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How can urban green spaces be planned to mitigate urban heat island effect under different climatic backgrounds? A threshold-based perspective

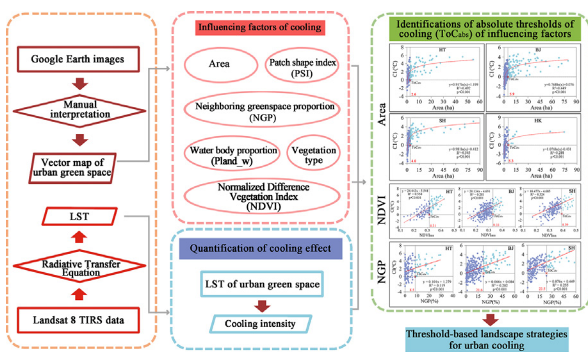
Wen Zhou *, Wendong Yu, Ziyi Zhang, Wei Cao, Tao Wu

College of Horticulture and Landscape Architecture, Yangzhou University, 225000, China

HIGHLIGHTS

- Local climatic backgrounds affect the cooling effect of urban green space (UGS).
- Effects of landscape indicators on the cooling effect of UGS were quantified.
- The threshold values for effective cooling of UGS were identified.
- Strategies for UGS planning and management for climate mitigation were proposed.
- The methodology can be applied in other climate zone-based studies.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban green space (UGS) was widely regarded as an effective nature-based solution to mitigate the urban heat island (UHI) effect, therefore, developing landscape strategies to enhance its cooling intensity (CI) is crucial. However, two main problems prevent the application of results to practical actions: one is the inconsistency of relationships between influencing factors of landscape and the thermal environment; another is the unfeasibility of some common conclusions such as simply increasing the amount of vegetation cover in highly-urbanized areas. This study compared the CIs of UGSs, investigated the influencing factors of CI and identified the absolute threshold of cooling (ToC_{abs}) of the influencing factors in four Chinese cities with very different climatic backgrounds (Hohhot, Beijing, Shanghai and Haikou). Results demonstrate that local climate condition affects the cooling effect of UGS. The CI of UGS is weaker in cities with humid and hot summer than in cities with dry and hot summer. Patch characteristics (area and shape), the percentage of water bodies within the UGS (Pland_w) and neighboring greenspace (NGP), vegetation abundance (NDVI) and planting structure together can explain a significant proportion (R^2 = 0.403–0.672, p < 0.001) of the CI variations of UGS. The inclusion of water bodies can ensure effective cooling of UGS, except in the tropical city. Besides, ToC_{abs} of area (Hohhot, 2.6 ha; Beijing, 5.9 ha; Shanghai, 4.0 and Haikou, 5.3 ha), and NGP (Hohhot, 8.5 %; Beijing, 21.6 %; and Shanghai, 23.5 %), NDVI (Hohhot, 0.31; Beijing, 0.33; and Shanghai, 0.39) were identified and related landscape strategies of cooling were proposed. The identification of ToC_{abs} values can provide easy-to-use landscape recommendations to UHI mitigation.

Abbreviations: UGS, urban green space; UHI, urban heat island; CI, cooling intensity; ToC_{abs}, absolute threshold of cooling; LST, land surface temperature; PSI, patch shape index; $NDVI_{mn}$, mean value of normalized difference vegetation index; Pland_w, Percentage of water bodies within the green space; NGP, percentage of neighboring greenspace; Veg Type, vegetation type; T_{ref}, reference LST; T_i, mean LST of an UGS patch.

* Corresponding author.
E-mail address: wenzhou0305@hotmail.com (W. Zhou).

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1. Introduction

The proportion of the world's population living in cities has increased from about one-third in 1950 to more than half in 2008 (Grimm et al., 2008), and is projected to increase to two-thirds by 2050 (United Nations Department of Economic and Social Affairs, 2019). Rapid urbanization is accompanied by profound changes in landscape patterns and material and energy processes (Cao et al., 2016; He and Zhu, 2018; Jin et al., 2005; Rizwan et al., 2008). The transformation of natural and semi-natural surfaces into impervious surfaces and built-up areas has dramatically altered the surface energy balance (Foley et al., 2005; Stewart and Oke, 2003), resulting in higher air and surface temperatures in urban areas than in surrounding rural areas, known as the Urban Heat Island (UHI) effect (Oke, 1982). There is growing evidence that urban warming may lead to significant increases in mortality from many common human diseases and morbidities (Anderson and Bell, 2011; McGeehin and Mirabelli, 2001; Mora et al., 2017; Rydin et al., 2012), especially among workers who engaged in outdoor and labour-intensive activities in the agricultural sector (Di Blasi et al., 2023). As one of the deadliest natural disasters with great impact worldwide in terms of mortality (Morabito et al., 2017), heat waves have resulted in approximately 70,000 deaths on the European continent (Anderson and Bell, 2011). The superposition of the preexisting UHI effect and climate change is expected to lead to more frequent and intense heat waves in urban areas worldwide (Corburn, 2009; Hoag, 2015; Li and Bou-Zeid, 2013), especially in South Asia (Ullah et al., 2022). Against this backdrop, potential adaptation and mitigation strategies to counteract the UHI effect have attracted global interest as urban areas expand, urban populations concentrate and extreme climate events increase in frequency and intensity in a warming world.

The relationship between land cover/use types and the urban thermal environment, and associated landscape strategies to mitigate the UHI effect have been continuously studied. For instance, Morabito et al. (2021) have demonstrated that an increase in impervious surfaces combined with a low density of tree cover would increase the surface UHI intensity, and an increase in tree cover density can effectively enhance the cooling effect in 10 major Italian cities on the peninsula. The study by Guerri et al. (2022) showed that >50 % of industrial buildings in the Florence metropolitan area were characterized as hot-spot areas, and replacing 10 % of impervious surfaces with planted areas can reduce LST by 2 °C in summer. Similarly, Marando et al. (2022) suggested that a minimum 16 % increase in tree cover leads to a 1 °C decrease in urban temperature. Many studies have confirmed that urban green space (UGS; i.e. forests, parks, roadside green space and other planted areas) can effectively reduce ambient air and surface temperatures, and provide an "urban cool island" effect primarily through evapotranspiration and shading (Fan et al., 2019; Gomez-Martinez et al., 2021; Grimmond and Oke, 1991; Yan et al., 2018). The application of cool roofs and cooling materials and colors of buildings (Akbari and Kolokotsa, 2016; Gilbert et al., 2016), the improvement of urban green coverage (Xiao et al., 2018; Zhou and Cao, 2020), and the enhancement of urban shading and ventilation (Emmanuel et al., 2007; He et al., 2020) have proven to be effective strategies to mitigate the UHI effect. However, many studies claimed that the development of urban blue-green space are cost-effective, environmentally friendly and politically acceptable, and is therefore increasingly recognized as a promising approach to mitigating the UHI effect (Santamouris et al., 2018; Yu et al., 2018a).

Landscape indicators that influence the magnitude of the cooling effect of UGS have been studied extensively, and can be divided into two scales: Patch-level and Class -level. Patch-level studies have focused on quantifying the relationship between the cooling intensity of a single UGS patch and its characteristics (e.g., size, shape, type and planting structure) (Bowler et al., 2010; Chen et al., 2014; Lehmann et al., 2014; Park et al., 2017), while class-level studies refer to those studies that aim to reveal the effects of landscape composition or spatial distribution of UGS patches on the local thermal environment using different analytical units (e.g. grids, city blocks and sub-districts) (Dugord et al., 2014; Kong et al., 2014; Li et al., 2013; Peng et al., 2016; Zhou and Cao, 2020). The relationship between the spatial configuration of UGSs and the thermal environment is contradictory in many cases (Zhou et al., 2017). For example, regular and compact shaped UGS led to a greater reduction in land surface temperature (LST) in Addis Ababa, Ethiopia (Feyisa et al., 2014), Fuzhou, China (Yu et al., 2017) and Singapore (Masoudi and Tan, 2019), while in Beijing, China (Chen et al., 2014) and Berlin, Germany (Dugord et al., 2014), they were associated with an increase LST. Similarly, many studies have claimed that patch density of UGSs was negatively correlated with the local LST in many cities (Dugord et al., 2014; Li et al., 2011; Zhou et al., 2019; Zhou et al., 2011), but some studies conducted in other cities hold the opposite view (Li et al., 2013; Li et al., 2012). Since most of these studies are case- or city-based, it remains uncertain whether these inconsistencies are due to the different climatic conditions in each city.

In addition to the inconsistency of the current conclusions, the lack of land for blue-green spaces in compact urban areas largely prevents the application of the results in practice. For example, it is well known that increasing the area or percentage cover of planted area or water bodies can significantly reduce ambient air temperature and LST (Bowler et al., 2010; Theeuwes et al., 2013; Upmanis et al., 1998; Xiao et al., 2018; Zhou et al., 2014), but increasing the size of a remaining water body or planted area or changing its geometry is difficult to implement. Zhou et al. (2022) proposed the concept of absolute threshold of cooling (ToC_{abs})—the specific threshold of a particular influencing factor that ensures effective cooling of a particular landscape type, to address implementation challenges by linking results to actionable mitigation strategies. For instance, if the ToC_{abs} for NGP (percentage of neighboring greenspace) of water body is 30 %, meaning that the vegetation cover along/around a water body is >30 % of the total landscape in the buffer zone (varying by landscape type, e.g. 120 m for a water body reported in previous study), effective cooling of the water body is ensured without further consideration. With the identification of ToC_{abs} values for other influencing factors, decision makers will have more opportunities to develop actionable landscape strategies to better mitigate the UHI effect with relatively low costs and interventions.

To address these insufficiencies and provide climate-zone-based strategies for UGS planning and management, we selected four Chinese cities with different climatic backgrounds—Hohhot, Beijing, Shanghai and Haikou (Table 1), for a comparative study. First, we investigated the differences in spatial patterns of UGS and the cooling effect of UGS in four cities. We hypothesized that the magnitude of cooling effect of UGSs varies from city to city, and different climatic background conditions influence the

Table 1
Climate types of cities and descriptions of the Landsat 8 OLI/TIRS images used.

City	Climate zone	Summer type	Acquisition date	Acquisition time (BJT)	Reference LST (°C)
Hohhot	Mid-temperate monsoon	Dry and hot	2 Aug, 2021	11:18 am	36.8
Beijing	Temperate monsoon	Rainy and hot	17 Aug, 2019	10:53 am	36.5
Shanghai	Subtropical monsoon	Rainy and hot	16 Aug, 2020	10:25 am	39.1
Haikou	Tropical monsoon	Rainy and hot	10 Aug, 2020	11:05 am	27.7

BJT, Beijing time.
Note: the reference LST represents the mean LST of the study area after excluding the water bodies.

cooling intensity of UGS. We also predicted that UGS would perform better in urban cooling in cities with dry and hot summers than in cities with humid and hot summers, because the evapotranspiration rate is affected by air humidity. Second, the relationship between the cooling intensity of UGSs and landscape indicators was quantified. Finally, we determined the absolute threshold for cooling (ToC_{abs}) values for influencing factors of cooling intensity of UGS if exist. We hypothesized that a large patch area, compact patch shape, high vegetation cover and density of an UGS, as well as a high percentage of water bodies inside and a high percentage of adjacent green spaces outside an UGS will lead to a stronger cooling effect. We also hypothesized that there is a threshold for a certain influencing factor that guarantees the effective cooling of an UGS, e.g., all UGSs with a patch area of >5 ha, or a proportion of water bodies in the interior of >5 % are effective and stable in urban cooling. The results of the present study can inform the development of guidelines for the design and management of UGS to achieve better cooling specific to cities with different climatic conditions.

2. Methodology

2.1. Study area

The study areas include the urban areas (i.e., areas within the outer ring road in this study) of Hohhot, Beijing, Shanghai, and Haikou. The region within the Fifth Ring in Beijing was chosen as the study area since it is the main metropolitan area (Chen et al., 2016). These four metropolitan areas with different climatic backgrounds (Table 1) are all located in different climatic zones of China (Fig. 1 (a)). Hohhot (110°46′–112°10 ′ E, 40°51 ′–41°8 ′ N), with a total area of approximately 17,188.2 km^2, is the capital of the Inner Mongolia Autonomous Region. It is located in the mid-temperate zone with a continental monsoon climate. The average annual temperature is 7.7 °C and the average annual precipitation is 401.8 mm in 2020 (Hohhot Municipal Bureau Statistics, 2021). Beijing (115°25′–117°30 ′ E, 39°28 ′–41°05 ′ N), covers a total area of about 16,410.54 km^2, and had a permanent population of about 21.89 million at the end of 2020. Beijing is characterized by a typical semi-humid and semi-arid monsoon climate in the warm temperate zone, and had an average annual precipitation of 527.1 mm in 2020 (Beijing Municipal Bureau Statistics, 2021). Shanghai (120°52 ′–122°12 ′ E, 30°40′–31°53 ′ N) covers a total area of about 6340.5 km^2, and had a permanent resident population of approximately 24.8836 million at the end of 2020. Shanghai has a subtropical monsoon climate with four distinct seasons, mild climate and abundant rainfall. In 2020, the mean annual temperature was 17.8 °C and the mean annual precipitation was 1660.8 mm (Shanghai Municipal Bureau Statistics, 2021). Haikou (110°07′–110°42′ E, 19°31′–20°04′ N) is the capital of Hainan Province with a total area of approximately 3126.82 km^2, and a permanent resident population of about 2.87 million. Haikou is located in the tropical climate

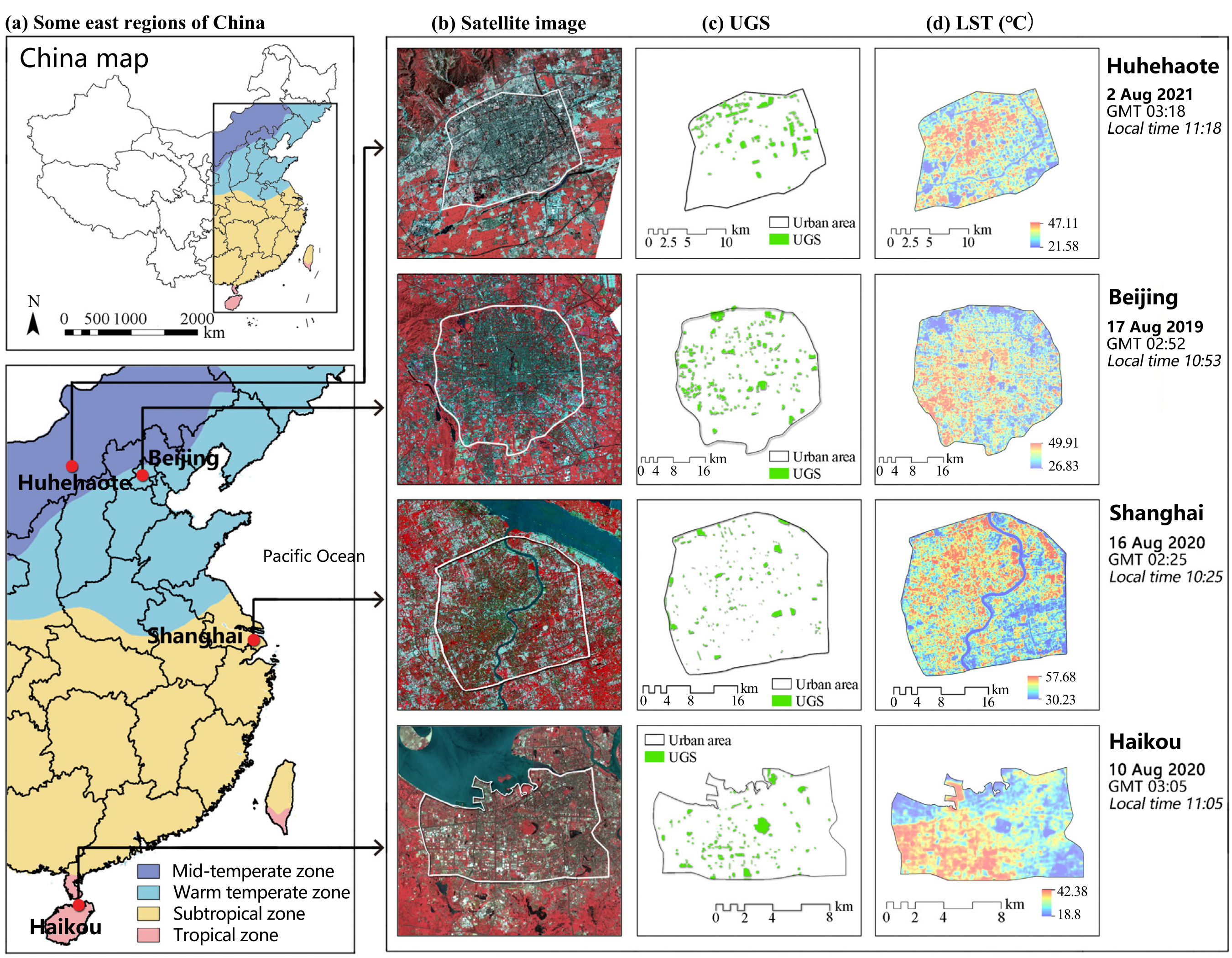

Fig. 1. (a) Map of China showing the different climatic zones and locations of the study areas (Hohhot, Beijing, Shanghai and Haikou); (b) Landsat 8 images of the study areas in Hohhot, 2021; Beijing, 2019; Shanghai, 2020 and Haikou, 2020 displayed with RGB composition of band 5 (near infrared), band 4 (red), and band 3 (green); (c) The distribution of 144 urban green spaces (UGSs) in Hohhot, 277 UGSs in Beijing, 191 UGSs in Shanghai and 152 UGSs in Haikou; (d) LST maps of Hohhot, Beijing, Shanghai and Haikou derived from the Landsat-8 TIRS images.

zone with a monsoon maritime climate and had a mean annual temperature of 25.4 °C and a mean annual precipitation of 1220.4 mm in 2020 (Haikou Municipal Bureau Statistics, 2021). The average elevation is 1040 m, 45 m, 2.19 m and 15 m for Hohhot, Beijing, Shanghai and Haikou, respectively.

As shown in Table 1, summer in Hohhot is dry and hot, while it is rainy and hot in Beijing, Shanghai and Haikou. In the year of satellite data collection, the maximum air temperature in summer (June to August) reached 34 °C for Hohhot and 38 °C for Beijing, Shanghai and Haikou. Besides, the average relative humidity is 49.1 %, 47.7 %, 75.2 % and 79.9 % for Hohhot, Beijing, Shanghai and Haikou, respectively (http://data.cma.cn/). A total of 764 UGSs were included in this study, including 144 UGSs in Hohhot, 277 UGSs in Beijing, 191 UGSs in Shanghai and 152 UGSs in Haikou all located in urban areas (Fig. 1 (c)). These UGSs mainly included forests, parks and roadside green spaces in this study. Since the spatial grid of the LST data is 30 m × 30 m, green spaces smaller than one grid (i.e., 0.09 ha) were excluded in this study.

2.2. Satellite data description and processing

The data used in this study includes four cloud-free Landsat 8 OLI/TIRS images (Fig. 1 (b)) and high-resolution Google Earth images. The Landsat 8 OLI/TIRS data were acquired from the United States Geological Survey (https://glovis.usgs.gov/) and detailed information were shown in Table 1. Four Landsat 8 images were all acquired in summertime including on 2 Aug, 2021, 17 Aug, 2019, 16 Aug, 2020, and 10 Aug, 2020. The OLI data were used to calculate Normalized Difference Vegetation Index (NDVI); and the TIRS data were used to derive LST. The boundaries of the UGSs and the landscape indicators were interpreted and quantified based on high-resolution Google Earth images through manual interpretation based on the map of present land use (https://map.baidu.com/). The LST maps were derived using radiative transfer equation (RTE) method (Jiménez-Muñoz et al., 2014) and results were shown in Fig. 1(d).

2.3. Selections and definitions of landscape indicators

Based on previous research, data availability and relevance to planning, several easy-to-use landscape indicators were selected that are capable of quantifying patch characteristics, vegetation abundance, planting structure, and the composition of the interior and surrounding landscape of UGS patches. Specifically, area and patch shape index (PSI = perimeter $/2\sqrt{\pi}$Area; PSI = 1 when the patch is maximally compact, i.e., circle or almost circle and increases without limit as patch shape becomes more irregular) were applied to quantify the patch characteristics of UGS; the mean value of Normalized Difference Vegetation Index of the UGS patch ($NDVI_{mn}$) and the vegetation type (Veg Type) were selected to determine the state of vegetation growth, vegetation cover and planting structure. Veg Type was used to indicate the main type of planting structure, including Veg Type 0 (tree-dominated, >50 % of the total green cover was tree-dominated) and Veg Type 1 (grass-dominated, >50 % of the total green cover was grass-dominated). The percentage of water bodies (Pland_w) was the ratio of the area of water body within an UGS to the total area of the UGS, and the percentage of neighboring greenspace (NGP) was used to quantify the amount of vegetation cover around the UGS patch (Fig. 2). The values of area and perimeter of UGSs were calculated based on the vector map using the ArcMap platform (Environmental Systems Research Institute, Inc., Redlands, CA, USA).

2.4. Definition of cooling intensity and ToC_{abs}

In this study, the mean LST of the study area, i.e. the mean LST of total grids (all water bodies excluded), was treated as the reference LST (T_{ref}). Same as previous studies (Kong et al., 2014; Zhou et al., 2022), the cooling intensity (CI) of an UGS patch was therefore defined as the difference between the mean LST of an UGS patch (T_i) and the T_{ref} ($CI = T_{ref} - T_i$). Thus, an UGS patch was considered to have positive cooling intensity when its mean LST (T_i) was lower than the T_{ref} (CI>0), and defined to have negative cooling intensity if its mean LST (T_i) was higher than the T_{ref} (CI<0). It was important to note that water bodies, if any, were excluded when calculating the mean LST of UGS patch as this study focused on the cooling effect of UGS and also on the impact of internal water bodies on the CI of UGS.

The ToC_{abs} value (absolute threshold of cooling) is the specific threshold of a particular influencing factor to ensure the positive CI of a particular patch type (Zhou et al., 2022). In this study, the ToC_{abs} of area, PSI, Pland_w, NGP and $NDVI_{mn}$ of UGS for different cities were investigated and further identified if present. Identifying the ToC_{abs} value of an

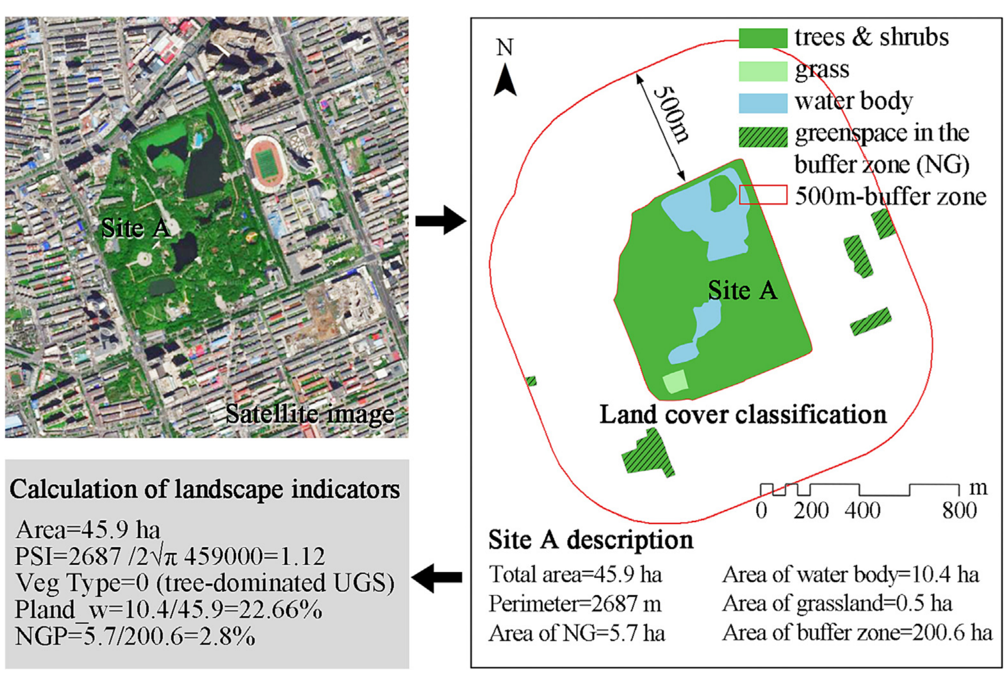

Fig. 2. Diagrams of area, PSI, Veg Type, Pland_w and NGP. Note: PSI is patch shape index, Veg Type is vegetation type, Pland_w is the percentage of water bodies within green space, and NGP is the percentage of neighboring greenspace.

influencing factor (x) works under an important assumption: an obvious linear or logarithmic relationship between the x values and the patch LST (Supplementary Fig. 1). Taking one well-documented influencing factor of CI—area (of UGS patch), as an example to explain its ToC_{abs} identification. Many previous studies have demonstrated that an increase in the patch area of UGS can lead to a linear or logarithmic decrease in patch LST (Cao et al., 2010; Chang et al., 2007; He et al., 2019). Therefore, ToC_{abs} of area is the intersection of the T_{ref} line and the trend line, which means that the positive CI is guaranteed if the patch area is larger than this intersection (Supplementary Fig. 1). In other words, a positive cooling effect became a "certain event" when an influencing factor of the CI of UGS exceeded its ToC_{abs} value.

2.5. Statistical analysis

Bivariate correlation analyses and regression analyses were conducted to analyze the relationships between selected landscape indicators and the cooling intensity (CI) of UGS. Analysis of variance (ANOVA) was used to compare the overall difference in CI of UGS among four cities. Statistical *t*-tests were also used to compare the difference in CI of UGS between any two groups of four cities, and the UGS with and without water bodies in the four cities. The normal P-P plot was carried out before ANOVA and t-tests to examine the distribution of CI values of four cities and the results showed normal distributions (Supplementary Fig. 2). The stepwise multiple linear regression method (SW-MLR) was further applied to explore the combined effect of selected landscape indicators on the CI variations of UGS. Veg Type was transformed into a dummy variable (grass-dominated UGS = 1; tree-dominated UGS = 0) before data analysis. All statistical analyses were performed using SPSS 23.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. General characteristics of the UGS patches in four cities and the corresponding CI

General information of UGS patches in four cities is shown in Fig. 3. The results indicate that UGSs in the urban area of four cities are mainly small and medium-sized (area ≤ 5 ha), especially in Haikou, where only a few UGSs (7.9 %) have an area >5 ha. The proportion of large UGSs (area > 5 ha) was largest in Beijing, and the overall size of UGSs in Hohhot and Shanghai is similar. In terms of shape, the PSI values of UGSs in Shanghai are lower than those in the other three cities, indicating that the UGS patches in Shanghai are more regular than those in the other cities. In addition, the proportion of Pland_w was highest in Shanghai, followed by Beijing, Hohhot and Haikou. The results show that the overall NGP of UGSs is highest in Shanghai, followed by Beijing and Haikou, and lowest in Hohhot, implying that the spatial distribution of UGSs in Shanghai is more aggregated and had a relatively high degree of connectivity. The NDVI values of UGS in Shanghai are also the highest, followed by Haikou and Hohhot, and the lowest in Beijing. This is probably due to the fact that the majority of UGSs (94.8 %) in Shanghai are dominated by trees rather than grass. Unlike other cities, 31.6 % of the UGSs in Haikou are grass-dominated, indicating that a simpler planting structure was common in Haikou than in other cities.

As shown in Fig. 4, the overall CI of UGS was strongest in Hohhot, followed by Shanghai and Beijing, and weakest in Haikou. Significant difference ($p < 0.001$) in the CI of UGSs was observed between four cities. Specifically, there was significant difference in CI between Haikou and other cities, but no significant difference was observed either in CI between Beijing and Shanghai, or in Hohhot and Shanghai. Meanwhile, the CI of UGS in Hohhot was significantly higher than that in Beijing. More specifically, the proportion of UGS with CI values of 0 °C to 2 °C was highest in Hohhot, Beijing and Shanghai, and UGS with CI between −2 °C and 0 °C were most common in Haikou. The average CI of UGSs in Hohhot was highest in all area groups, followed by Shanghai. The average CI of UGSs in Haikou smaller than 3 ha was negative, indicating that small UGSs in Haikou do not necessarily have effective cooling. Similarly, the average CI of UGSs in Beijing smaller than 3 ha was significantly lower than in Hohhot and Shanghai, but still much higher than in Haikou. The amount of UGSs with the highest CI level (4 °C–6 °C) was much greater in Hohhot than in the other three cities.

In this study, the mean values of CI of UGS were 1.7 °C, 1.1 °C, 1.5 °C and −0.7 °C in Hohhot, Beijing, Shanghai and Haikou, respectively, and specifically ranged from −2.6 °C to 5.9 °C in Hohhot, −3.5 °C to 5.1 °C in Beijing, −3.6 °C to 5.2 °C in Shanghai and −5.2 °C to 5.8 °C in Haikou (Supplementary Table 1). The combination of the range and standard deviation values suggests that the cooling heterogeneity of UGS was much more pronounced in Haikou than in the other three cities. The proportion of positive CI was greatest in Hohhot (82.4 %), followed by in Shanghai (77.6 %), Beijing (69.5 %) and Haikou (38.8 %) (Supplementary Table 1), suggesting that the cooling effect of UGS is strongest in Hohhot, followed by Shanghai and Beijing, and weakest in Haikou.

3.2. Modelling the relationship between landscape indicators and CI of UGSs in four cities

Table 2 summarizes the results of the stepwise multiple linear regression (SW-MLR) analysis. The VIF (variance inflation factor) values ranging from 1.036 to 2.103 indicated a low degree of collinearity among the landscape variables used in this study. The results of Durbin-Watson test were 1.653, 1.329, 1.847 and 0.969 (between 0 and 4) for four models, indicating independence of the residuals. Besides, normality and homoscedasticity were observed in the residuals (Supplementary Fig. 3), indicating that the SW-MLR model was suitable for modelling the relationship between CI of UGSs and selected landscape indicators in this study. Overall, the results indicated that Log10Area (i.e., the logarithm transformation of area, since the linear relations between Log10Area and CI of four cities were guaranteed, Supplementary Fig. 4), PSI, Pland_w, NGP, $NDVI_{mn}$ and Veg Type together had the power to explain a significant proportion of the CI variations of UGS in Hohhot ($R^2 = 0.672$, $p < 0.001$), Beijing ($R^2 = 0.588$, $p < 0.001$), Shanghai ($R^2 = 0.657$, $p < 0.001$) and Haikou ($R^2 = 0.403$, $p < 0.001$).

Based on the results of SW-MLR analysis (Table 2), the relationships between selected landscape indicators and CI varied in magnitude and significance across cities. There were significant positive correlations between patch area, $NDVI_{mn}$ and CI of UGS in four cities, with the effect of $NDVI_{mn}$ on CI of UGS being greatest in Hohhot and the effect of patch area on CI of UGS being greatest in the other three cities. The results showed that Pland_w was positively correlated with CI of UGS in Hohhot and Beijing, and NGP was positively correlated with CI of UGS in Beijing and Shanghai. Negative correlations between Veg Type and CI of UGSs were found in Hohhot, Beijing and Haikou.

3.3. ToC_{abs} of influencing factors: identification and comparison

Based on the results of the curve estimation analysis, the area and CI of UGS in all cities can be well fitted by logarithmic models ($R^2 = 0.269$–0.579, $p < 0.001$), suggesting that the CI value becomes more stable when the area reaches a certain threshold (Fig. 5(a)). The results indicated that the ToC_{abs} of Area for UGS existed and were 2.6 ha for Hohhot, 5.9 ha for Beijing, 4.0 ha for Shanghai and 5.3 ha for Haikou. That is, the positive CI was guaranteed when the area of UGS was larger than 2.6 ha, 5.9 ha, 4.0 ha and 5.3 ha for Hohhot, Beijing, Shanghai and Haikou, respectively. Besides, relationship between area and CI of UGS for Hohhot, Beijing and Shanghai could be well fitted by the linear regression model, when the area smaller than the ToC_{abs} values (Fig. 5(b)). Overall, there is a logarithmic relationship between the patch area and the CI as a whole, and a partial linear relationship when the value of area is within a certain threshold (e.g., ToC_{abs} of Area in this study).

There were positive linear relationships ($p < 0.001$) between $NDVI_{mn}$ and CI of the UGSs in four cities, indicating that the higher the $NDVI_{mn}$, the stronger the CI of the UGS. In addition, the ToC_{abs} of $NDVI_{mn}$ were

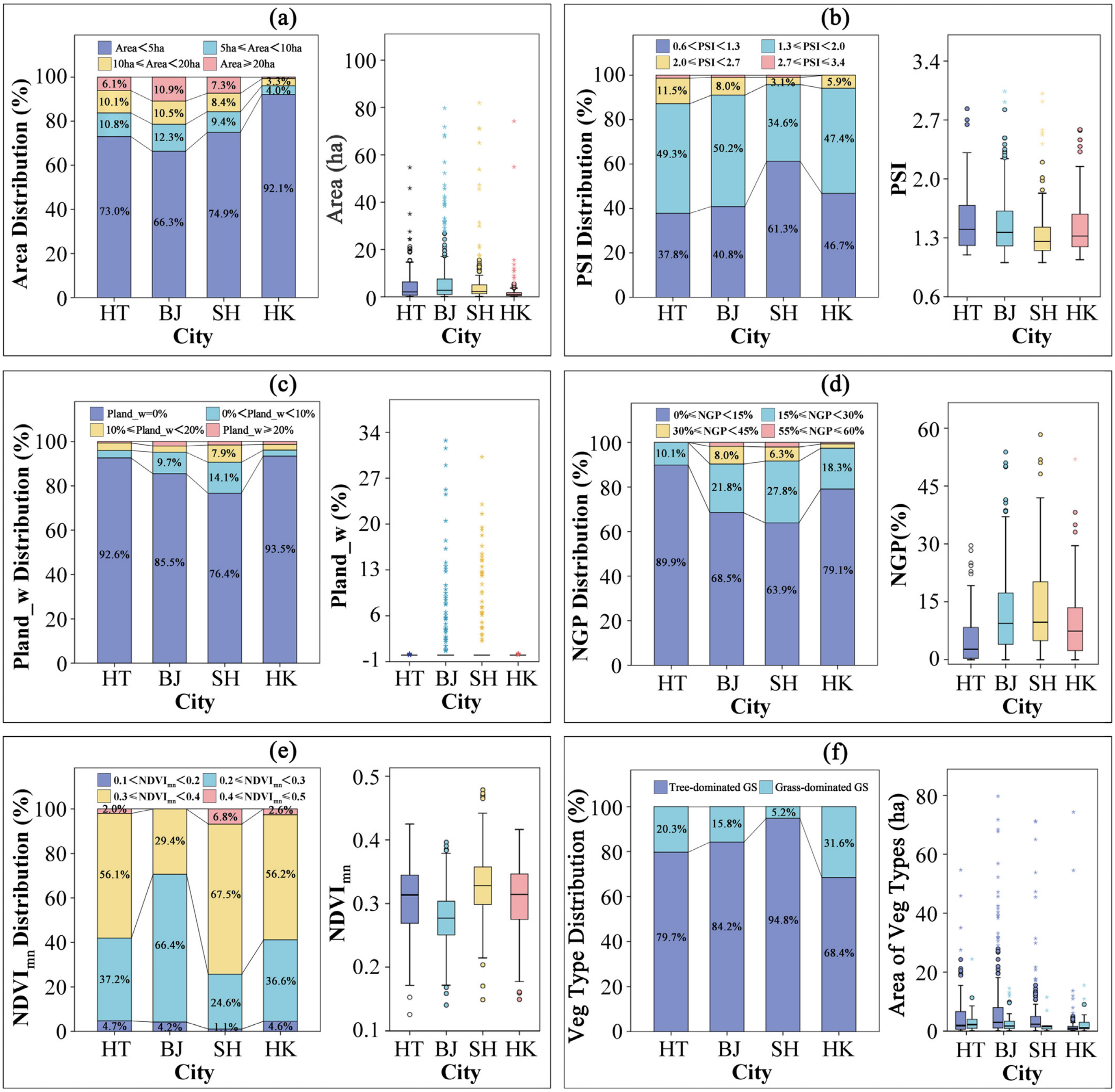

Fig. 3. The distributions of (a) area, (b) PSI, (c) Pland_w, (d) NGP, (e) $NDVI_{mn}$ and (f) Veg Type of urban green space (UGS) patches in four cities. Note: PSI is patch shape index, Pland_w is the percentage of water bodies within green space, NGP is the percentage of neighboring greenspace, $NDVI_{mn}$ is the mean value of normalized difference vegetation index, and Veg Type is vegetation type. HT, BJ, SH and HK represent Hohhot, Beijing, Shanghai and Haikou, respectively.

0.31, 0.33 and 0.39 for Hohhot, Beijing and Shanghai, respectively (Fig. 5(c)). The results also showed that ToC_{abs} of NGP existed in Hohhot, Beijing and Shanghai, and were 8.5 %, 21.6 % and 23.5 %, respectively (Fig. 5(d)). ToC_{abs} of NGP and $NDVI_{mn}$ (of UGS) were not observed in Haikou, so the results were not shown in the figure.

There were significant differences between UGSs with and without water bodies on the CI in four cities, and the difference was most remarkable in Hohhot, followed by Beijing and Shanghai (Fig. 6). In particular, the CI of UGS with water body (Pland_w>0) was significantly stronger than that of UGS without water body (Pland_w = 0). It can be seen that UGSs with water bodies in Hohhot, Beijing and Shanghai all had positive CIs. Unlike other three cities, UGS with water body could not guarantee a positive CI in Haikou.

4. Discussion

4.1. The influence of local background climate on the cooling effect of UGS

This study found that local climatic background conditions influence the cooling effect of UGS, and this conclusion is partly supported by previous studies (Akbari and Kolokotsa, 2016; Oliveira et al., 2011). In this study, the cooling effect of UGS is much stronger in mid-temperate city (e.g., Hohhot in this study) with dry summers than in cities with rainy and hot summers (e.g., Beijing, Shanghai and Haikou in this study). Thus, the results suggest that the high CI of UGS is most likely associated with the low humidity levels, which is consistent with the study of Oliveira et al. (2011). Besides, the CI of UGS in tropical city (e.g., Haikou in this

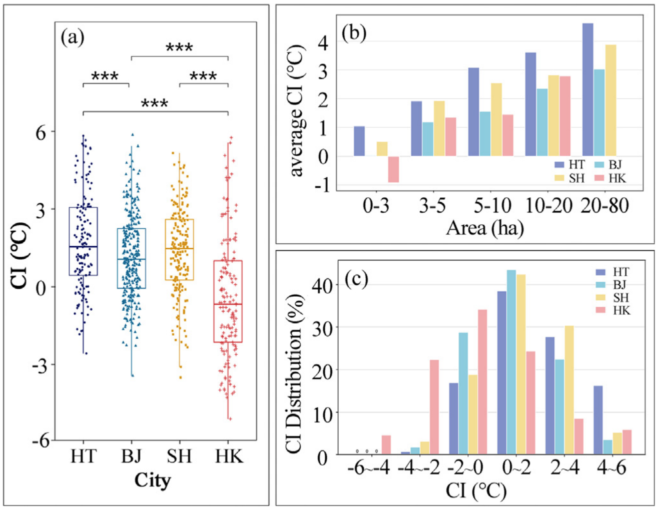

Fig. 4. (a) The distribution of cooling intensity (CI) (°C) of urban green spaces (UGSs) in different cities; (b) Average CI (°C) of UGSs in different areas (ha); (c) The distribution of different CI intervals. Note: ***indicate significantly different means based on an Independent-Sample *t*-test at 0.001 level. HT, BJ, SH and HK represent Hohhot, Beijing, Shanghai and Haikou, respectively.

study) with high relative humidity level is significantly lower than in other cities. This can be explained by the study of Santamouris (2014) which suggests that evapotranspiration rate is reduced at high humidity conditions, as well as the cooling effect of UGS. The results of this study also suggested that high altitude is likely associated with a strong cooling effect of UGS, but further research should be conducted to confirm the current results.

The effect of landscape indicators on the CI of UGS varied among cities with different climatic backgrounds. Specifically, the shape complexity of UGS patch in Hohhot is unrelated to the CI of UGS, but is associated with the CI variation of UGS in the other three cities (Supplementary Table 2). This result can partially explain the inconsistent conclusions of previous studies about the effect of shape on the cooling effect of UGS (Dugord et al., 2014; Feyisa et al., 2014; Masoudi and Tan, 2019; Zhou et al., 2022). Besides, the percentage of water bodies within UGS did not affect the CI of UGS in tropical cities (e.g. Haikou in this study). However, as expected, the presence of water bodies can significantly enhance the cooling capacity of UGS in the other three cities (Supplementary Table 2), as urban water bodies have been consistently demonstrated as another promising strategy to mitigate the UHI effect due to their high heat capacity and evaporation (sensible-to-latent heat conversion) and convection processes (Gunawardena et al., 2017; Manteghi et al., 2015). The reason for this could be that high humidity suppresses the evaporation rate and reduces the latent heat flux (Jim and Peng, 2012). This study also suggested that the CI of UGS is most dependent on vegetation abundance and growth condition in cities with dry summer, whereas patch area is the most important factor influencing the CI of UGS in cities with humid summer. However, most previous studies on this topic have been conducted in humid subtropical cities (Chen et al., 2019; Xu et al., 2010; Yu et al., 2017; Zhou et al., 2019), and climate-zone-based studies that include more cities with different climatic background conditions are urgently needed to reduce uncertainties.

Table 2
Results of the SW-MLR analyses (Dependent Variable is cooling intensity (CI)).

City	Variables	Unstandardized coefficients β	Unstandardized coefficients Std. error	Standardized coefficients (β)	Sig.	VIF
Hohhot	(Constant)	−3.750	0.637		0.000	
	$NDVI_{mn}$	17.483	2.159	0.534	0.000	1.804
	$Log_{10}Area$	0.887	0.211	0.295	0.000	2.043
	Pland_w	0.075	0.029	0.139	0.011	1.220
	Veg Type	−0.551	0.233	−0.118	0.020	1.031
	R^2 = 0.672; Adjusted R^2 = 0.662					
Beijing	(Constant)	−0.418	0.624		0.504	
	$Log_{10}Area$	1.245	0.144	0.486	0.000	2.103
	NGP	0.026	0.007	0.174	0.000	1.378
	PSI	−0.691	0.193	−0.143	0.000	1.062
	Veg Type	−0.689	0.180	−0.159	0.000	1.038
	$NDVI_{mn}$	5.406	2.040	0.139	0.009	1.824
	Pland_w	0.035	0.016	0.098	0.026	1.264
	R^2 = 0.588; Adjusted R^2 = 0.579					
Shanghai	(Constant)	−1.377	0.675		0.043	
	$Log_{10}Area$	1.727	0.174	0.595	0.000	1.886
	$NDVI_{mn}$	7.168	1.689	0.221	0.000	1.427
	NGP	0.027	0.008	0.178	0.001	1.408
	PSI	−0.514	0.252	−0.098	0.043	1.229
	R^2 = 0.657; Adjusted R^2 = 0.649					
Haikou	(Constant)	−1.567	1.322		0.238	
	$Log_{10}Area$	2.257	0.395	0.479	0.000	1.726
	$NDVI_{mn}$	10.458	3.416	0.239	0.003	1.506
	Veg Type	−1.245	0.335	−0.246	0.000	1.074
	PSI	−1.169	0.395	−0.207	0.004	1.200
	R^2 = 0.403; Adjusted R^2 = 0.387					

4.2. Implications for urban green space planning and design

Consistent with the study by Zhou et al. (2022), ToC_{abs} of Area were identified for four cities, suggesting that UGSs respectively larger than 2.6 ha, 5.9 ha, 4.0 ha and 5.3 ha for Hohhot, Beijing, Shanghai and Haikou have relatively stable and effective cooling effects. If the UGS is smaller than the threshold, increasing the area is an effective measure to improve the CI, while it is no longer so "effective" if the patch area is larger than this threshold. Therefore, we suggest that more attention should be paid to CI enhancement strategies for those relatively small UGSs. The study by Yu et al. (2018b) explained that cities with higher rainfall need a greater sized UGS to achieve the highest cooling efficiency, and similar pattern was observed in this study (e.g., ToC_{abs} of Area and precipitation are 2.6 ha and 401.8 mm for Hohhot, and are 5.3 ha and 1220.4 mm for Haikou).

The complexity of the patch shape is not as important as the patch area, but also affect the CI of UGS in Beijing, Shanghai and Haikou. The results demonstrated that a regular and compact shape (square or circular) in UGS planning has a greater cooling potential than irregular and complex patch of similar size, which is consistent with previous studies (Cao et al., 2010; Feyisa et al., 2014; Masoudi and Tan, 2019). The reason might be that a more complex boundary of an UGS provides more opportunities to interact with surrounding land cover types (e.g., impervious pavement, residential and commercial areas, etc.), resulting in more heat exchange. The CI of UGS in Hohhot is not correlated with the patch shape, suggesting that its shape does not need to be critically considered in the planning and design of UGS for better cooling.

The ToC_{abs} of NGP for water body and grassland were identified by the study of Zhou et al. (2022), and the results of this research further confirmed the existence of ToC_{abs} of NGP for UGS. The results suggested that the positive CI of UGS was guaranteed when the NGP were >8.5 %, 21.6 % and 23.5 % for Hohhot, Beijing and Shanghai, respectively. The results indicate that the higher the NGP, the stronger the CI of UGS in four cities (Supplementary Table 2 and Fig. 5(d)). In a highly urbanized area, it is not practical to enlarge the area of an existing UGS to enhance its cooling effect, but interspersing small vegetation patches on the spare land near it to increase the NGP is an alternative method to intensify its cooling effect. Besides, landscape strategies such as building green corridors connecting UGS patches to increase the degree of connectivity and aggregation of urban green space system are also effective to better counteract the UHI effect.

Previous study found that an UGS with water bodies provide more LST deduction than a waterless UGS of similar size in a subtropical city in China (Zhou et al., 2023), which is in line with our results. This study has shown that the CI of UGS with water bodies inside is significantly greater than that of waterless UGS, and all UGSs with water bodies inside are effective in urban cooling in Hohhot, Beijing and Shanghai. Thus, the reasonable

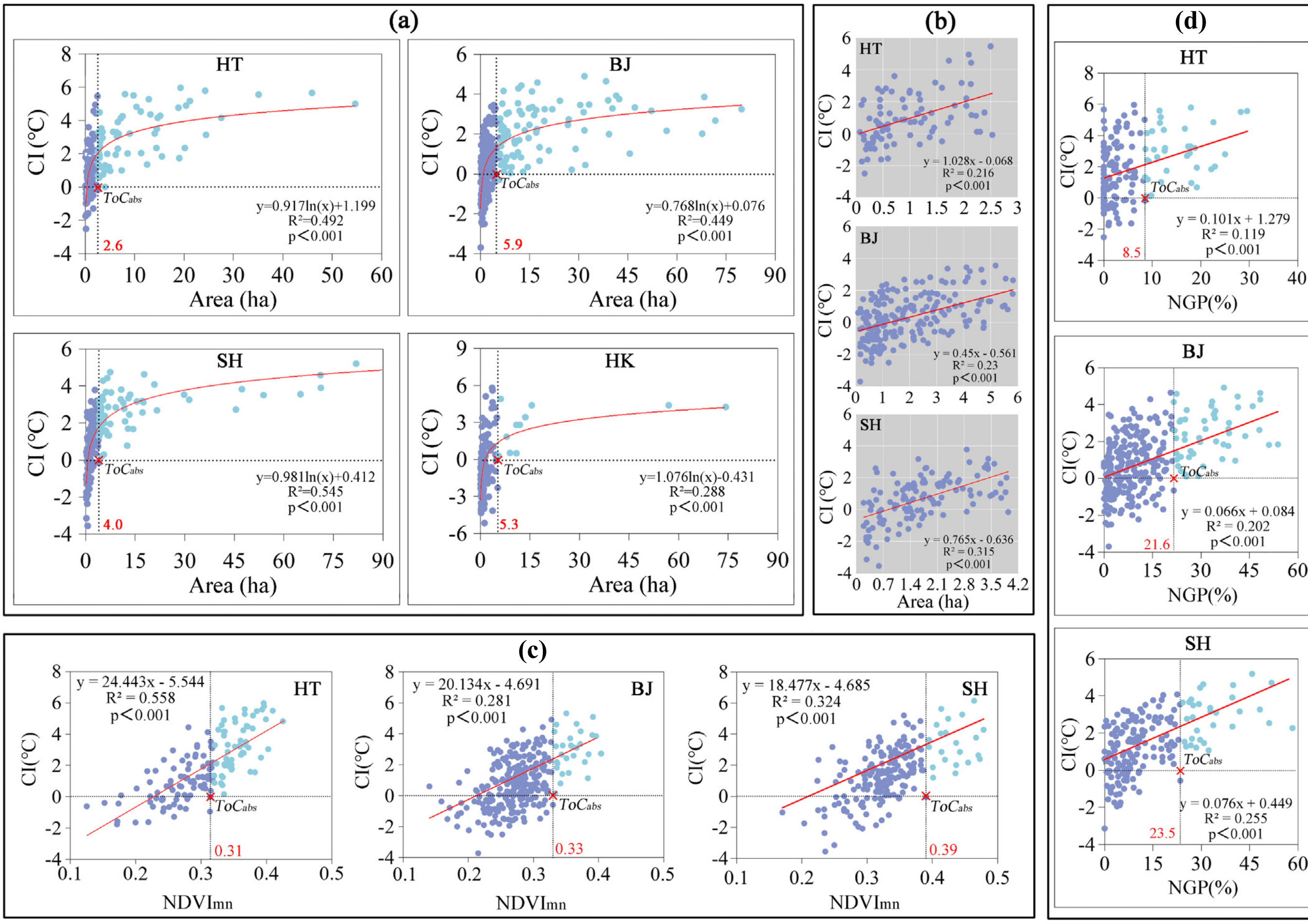

Fig. 5. Relationships between cooling intensity (CI) of urban green spaces (UGSs) with (a) patch area, (b) patch area (only smaller than ToC_{abs} of Area) for four cities; and CI of UGSs with (c) $NDVI_{mn}$ and (d) NGP in Hohhot, Beijing, and Shanghai. Note: ToC_{abs} is the absolute threshold of cooling, NDV_{Imn} is the mean value of normalized difference vegetation index, and NGP is the percentage of neighboring greenspace. HT, BJ, SH and HK represent Hohhot, Beijing, Shanghai and Haikou, respectively.

organization of water bodies in the planning of UGS is a promising measure to enhance the cooling effect of the UGS patch in the three cities. Unlike these three cities, Pland_w in Haikou was not relevant to the CI of UGS, which meant that integrating water bodies into an UGS would not necessarily enhance the cooling effect of UGS in Haikou.

The results of this study suggest that NDVI is one of the critical and positively correlated factors affecting the CI of UGS patch, which is consistent with previous studies (Weng, 2001; Zhang et al., 2009). ToC_{abs} of NDVI for UGS was observed only in Hohhot, Beijing and Shanghai, and meanwhile, showed similarities among cities (0.31, 0.33 and 0.39 for Hohhot, Beijing and Shanghai, respectively) with different climatic backgrounds. This implies that increasing vegetation cover and density, and improving vegetation health are effective landscape strategies to improve the cooling effect of UGS patches. Consistent with previous studies (Gunawardena et al., 2017; Kong et al., 2014; Zhou et al., 2022), the cooling effect of tree-dominated UGS is significantly greater than that of grass-dominated patches. Therefore, multi-layered planting structure should be the first consideration in the planning and design of UGS to achieve better urban cooling.

4.3. Limitations of the study

There are some limitations of this study that should be addressed. First, this study was case- and city-based, and only four cities each located in a different climatic zone of China were involved in this study, so the results may not be transferable to other cities even with similar climatic background. Therefore, more cities should be included in future studies to increase the certainty of the results, and the understanding of the impact of the local background climate on the cooling effect of UGS. Second, remote-sensing images are acquired instantaneously, so the conclusions depend on the time of acquisition and may be inconsistent in other times and seasons. Thus, future studies could be conducted to investigate seasonal and diurnal variations of cooling effect of urban green spaces. Finally, the influence of tree species in urban green spaces was not considered in this study and requires further investigation.

5. Conclusions

By studying 144 UGSs in Hohhot, 277 UGSs in Beijing, 191 UGSs in Shanghai, and 152 UGSs in Haikou, China, this study used various geospatial and analytical approaches to quantify the cooling effects of UGSs, reveal the influencing factors of CI and propose potential landscape recommendations for climate adaptation specific to cities with different climatic conditions. The results showed that UGS may or may not have a significant cooling effect. The patch area, the abundance of vegetation, the planting structure, the proportion of neighboring vegetation cover, the proportion of internal water body and the shape complexity affect the CI of UGS in varying degree, resulting in cooling heterogeneity among UGSs. Besides, the magnitude of the cooling effect of UGS is also associated with climatic background conditions. More climate-zone-based studies should be conducted to generate further understanding of cooling effect of UGS from case- or city-based level to global scale.

The absolute threshold of cooling (ToC_{abs}) of influencing factors of CI were determined and related landscape strategies were proposed. In this

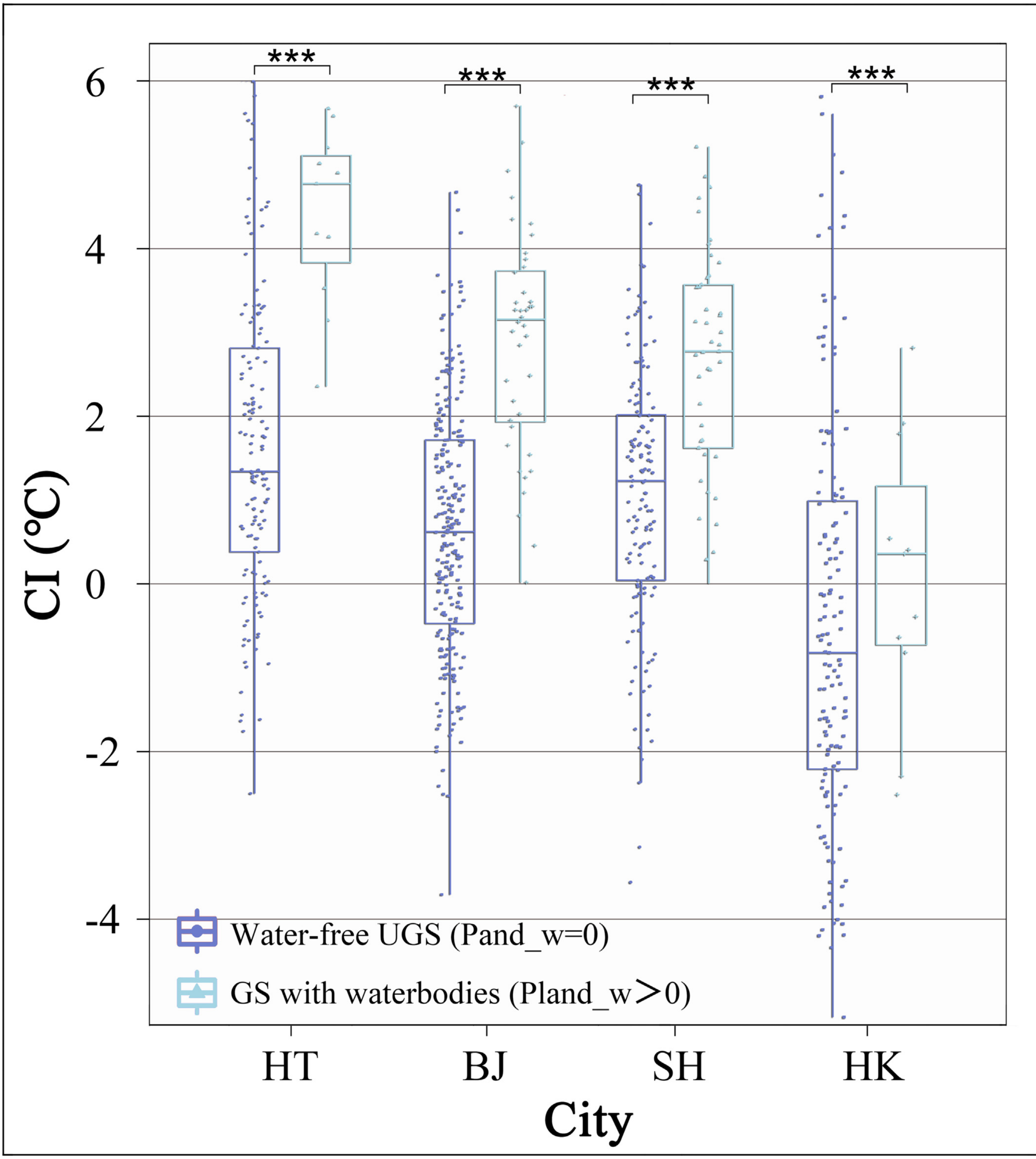

Fig. 6. Distribution of cooling intensity (CI) of urban green space (UGS) with and without waterbody. HT, BJ, SH and HK represent Hohhot, Beijing, Shanghai and Haikou, respectively. ***indicate significantly different means based on an Independent-Sample *t*-test at 0.001 level.

study, the ToC_{abs} values of Area for UGS are 2.6 ha, 5.9 ha, 4.0 ha and 5.3 ha for Hohhot, Beijing, Shanghai and Haikou, respectively. In addition, ToC_{abs} values for Pland_w (0 % for Hohhot, Beijing and Shanghai), NGP (8.5 %, 21.6 % and 23.5 % for Hohhot, Beijing and Shanghai, respectively) and NDVI of UGS (0.31, 0.33 and 0.39 for Hohhot, Beijing and Shanghai, respectively) were also identified. With the identification of ToC_{abs} values for more influencing factors, the decision-makers will have more options to generate actionable landscape strategies to better mitigate the UHI effect with relatively low cost and interference. For example, results suggested that the ToC_{abs} values of Area, Pland_w, NGP and NDVI of UGS in Shanghai are respectively 4 ha, 0 %, 23.5 % and 0.39, therefore, the effective cooling effect of an UGS can be guaranteed if satisfying any one of the conditions. Therefore, our results highlighted the need to observe more ToC_{abs} values of other influencing factors at different scales (patch and class levels), as the results can be directly transformed to quantitative and actionable landscape mitigation strategies to cool down cities.

CRediT authorship contribution statement

W. Z. conceived the idea and wrote the manuscript, W. Z., W.Y. and Z. Z. conducted the analyses, W. C. and T. W. reviewed and edited the manuscript. All authors contributed in the discussion of the results and in writing the paper.

Data availability

Data will be made available on request.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164422.

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