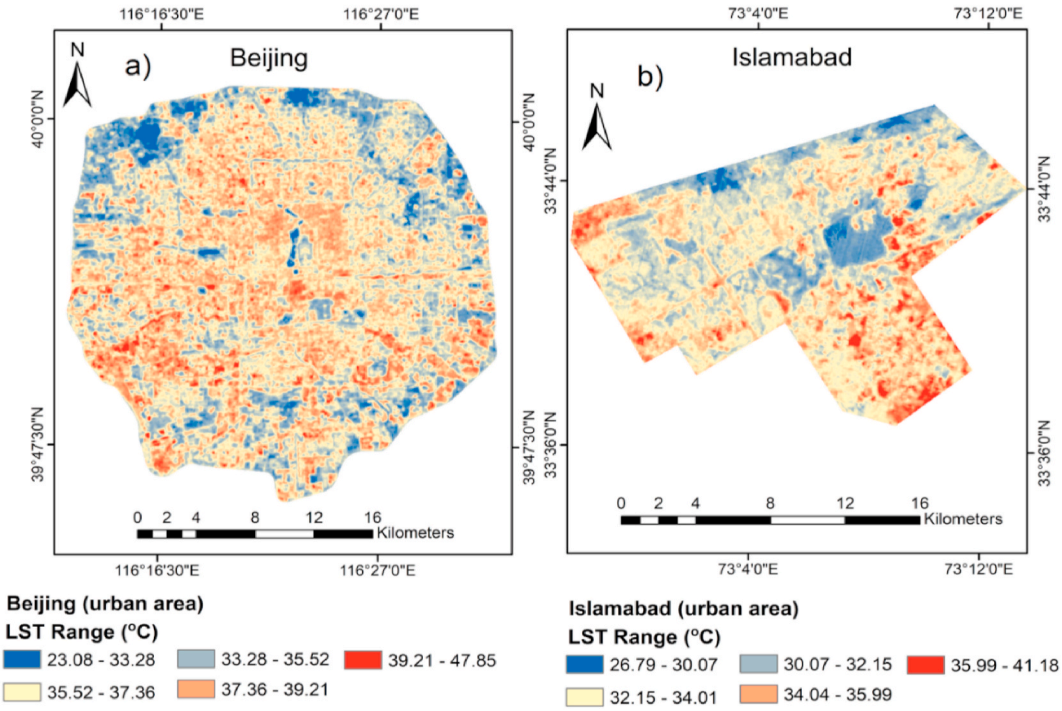

Fig. 5. Spatial distribution of LST (**a**) Beijing LST map (**b**) Islamabad LST map.

Table 2
Descriptive statistics of Land surface temperature (°C) of various LULC in the city of Beijing and Islamabad.

LULC	Beijing			Islamabad		
	Min	Max	Mean LST	Min	Max	Mean LST
Forest land	31.20	37.41	34.31	26.62	32.02	29.66
Impervious	37.05	42.45	39.75	27.67	39.16	32.97
Waterbodies	29.01	36.35	32.68	27.99	37.94	28.54
Barren Land	36.58	37.70	37.14	28.23	41.96	36.35
Grass/Agri	35.69	35.80	35.75	28.23	32.96	34.66

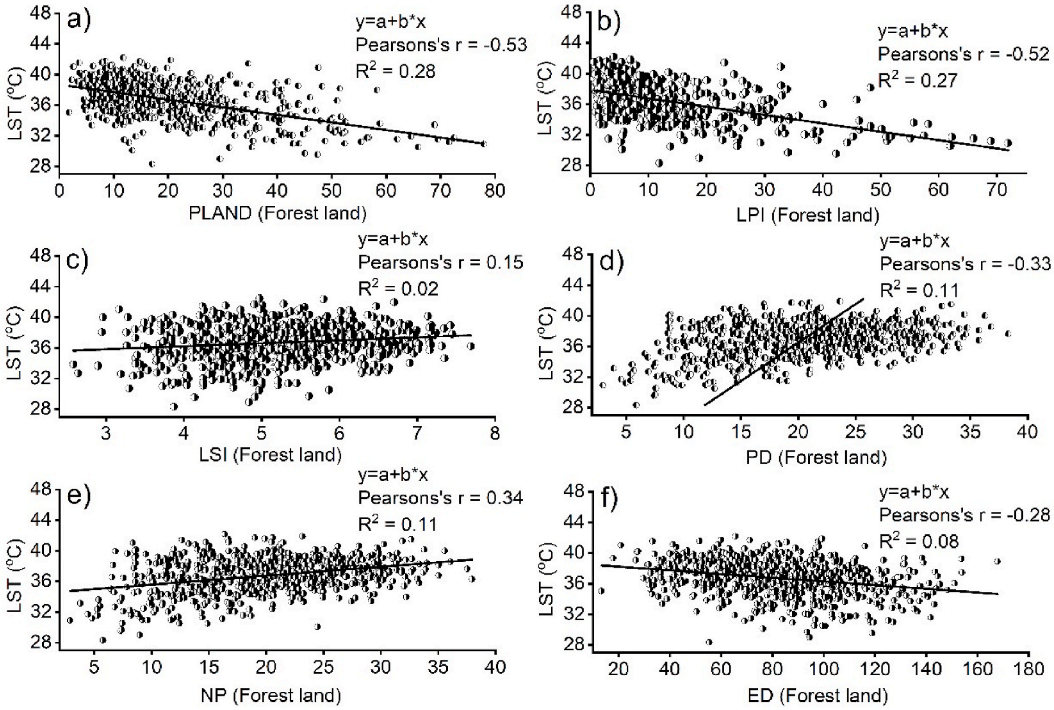

Fig. 6. Effect of landscape metrics on LST in the urban landscape of Beijing (**a**) PLAND (**b**) LPI (**c**) LSI (**d**) PD (**e**) NP (**f**) ED.

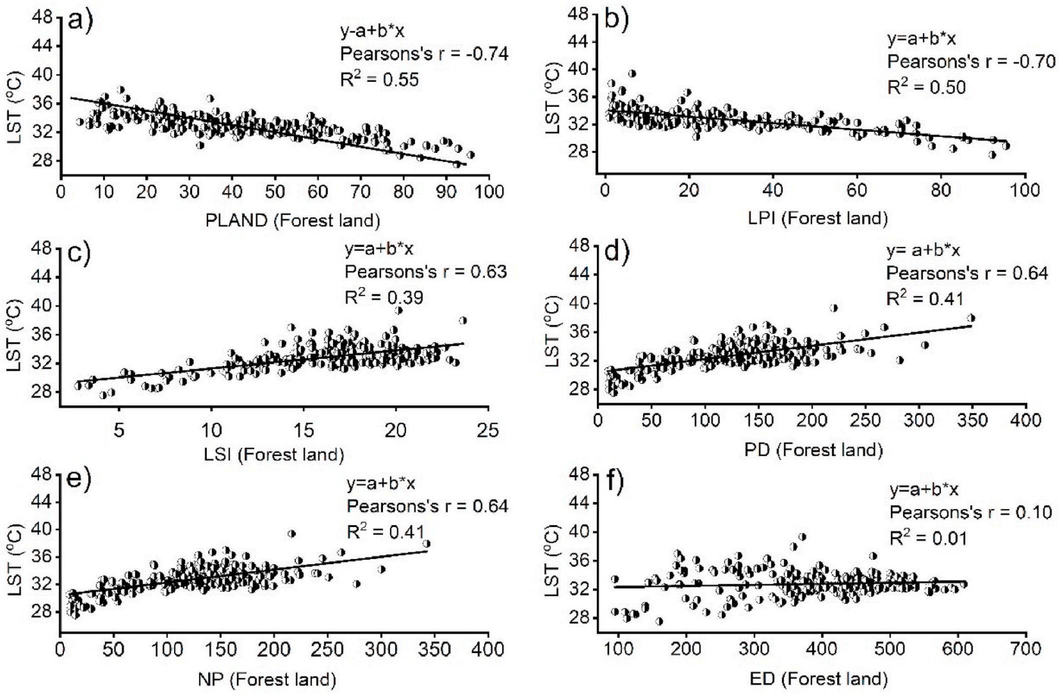

Fig. 7. Effect of landscape metrics on LST in the urban landscape of Islamabad (**a**) PLAND (**b**) LPI (**c**) LSI (**d**) PD (**e**) NP (**f**) ED.

LST (Fig. 7c, d, 7e, 7f). This means the GS configuration performed well in Islamabad, embracing the sustainable urban ecological environment compared to Beijing.

3.3. Green space surface temperature and heterogeneity

Different GS patches and impervious surfaces significantly affect LST in urban landscapes with different climatic backgrounds. In Beijing, scattered GS had significantly contributed to urban cooling relative to their sizes (i.e., 0.1–0.5 ha to 15–20 ha), as shown in Fig. 8a. Similarly, the LST in impervious surfaces soared up and was found to be higher with respective patch sizes in Beijing (Fig. 8b). Overall, the cooling effect of GS patches (0.1–0.5 ha) was more substantial than large patches (15–20 ha) distributed randomly within the core city compared to the proper distribution of small GS patches. In Islamabad, the GS cooling showed an increase with the increase in GS patch size (Fig. 8c), and the patches were found to be close to each other, while the mean LST values fluctuated with the increase in built-up patch size, delimited by vegetation cover (Fig. 8d).

Furthermore, we found that the GS and the impervious surface influenced surface temperature. In both urbanities, the cooling-warming effect was observed in Beijing (16 samples) and Islamabad (20 samples). In the buffer analyses, outside the GS, the surface temperature was 36.48 °C and 32.91 °C for Beijing and Islamabad, respectively, apparently more remarkable than the latter. The results confirmed that GS contributed to the cooling effects in cities in many ways. The distance from the GS edge to the point where the temperature drops refers to the GS Range (GR). Additionally, the change in surface temperature from the GS/impervious surface to the culminating point represents the temperature gradient (TG), indicated by a blue line in Fig. 9. In addition, the GS surface temperature varied between the 0–550 m range in Beijing and 0−260 m in Islamabad. The mean GS surface temperature fluctuates between 31.20 and 34.31 °C and 26.62−32. For Beijing and Islamabad, respectively (Fig. 9a and b). In Beijing, the TD ranged from 1.3 to 8.6 °C, with an average value of 5.01 °C (Fig. 9a). In Islamabad, the TD ranged between 0.87 and 5.84 °C, with a mean value of 3.3 °C. On average, the TG of 0.4 °C/10 m extended up to 240 m from the GS edge in Beijing and 0.21 °C/10 m in Islamabad. The mean temperature difference was 4.3 °C, observed up to a distance of 500 m in Beijing (Figs. 9a) and 2.1 °C up to 230 m in Islamabad (Fig. 9b). The surface temperature of the impervious patches increased as the distance from the GS increased. The trend reduces with a far-off distance from the GS edge and eventually declines.

The warming effects of impervious surfaces within fragmented GS contributed to LST. Based on the GS and adjacent impervious surface samples, the results indicated that the mean LST varied between 35.13 and 37.87 °C for Beijing and 34.55−38.67 °C for Islamabad (Fig. 9d and f). Outside the fragmented GS samples, the mean surface temperature was 34.23 °C and 32.67 °C for Beijing and Islamabad, respectively, lower than the inside. The warming effect declined as the distance from the edge of the impervious surface increased. The trend becomes slight and stable when approaching the GS proximity. The distance between the impervious surface and the GS edge, where the temperature drops at the initial point, is considered the warming range (WR). The difference in temperature

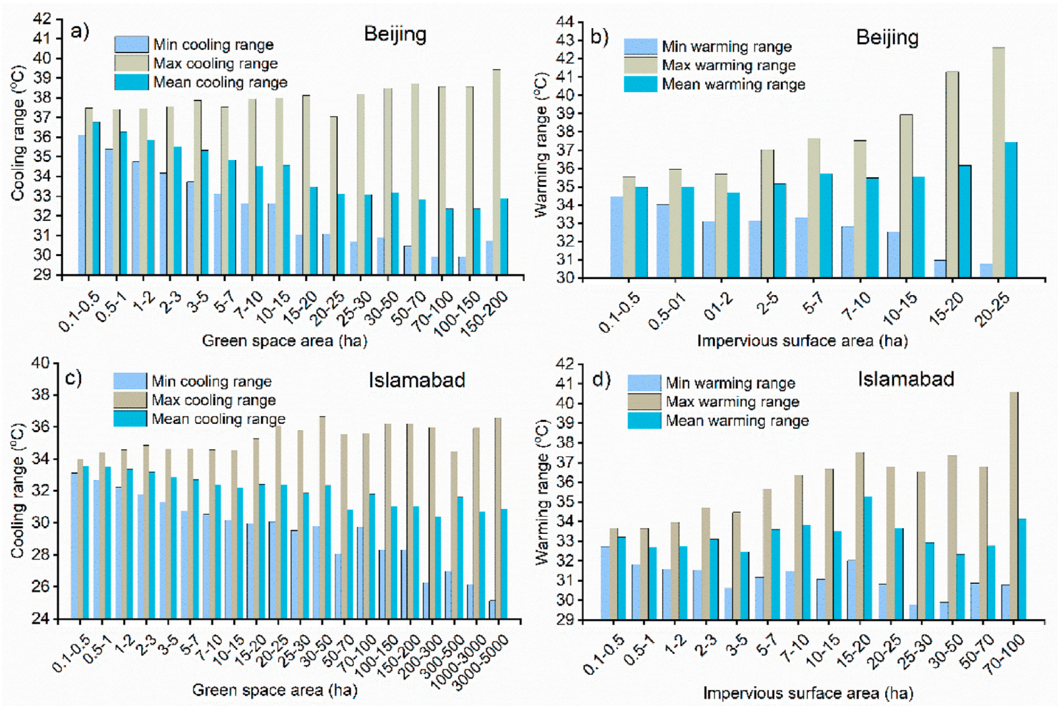

Fig. 8. GS and impervious surface patches and their effect on LST in the urban landscape in both cities (**a**) GS cooling effect in Beijing (**b**) warming effect in Beijing (**c**) cooling effect in Islamabad (**d**) warming effect in Islamabad.

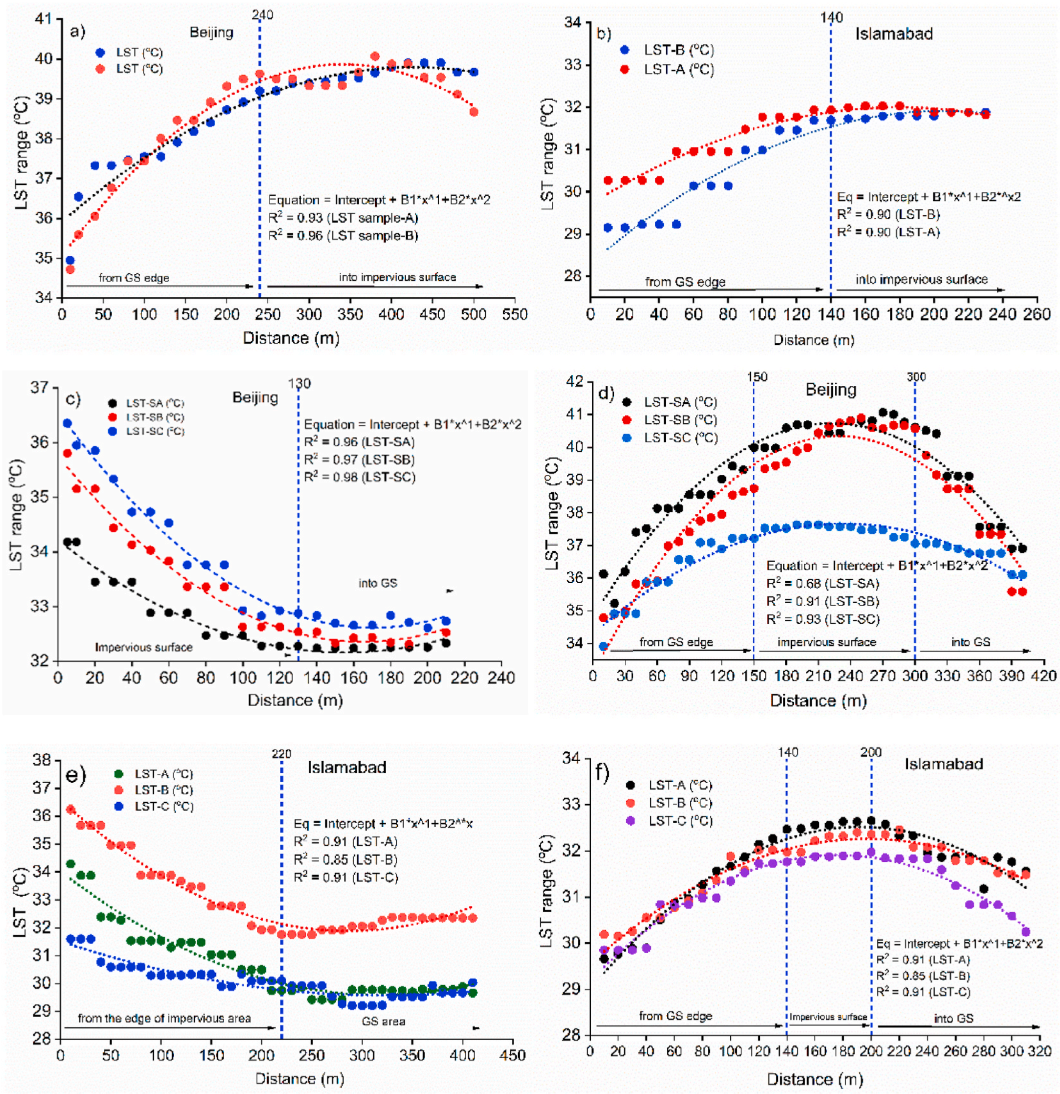

Fig. 9. Green space and impervious surface warming and cooling effect on LST and urban landscapes (**a**) Beijing (**b**) Islamabad (**c**) LST difference between the impervious surfaces and adjacent GS in Beijing (**d**) Temperature variation in mosaic impervious surfaces inside the GS in Beijing (**e**) The LST difference from the grey structure and proximity GS in Islamabad (**f**) The temperature fluctuation in an adjacent landscape surrounded in fragmented in Islamabad.

from the impervious surface to the culminating point denoted TD is indicated by a blue line (Fig. 9d and f).

As shown in Fig. 9c and e, the results confirmed that the impervious surfaces contributed to warming effects, as observed between 0 and 210 m (Islamabad) and 0–410 m (Beijing) from the edge of impervious surfaces. The LST varied by 4.3 °C/500 m for Beijing and 2.1 °C/210 m in Islamabad from the edge of the impervious surface. Similarly, Beijing's impervious surface's TD fluctuated between 34.33 and 36.83 °C, with a difference of 2.5 °C. On the other hand, the TD range was found to be between 34.37 and 38.67 °C, with a mean of 4.31 °C in Islamabad. However, TG varied between the lowest and highest points from the edge of the impervious surface, with a mean difference of 0.13 °C/10 m in Beijing and 0.21 °C/10 m in Islamabad.

In addition, the study investigated fragmented impervious surfaces using equidistance buffers and quantified the cooling (GS) and warming effects (impervious surfaces). The study clarified that the GS contributed a cooling effect up to a specific range, followed by a stable state entering into the impervious surface, and declined when extended to adjacent GS This indicates that the cooling extent varied within GSs was fragmented by impervious surfaces. In contrast, inside the impervious surface, the temperature showed no significant difference (i.e., 150–300 m) until the temperature decreased at a distance of 410 m. The TD (warming) ranged between 3.2 and 4.2 °C and continued to a distance of 150 m until the stable region (i.e., 160–300 m), which was negligible (0.04 °C), and the temperature dropped by 2.2–3.2 °C between 300 and 420 m within the proximity of the GS in Beijing (Fig. 9d and f).

4. Discussions

4.1. Exploring the impact of GS on LST in urban environments

This study intensively explored the effect of LULCs and GS arrangements on the LST in the core urban areas of Beijing and Islamabad. Landscape metrics quantify the relationship between GS and LST, focusing on the spatial arrangements of GS in urban areas [33]. The results revealed that GS composition and configuration are essential in mitigating increasing LST by providing a cooling effect, and the GS composition is more significant and influential in urban areas. However, in green cities such as Islamabad and Singapore, approximately 50 % of the surface area is vegetation cover, where the GS configuration significantly contributes to the cooling effect. The GS cooling extent varies and depends on the surrounding landscapes in urban core areas. However, their intensity may vary from region to region depending on climate and green-impervious landscapes [34]. Our results are consistent with previous studies [26,35,36] but more significant, particularly in urban areas GS and LST configurations.

The correlation analysis between GS and LST demonstrated that the landscape composition and configuration affect the LST to a certain extent (Figs. 6 and 7). As confirmed in research studies, the GS composition has a more significant effect than configuration [19]. The study found that the PLAND and LPI are more critical metrics and have a substantial relationship with LST, confirmed by study findings [17,37]. The relationship of both compositional metrics (PLAND, LPI) is negatively correlated with LST and is more effective among metrics in both cities. The significance level is vital in the case of Islamabad, where 50 % of the urban area is covered by vegetation compared to the GS (24 %) in Beijing. This indicates that more vegetation cover can help maintain urban cooling. It has been reported that the spatial arrangement of GS determines the LST in metropolitan areas [20,38].

The GS patch area, shape, and distribution may significantly influence the urban LST. Configuration metrics such as PD, NP, and LSI have a more significant effect on the urban thermal environment in the city of Islamabad than in Beijing. In the landscape of Beijing, the GS configuration metrics, such as LSI, ED, and NP, show a weak relationship due to the dense building infrastructure.

In the landscape of Islamabad, the PD, NP, and LSI significantly affect LST, and GS composition and configuration metrics are related considerably to LST, except ED (Fig. 7). This means that the planned GS arrangements in Islamabad fully represent the sustainable green city to combat the LST. Although we found a weak correlation between ED and LST, still at a certain level, it might influence the intensity of warming. The negative correlation between ED and LST specifies that GS with equal distribution and in a specific order can reduce the surface thermal impacts, consistent with the results reported by earlier studies [39]. The positive correlation of PD with LST demonstrates that more fragmentation of GS leads to a higher temperature in urban areas [40,41], as observed in Islamabad city. The abovementioned studies suggested that increasing patch density will decrease the mean patch size, ultimately expanding the patch edges. Hence, the LST is affected by an increase in the mean patch size.

Furthermore, even a sizeable continuous vegetation patch has a greater cooling effect than several small patches if the area sum is more than a large patch. Therefore, there is a direct relationship between the mean patch size and LST (Figs. 6 and 7). The landscape shape index has a strong positive correlation with LST in the case of Islamabad due to the dispersal and gaps in buildings inside the urban landscape, which is consistent with those reported by Ref. [15]. Several studies have investigated Beijing's urban landscape, while few studies have explained SUHIs in Islamabad. Naeem et al. [42] reported that the Islamabad GS and LST have a mutual dependency and somehow affect the SUHI.

The urban GS heterogeneity is directly related to GS size and LST. The impervious surface warming and GS cooling effects depend on the relative patch sizes. The mean LST values increased with the impervious surface area in Beijing and Islamabad. The maximum LST values showed an increasing trend in Beijing, while there was some fluctuation in Islamabad's maximum and mean LST values (i.e., 32.9 °C) (Table 2). In Beijing, the trend is consistently increasing with increasing areas of impervious surfaces (Fig. 8b). This indicates that Islamabad's impervious landscape is embedded in several vegetation patches (Fig. 3).

Similarly, the mean LST values decrease with the increase in the area of GS. The LST values concerning the impervious surface area and GS affect the localized climate of both Beijing and Islamabad's urban areas. The values decreased by approximately 7 °C from green patches ranging from 0.1 to 0.5 ha to 150−200 ha in Beijing (Fig. 8a). In Islamabad, the difference is 5 °C for 0.1–0.5 ha to 150–200 ha (Fig. 8c). The warming values of the impervious surface size were lower than the cooling values of GS, as the patch size ranged from 0.1–0.5 ha to 20–25 ha and had higher LST values of 2 °C in both city landscapes.

The warming and cooling effects from the edge of the GS and impervious surfaces are evaluated based on the samples. The mean LST value in both urban areas was lower inside the GS than outside, with a difference of approximately 2 °C between the center and edge of the GS. Furthermore, the study quantified the distance from their boundaries where the cooling and warming extent persisted. The correlation between the warming and cooling values was significant in both cities. For instance, the warming effect range in Islamabad was higher than that in Beijing, a subtropical climate. However, Islamabad is lusher and greener than Beijing. This proved that GS could maintain the cooling of the urban area, and the cooling extent reached 240 m in Beijing and 140 m in Islamabad (Fig. 9a and b), consistent with previous study findings [43]. The results indicated that the TD was extended to a maximum distance in Beijing compared to Islamabad because of the compact impervious surface where the TD is observed to have a maximum length. The average temperature gradient was higher in Beijing than in Islamabad. Furthermore, the impact of GS on LST was investigated as being surrounded by a large patch of impervious surface in both cities.

Sometimes, there is a bias in extracting the LST values from the edge of GS using satellite data because it depends on the proximity of other landscapes. The present study precisely plotted a few samples within an impervious surface surrounded by green patches in opposite directions in both cities. The results show that the LST of the fragmented impervious surface increased, peaked, and declined again when approaching the next edge of the GS (Fig. 9d, f). The cooling effect as a sink source was reported to keep the surrounding urban area cooler [15]. The correlation between the impervious surface and GS with the LST was significant. Nevertheless, the LST (warming effect) dominates over cooling when it reaches the center of the impervious surface. This means that there was an excellent effect on both impervious surfaces and GS on LST in both urban areas.

4.2. Implications for urban GS planning and policy

The study highlights the importance of optimizing green spaces (GS) and strategic urban planning to mitigate city temperature. The research shows the role of the configuration and composition of GS affecting temperature in urban areas. Consequently, this approach would help urban planning and policy strategy implementations to endorse urban cooling. For instance, in Islamabad, the study presents that GS configuration is crucial in determining LST. Therefore, urban green-scape policy should be oriented to optimize the GS spatial arrangements more than other landscape elements. Similar strategies are now being used to increase the GS of London by 50 % since July 2019 (https://www.euronews.com), emphasizing the configurations and composition to maintain the urban cooling effect.

In contrast, in the large city of Beijing, the configuration of GS, except LSI, shows less influence, while the composition metrics explain the LST well. However, to increase city cooling further, the primary focus should be on the configuration of GS, which experiences higher SUHIs. Water and vegetation emerge as crucial landscape elements in mitigating heat in urban areas, as investigated in the landscape of Beijing [2], Islamabad [22], and Nanjing [17]. These studies consistently demonstrate lower temperatures than impervious surfaces, making them valuable components of urban cooling strategies. With continued urbanization, integrating these outcomes into planning, management, and design can contribute to sustainable smart-green city layouts that are resilient to soaring LST and highlight the well-being of urban dwellers. Therefore, sustainable urban environments should prioritize spatial configurations of GSs and consider these implications in planning and policy-making.

4.3. Methodological considerations for studying urban GS and LST relationships

Based on these findings, this research offers deliberate methodological suggestions for studies on the relationship between GS and LST. First, early research studies investigating associations between urban GS, GS spatial design, and LST through several landscape metrics limit their finding comparability. This study presented six metrics, LPI, PLAND, ED, PD, NP, and LSI, which are suitable for efficiently describing the spatial arrangement of GS and their relationships with LST in the two urban landscapes. Understanding the urban GS and LST relationship is imperative, as is using perspective-reliable landscape metrics in urban areas with different spatial patterns, climates, and cultural and socioeconomic situations. Future investigations are projected to compare and include cities of different compositions and configurations to test the appropriateness of the six metrics, understanding the interaction between diverse urban landscapes and respective LSTs.

Second, the spatial arrangement of GS and its association with LST is sensitive to spatial resolution and scale [9,44]. Several studies applied different spatial scales and methodologies, which must be explained while studying the city's core urban areas. For instance, a negative correlation resulted in PD and LST using moderate resolution. At the same time, using Spot or Quick Bird for the same area between the urban GS spatial pattern and LST results was positive [45]. Spatial resolution, scale, and extent may result in different correlations for the same study area. For instance, thermal drones may result in more contrasting conclusions than moderate-resolution data. This indicated that these factors could affect the spatial relationship between urban GS and LST, further complicating the interpretation. To understand their effect, studies should be conducted to determine the scale, grain, and extent.

This study compares the results on similarity and differences, particularly the spatial arrangement of GS and its effect on LST from two cities, to be distinguished and measured against factors (LULC, spatial structure, LST, GS arrangement, cooling extent, fragmented GS-impervious patches). Such comparative findings will ultimately lead to more understanding and help formulate policies and theories for sustainable cities.

5. Conclusion

In conclusion, this comparative study provides valuable insights into the effects of urban green spaces (GS) on land surface temperature (LST) in the Metropolis of Beijing and the green city of Islamabad. The findings highlight the significant influence of GS composition and configuration on LST, with additional considerations for well-configured GS patterns in Islamabad. The study demonstrates that optimizing GS composition and configuration is fundamental for mitigating soaring LST in urban areas. While GS composition plays a dominant role in controlling LST, the configuration of GS also contributes to LST variations, particularly in well-planned arrangements of GS observed in Islamabad. These results emphasize the importance of considering both aspects when designing urban GSs. Moreover, the study reveals the complex relationship between GS fragmentation, shape, and LST. Higher fragmentation and intricate shapes of GS contribute to urban heat islands and elevated LST. Conversely, GS fragmentation with a higher vegetation cover can help to mitigate LST. The study further emphasized the influence of surrounding landscapes and interior characteristics on the efficacy of urban GS in curbing LST. The findings fill a research gap by shedding light on the understudied area of urban GS and surface heat islands in Islamabad, expanding our understanding of complex urban landscapes. The insights gained from this study have practical implications for urban designers, managers, and landscape practitioners in developing sustainable city layouts. Specifically, increasing GS coverage around impervious surfaces and minimizing GS fragmentation are essential strategies for enhancing cooling efficiency and reducing LST. Moving forward, future research should explore the relationship between the spatial arrangement of GS and LST in the surrounding urban environment. This will provide valuable guidance for urban managers and landscape practitioners in designing sustainable cities that effectively address LST challenges. It is important to acknowledge the limitations of this study, including the evaluation of a limited number of GS samples for cooling extent and the reliance on a literature review for comparisons in the case of Islamabad. Nevertheless, this study significantly advances our understanding of LST in both cities and offers critical insights for combating LST in large metropolises.

Funding

This work was financially supported by the National Natural Science Foundation of China [Grant No. 31961143023].

Data availability statement

Data included in article/supplementary material/referenced in article.

CRediT authorship contribution statement

Muhammad Sadiq Khan: Writing – review & editing, Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Yuelin Li:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Investigation, Funding acquisition.

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 address their special thanks to the South China National Botanical Garden, University of Chinese Academy of Sciences, China for their support. Thanks also to anonymous reviewers and editors for their continuous quick assessment.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e24912.

References

[1] L. Howard, The Climate of London, deduced from Meteorological observations, made at different places in the neighborhood, Metropolis 1 (1818) 346.
[2] M.S. Khan, S. Ullah, L. Chen, Comparison on land-use/land-cover indices in explaining land surface temperature variations in the city of beijing, China, Land 10 (2021), https://doi.org/10.3390/land10101018.
[3] C.I. Portela, K.G. Massi, T. Rodrigues, E. Alcântara, Impact of urban and industrial features on land surface temperature: evidences from satellite thermal indices, Sustain. Cities Soc. 56 (2020) 102100, https://doi.org/10.1016/j.scs.2020.102100.
[4] F. Ascione, R.F. De Masi, V. Festa, G.M. Mauro, G.P. Vanoli, Optimizing space cooling of a nearly zero energy building via model predictive control: energy cost vs comfort, Energy Build. 278 (2023) 112664, https://doi.org/10.1016/j.enbuild.2022.112664.
[5] Y. Li, D. Lin, Y. Zhang, Z. Song, X. Sha, S. Zhou, C. Chen, Z. Yu, Quantifying tree canopy coverage threshold of typical residential quarters considering human thermal comfort and heat dynamics under extreme heat, Build. Environ. 233 (2023) 110100, https://doi.org/10.1016/j.buildenv.2023.110100.
[6] P. Shen, S. Zhao, Y. Ma, S. Liu, Urbanization-induced Earth's surface energy alteration and warming: a global spatiotemporal analysis, Remote Sens. Environ. 284 (2023) 113361, https://doi.org/10.1016/j.rse.2022.113361.
[7] P.Y. Tan, J. Wang, A. Sia, Perspectives on five decades of the urban greening of Singapore, Cities 32 (2013) 24–32, https://doi.org/10.1016/j.cities.2013.02.001.
[8] P. Kowe, O. Mutanga, J. Odindi, T. Dube, Impacts of eco-environmental quality, spatial configuration, and landscape connectivity of urban vegetation patterns on seasonal land surface temperature in Harare metropolitan city, Zimbabwe, African Geogr. Rev. 0 (2022) 1–19, https://doi.org/10.1080/19376812.2022.2117215.
[9] R.C. Estoque, Y. Murayama, S.W. Myint, Effects of landscape composition and pattern on land surface temperature: an urban heat island study in the megacities of Southeast Asia, Sci. Total Environ. 577 (2017) 349–359, https://doi.org/10.1016/j.scitotenv.2016.10.195.
[10] Y. Zhang, I.O.A. Odeh, E. Ramadan, Assessment of land surface temperature in relation to landscape metrics and fractional vegetation cover in an urban/peri-urban region using landsat data, Int. J. Rem. Sens. 34 (2013) 168–189, https://doi.org/10.1080/01431161.2012.712227.
[11] M.S. Khan, S. Ullah, T. Sun, A.U. Rehman, L. Chen, Land-use/land-cover changes and its contribution to urban heat Island: a case study of Islamabad, Pakistan, Sustain. Times 12 (2020), https://doi.org/10.3390/su12093861.
[12] B.X. Huang, W.Y. Li, W.J. Ma, H. Xiao, Space accessibility and equity of urban green space, Land 12 (2023), https://doi.org/10.3390/land12040766.
[13] P. Kowe, O. Mutanga, J. Odindi, T. Dube, Impacts of the spatial configuration of built-up areas and urban vegetation on land surface temperature using spectral and local spatial autocorrelation indices, Remote Sens. Lett. 13 (2022) 1222–1235, https://doi.org/10.1080/2150704X.2022.2142073.
[14] J.P. Connors, C.S. Galletti, W.T.L. Chow, Landscape configuration and urban heat island effects: assessing the relationship between landscape characteristics and land surface temperature in Phoenix, Arizona, Landsc. Ecol. 28 (2013) 271–283, https://doi.org/10.1007/s10980-012-9833-1.
[15] S. Naeem, C. Cao, C. Academy, Studying the Association between Green Space Characteristics and Land Surface Temperature for Sustainable Urban ... Studying the Association between Green Space Characteristics and Land Surface Temperature for Sustainable Urban Environments : an Analysis, 2018, https://doi.org/10.3390/ijgi7020038.
[16] R. Sun, L. Chen, Effects of green space dynamics on urban heat islands: mitigation and diversification, Ecosyst. Serv. 23 (2017) 38–46, https://doi.org/10.1016/j.ecoser.2016.11.011.

[17] J. Yin, X. Wu, M. Shen, X. Zhang, C. Zhu, H. Xiang, C. Shi, Z. Guo, C. Li, Impact of urban greenspace spatial pattern on land surface temperature: a case study in Beijing metropolitan area, China, Landsc, Ecol. 34 (2019) 2949–2961, https://doi.org/10.1007/s10980-019-00932-6.
[18] A. Chen, X.A. Yao, R. Sun, L. Chen, Effect of urban green patterns on surface urban cool islands and its seasonal variations, Urban For. Urban Green. 13 (2014) 646–654, https://doi.org/10.1016/j.ufug.2014.07.006.
[19] S. Naeem, C. Cao, W. Qazi, M. Zamani, C. Wei, B. Acharya, A. Rehman, Studying the association between green space characteristics and land surface temperature for sustainable urban environments: an analysis of Beijing and Islamabad, ISPRS Int. J. Geo-Inf. 7 (2018) 38, https://doi.org/10.3390/ijgi7020038.
[20] X. Li, W. Zhou, Z. Ouyang, W. Xu, H. Zheng, Spatial pattern of greenspace affects land surface temperature: evidence from the heavily urbanized Beijing metropolitan area, China, Landsc, Ecol. 27 (2012) 887–898, https://doi.org/10.1007/s10980-012-9731-6.
[21] M.S. Khan, S. Ullah, T. Sun, A.U. Rehman, L. Chen, Land-use/land-cover changes and its contribution to urban heat Island: a case study of Islamabad, Pakistan, Sustain. Times 12 (2020) 1–19, https://doi.org/10.3390/su12093861.
[22] S. Naeem, C. Cao, M.M. Waqar, C. Wei, B.K. Acharya, Vegetation role in controlling the ecoenvironmental conditions for sustainable urban environments: a comparison of Beijing and Islamabad, J. Appl. Remote Sens. 12 (2018) 1, https://doi.org/10.1117/1.jrs.12.016013.
[23] United Nations, The world 's cities in 2018. World's Cities 2018 - Data Bookl, ST/ESA/SER.A/417, 2018, p. 34.
[24] I.M. Frantzeskakis, Islamabad, a town planning example for a sustainable city, WIT Trans. Ecol. Environ. 120 (2009) 75–85, https://doi.org/10.2495/SDP090081.
[25] S. V Stehman, Estimating the Kappa Coefficient and its Variance under Stratified Random Sampling, 1996, p. 62.
[26] L. Tang, Q. Zhan, Y. Fan, H. Liu, Z. Fan, Exploring the impacts of greenspace spatial patterns on land surface temperature across different urban functional zones: a case study in Wuhan metropolitan area, China, Ecol. Indicat. 146 (2023) 109787, https://doi.org/10.1016/j.ecolind.2022.109787.
[27] M. Masoudi, P. Yok, S. Chin, Multi-city comparison of the relationships between spatial pattern and cooling effect of urban green spaces in four major Asian cities, Ecol. Indicat. 98 (2019) 200–213, https://doi.org/10.1016/j.ecolind.2018.09.058.
[28] S.A. McGarigal, E. Cushman, Ene, Spatial Pattern Analysis Program for Categorical and Continuous Maps, University of Massachusetts, London, 2012. Amherst, MA, USA. goo. gl/aAEbMk.
[29] L. McGarigal, B. Marks, FRAGSTATS Manual: spatial pattern analysis program for quantifying landscape structure PNW-GTR-351, URL Ftp//Ftp. Fsl. Orst. Edu/Pub/Fragstats, http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:FRAGSTATS+:+Spatial+Pattern+Analysis+Program+for+Quantifying+Landscape+Structure#2, 1995.
[30] S.A. Ali, F. Parvin, A. Ahmad, Retrieval of land surface temperature from landsat 8 oli and TIRS: a comparative analysis between radiative transfer equation-based method and split-window algorithm, Remote Sens. Earth Syst. Sci. 6 (2023) 1–21, https://doi.org/10.1007/s41976-022-00079-0.
[31] A.U. Rehman, S. Ullah, Q. Liu, M.S. Khan, Comparing different space-borne sensors and methods for the retrieval of land surface temperature, Earth Sci. Informatics (2021) 1–11, https://doi.org/10.1007/s12145-021-00578-6.
[32] H. Du, W. Cai, Y. Xu, Z. Wang, Y. Wang, Y. Cai, Quantifying the cool island effects of urban green spaces using remote sensing Data, Urban For. Urban Green. 27 (2017) 24–31, https://doi.org/10.1016/j.ufug.2017.06.008.
[33] M. Simwanda, M. Ranagalage, R.C. Estoque, Y. Murayama, Spatial analysis of surface urban heat Islands in four rapidly growing african cities, Rem. Sens. 11 (2019) 1–20, https://doi.org/10.3390/rs11141645.
[34] M.S. Khan, S. Ullah, L. Chen, Variations in surface urban heat island and urban cool island intensity: a review across major climate zones, Chin. Geogr. Sci. (2023), https://doi.org/10.1007/s11769-023-1375-8.
[35] R. Sun, L. Chen, Effects of green space dynamics on urban heat islands: mitigation and diversification, Ecosyst. Serv. 23 (2017) 38–46, https://doi.org/10.1016/j.ecoser.2016.11.011.
[36] H. Du, X. Song, H. Jiang, Z. Kan, Z. Wang, Y. Cai, Research on the cooling island effects of water body: a case study of Shanghai, China, Ecol. Indicat. 67 (2016) 31–38, https://doi.org/10.1016/j.ecolind.2016.02.040.
[37] M. Maimaitiyiming, A. Ghulam, T. Tiyip, F. Pla, P. Latorre-Carmona, Ü. Halik, M. Sawut, M. Caetano, Effects of green space spatial pattern on land surface temperature: implications for sustainable urban planning and climate change adaptation, ISPRS J. Photogrammetry Remote Sens. 89 (2014) 59–66, https://doi.org/10.1016/j.isprsjprs.2013.12.010.
[38] H. Xu, C. Li, Y. Hu, S. Li, R. Kong, Z. Zhang, Quantifying the effects of 2D/3D urban landscape patterns on land surface temperature: a perspective from cities of different sizes, Build. Environ. 233 (2023) 110085, https://doi.org/10.1016/j.buildenv.2023.110085.
[39] M. Masoudi, P.Y. Tan, S.C. Liew, Multi-city comparison of the relationships between spatial pattern and cooling effect of urban green spaces in four major Asian cities, Ecol. Indicat. 98 (2019) 200–213, https://doi.org/10.1016/j.ecolind.2018.09.058.
[40] Q. Yang, X. Huang, J. Li, Assessing the relationship between surface urban heat islands and landscape patterns across climatic zones in China, Sci. Rep. 7 (2017) 1–11, https://doi.org/10.1038/s41598-017-09628-w.
[41] R. Zhibin, Z. Haifeng, H. Xingyuan, Z. Dan, Y. Xingyang, Estimation of the relationship between urban vegetation configuration and land surface temperature with remote sensing, J. Indian Soc. Remote Sens. 43 (2015) 89–100, https://doi.org/10.1007/s12524-014-0373-9.
[42] S. Naeem, C. Cao, M.M. Waqar, C. Wei, B.K. Acharya, Vegetation role in controlling the ecoenvironmental conditions for sustainable urban environments: a comparison of Beijing and Islamabad, J. Appl. Remote Sens. 12 (2018) 1, https://doi.org/10.1117/1.jrs.12.016013.
[43] Z. Yu, X. Guo, Y. Zeng, M. Koga, H. Vejre, Variations in land surface temperature and cooling efficiency of green space in rapid urbanization: the case of Fuzhou city, China, Urban for, Urban Green 29 (2018) 113–121, https://doi.org/10.1016/j.ufug.2017.11.008.
[44] F. Guo, U. Schlink, W. Wu, D. Hu, J. Sun, Scale-dependent and season-dependent impacts of 2D/3D building morphology on land surface temperature, Sustain. Cities Soc. 97 (2023) 104788, https://doi.org/10.1016/j.scs.2023.104788.
[45] X. Li, W. Zhou, Z. Ouyang, Relationship between land surface temperature and spatial pattern of greenspace: what are the effects of spatial resolution? Landsc. Urban Plann. 114 (2013) 1–8, https://doi.org/10.1016/j.landurbplan.2013.02.005.