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Optimizing urban park cooling effects requires balancing morphological design and landscape structure

Lin Wang[1,3], Wenjia Wang[1,3], Fei Tang[2] & Hanqiu Xu[1,3]✉

Urbanization and global warming have led to more frequent extreme heat events, highlighting the importance of Park Cooling Islands. This study analyzes the cooling effect (PCE) of 50 urban parks in Fuzhou to explore the relationship between park area and cooling effect. The results indicate that there is no simple positive correlation between park area and cooling effect. Specifically, while larger parks may have greater cooling potential, a larger area does not necessarily lead to better cooling effects. The optimal park area for cooling effect ranges from 0.594 to 56 hm^2; beyond this range, an increase in park area does not significantly enhance the cooling effect. A low proportion of impervious surfaces, a high proportion of water bodies and vegetation, as well as complex patch patterns can enhance PCE, while excessive edge density and landscape fragmentation can weaken PCE. Based on importance analysis, the external morphological characteristics and internal patch characteristics of parks significantly influence cooling effects. Furthermore, the cooling effect of parks is jointly determined by internal and external conditions, with internal conditions having a more significant impact. Therefore, merely pursuing a "large" park area does not guarantee a "good" cooling effect; instead, greater emphasis should be placed on optimizing park design and layout, simplifying boundary shapes, reducing impervious surface ratios, and increasing vegetation diversity to maximize cooling effects.

Keywords Urban heat Island, Park cooling effect, Threshold value of efficiency, Urban park size, Landscape patch

As urbanization accelerates and the dangers of global climate change become more pronounced, cities worldwide face significant challenges posed by the Urban Heat Island (UHI) effect. Urban high temperatures and heatwave events exert tremendous stress on urban ecosystems and pose serious threats to public health[1,2]. Hence, the paramount importance of alleviating the negative impacts of heightened temperatures, fueled by both urbanization and climatic alterations, has surfaced as a pivotal research domain aimed at nurturing sustainable urban growth and protecting the health and overall welfare of societies. As research on the UHI effect deepens, the Park Cooling Effect (PCE), arising from water bodies and vegetation in urban parks, is increasingly perceived as an effective countermeasure to mitigate its impacts[3]. Furthermore, the PCE can propagate to adjacent areas in the process of air convection and heat transfer[4]. Considering the limited availability of urban land resources, enhancing the PCE constitutes a cost-effective strategy for mitigating UHI effect. The PCE plays a big part in fostering urban sustainability and adapting to climate change, while also exerting a notable influence on human health[5].

In current research, "cooling intensity" and "maximum cooling distance" are generally used as two core indicators to quantify the temperature difference between the park and its surrounding environment, as well as the maximum distance this cooling effect can extend to[6,7]. For example, Yu et al.[8] found that in their study of the cooling effects of parks in Zhengzhou, China, the cooling intensity of these parks ranged from 0.04 to 4.61 °C, with the maximum cooling distance primarily concentrated between 31 m and 370 m. Furthermore, the research conducted by Algretawee et al.[9] utilized two metrics, cooling intensity and maximum cooling distance, to explore the relationship between park size and its cooling effects. Large parks demonstrated particularly

[1]Fujian Provincial Key Laboratory of Remote Sensing of Soil Erosion and Disaster Prevention, College of Environmental and Safety Engineering, Fuzhou University, Fuzhou 350108, China. [2]Fujian Key Laboratory of Island Monitoring and Ecological Development (Island Research Center, MNR), Fuzhou 350116, China. [3]Institute of Remote Sensing Information Engineering, Fuzhou University, Fuzhou 350108, China. ✉email: hxu@fzu.edu.cn

remarkable cooling effects, achieving a cooling intensity of up to 3.28 °C and a cooling distance of 2500 m, which is significantly higher than that of medium-sized and small parks.

Is a larger park area always better? Many studies have shown that the PCE tends to increase with the expansion of park size[10–12]. However, in cities with strict land management and limited land resources, unrestricted expansion of park size is obviously unrealistic. Further exploration of this proportional relationship between park area and PCE helps in scientifically determining the appropriate size of urban parks. Cao et al.[13] found that in spring, summer and autumn, the correlation between the logarithm of the park area and PCE is much higher than that between the park area and PCE. Other studies have also successively confirmed the nonlinear relationship between PCE and park size[14,15], suggesting that there may be an efficiency balance point between them. To determine this balance point, Yu et al.[16,17] introduced the concept of Threshold Value of Efficiency (TVoE) by referring to the "law of diminishing marginal utility" in economics, which is used to represent the minimum area threshold for green space or park to achieve cooling effect. This method has been widely recognized by many scholars[10,18–20].

Some researchers have found that even urban parks with a certain area may exhibit weak cooling capabilities or even heat effects[21–23]. Therefore, besides the factor of park area, identifying other factors that influence the PCE of urban parks and exploring methods to enhance it have become one of the research hotspots. Currently, most scholars analyze this from two perspectives: the external morphological characteristics of a park and its internal landscape characteristics.

The external morphological characteristics of parks refer to the outer contour features such as area, perimeter, and shape. Feng et al.[24] conducted a regression analysis on the perimeter of urban parks and PCE, finding that the R^2 for the cubic fit between perimeter and PCE was 0.7391, indicating a strong nonlinear correlation between them. Some scholars have also discovered a logarithmic relationship between the perimeter of urban parks and PCE[24,25]. The complexity of the park boundary contour can also affect its cooling effect, with PCE decreasing as the shape becomes more complex[13,24,26]. Xiao et al.[14] identified a correlation between the perimeter-to-area ratio (PARA) of 15 urban green spaces and their cooling effects, and constructed an empirical fitting function model accordingly, finding a high correlation coefficient of − 0.905 ($p < 0.01$) between the cooling effect of urban green spaces and PARA, indicating a strong negative correlation between them. The influence of PCE is complex, and merely meeting the external morphological conditions of parks does not guarantee a cooling effect.

The internal landscape characteristics of parks refer to the landscape pattern features of internal patches within parks, such as the area proportion of land use types, mean patch area (AREA_MN), and patch density (PD). Cheung et al.[27] studied 100 sample points in 14 parks in Hong Kong, comparing the temperatures inside and outside the parks and finding that increased tree and shrub coverage, as well as water body proportion, could enhance cooling effect, whereas increased road proportion had the opposite effect. Similar studies have indicated that an increase in the proportion of green space and water bodies enhances PCE, whereas an increase in the proportion of impervious surfaces may reduce PCE[23,28]. Qiu and Jia[21] discovered that PD of impervious surfaces and AREA_MN of water bodies in the internal landscape configuration of parks significantly affect the cooling effect. Kong et al.[29] found in their study in Nanjing, China that increasing AREA_MN of vegetation and reducing its PD can effectively enhance the PCE.

Overall, researchers have conducted extensive studies to identify the main influencing factors of PCE in urban parks and methods to enhance it, achieving certain results. However, comprehensive studies combining the external morphological characteristics of parks with their internal landscape patterns are rarely mentioned. Additionally, there is a lack of systematic characterization of "negative cases" where urban parks do not exhibit a cooling effect. In view of this, this study utilizes the indicators of "cooling intensity" and "maximum cooling distance" to investigate the PCE and its influencing factors of urban parks in Fuzhou, the hottest provincial capital in China known as"furnace city", from the perspectives of both external morphological characteristics and internal landscape characteristics of the parks, aiming to explore: (1) whether all urban parks can cool the environment; (2) if not, what types of urban parks can achieve cooling, and is bigger always better? (3) how to design and configure the external form and internal patches of parks within the limited and valuable urban spaces to achieve greater cooling effects with smaller park areas? These questions deepen the comprehension of the PCE of urban parks and supply analytical data and transformation strategies for more efficient PCE in high-temperature scenarios.

Data and methods

Study area

Fuzhou, serving as the provincial capital of Fujian, is situated on the southeastern coast of China (Fig. 1). The city experiences a subtropical monsoon climate. According to the National Climate Center of China (http://www.ncc-cma.net/cn/), since 2000, Fuzhou has led major cities nationwide in terms of annual cumulative high-temperature days (days with the daily maximum temperature exceeding 35 °C)[30,31]. In 2013, it ranked as the top "furnace city" in China with a cumulative total of 32.6 high-temperature days[32]. In recent years, Fuzhou has continually broken records in both "cumulative high-temperature days" and "annual average temperature", ranking among the hottest provincial capitals nationwide[32]. This study focuses on the principal urban area the well-developed region of Fuzhou (Fig. 1).

Data sources and pre-processing

The framework of the study is illustrated in Fig. 2.

The LST data comes from the Landsat-9 Collection 2 (C2) Level 2 Science Product (L2SP)[33], downloaded from the U.S. Geological Survey EarthExplorer website (https://earthexplorer.usgs.gov/). This data was used to quantify the PCE. The imagery was obtained by the Landsat-9 satellite on July 7, 2023, with a path/row of 119/42 and a central point latitude/longitude of 119.983°/24.325°.

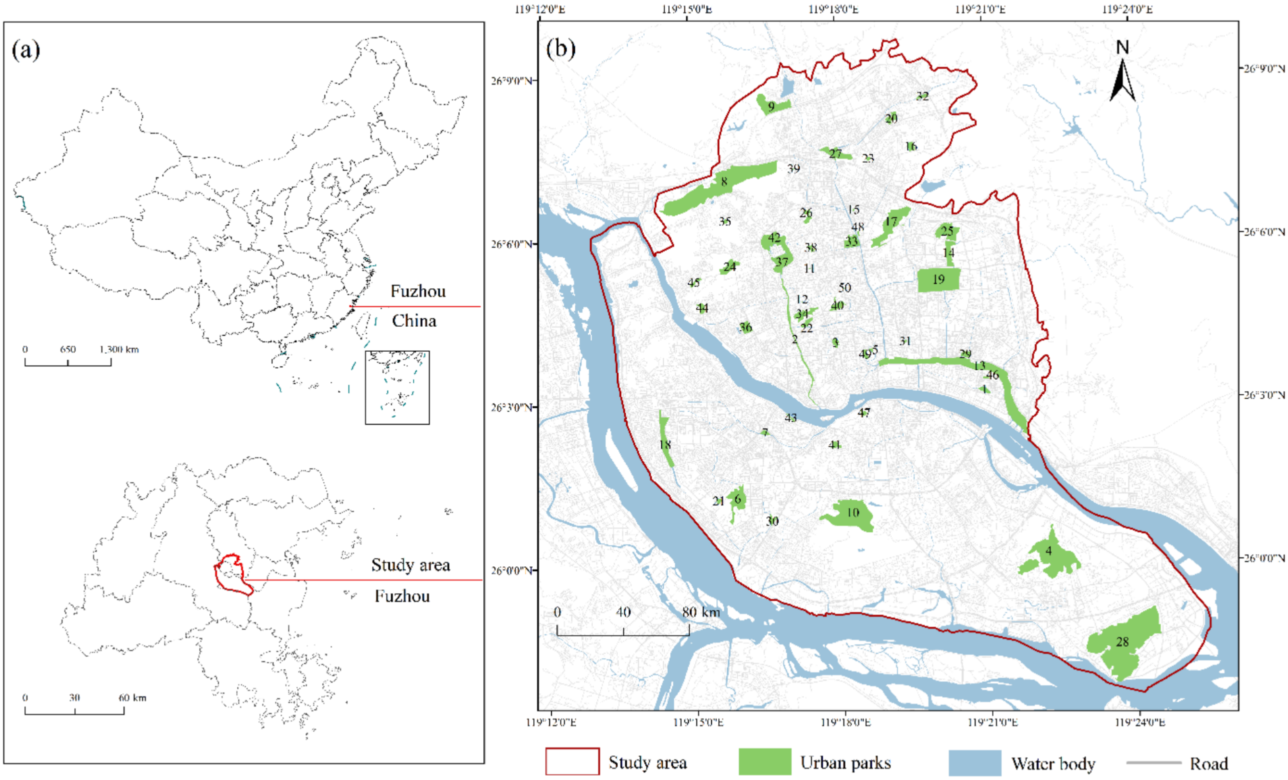

Fig. 1. (**a**) The location of Fuzhou within China; (**b**) the distribution of urban parks in Fuzhou. This map was created by the authors using ArcGIS software (version 9.2) (https://www.arcgis.com/). The base map was from the standard map with review number GS (2024) 0650 downloaded from the website of Standard Map Service of the Ministry of Natural Resources of the People's Republic of China, with no modification of the base map (http://bzdt.ch.mnr.gov.cn/).

Urban park extraction within the area followed these principles: (1) the distribution and boundaries of urban parks were provided by the Fuzhou Garden Center (https://ylj.fuzhou.gov.cn/) and Baidu Maps (https://map.baidu.com/); (2) since the spatial resolution of Landsat imagery is 30 m, parks smaller than 900 m^2 were excluded; (3) studies have indicated that parks connected to surrounding water bodies might receive additional cooling effects from these external water bodies[34]. As a result, urban parks directly connected to large environmental water bodies were excluded. Finally, a total of 50 urban parks were selected, with an average size of 31.71 hm^2, varying from 0.16 hm^2 to 307.6 hm^2 (Fig. 1, Appendix Table S1).

High spatial resolution Google Earth imagery was adopted to visually interpret the land use types of urban parks, classifying it into impervious surfaces, water bodies, and vegetation (Fig. 2). Specifically, buildings, roads, and plazas were classified as impervious surface type; water bodies within the parks were classified as water body type; woodlands and grasslands were classified as vegetation type.

Methods

Measurement of PCE

Based on the 30-meter resolution of the Landsat-9 imagery, a total of 20 buffer zones with an interval of 30 m were delineated around the outer contours of the parks[35]. The relationship between LST and distance was modeled, with distance from the park boundary *(l)* as the independent variable and mean LST in each buffer as the dependent (Fig. 3). The cubic polynomial function *T(l)* is as follows[36]:

$$T\left(l\right)=a\times l^{3}+b\times l^{2}+c\times\ l+d \tag{1}$$

where *T(l)* is the LST at a distance *l* from the edge of the park.

Figure 3 illustrates a trend where the LST within the buffer zone rises as one moves farther away from the park boundary, but this increase gradually decelerates, ultimately reaching a stagnation point where the slope of the *T(l)* function diminishes to zero, designated as the first turning point[5]. marking the initiation of its decline as distance from the park expands[6,18,24]. In scenarios devoid of an inflection point, this point is defined by the minimum slope of the *T(l)* function. Subsequent to this distance, the PCE notably wanes. The interval from the park's boundary to this first turning point is designated as maximum cooling distance ($L_{\Delta max}$), while cooling intensity (ΔT_{max}) denotes the disparity between mean LST in the buffer zone at this turning point and average LST within the park itself[21].

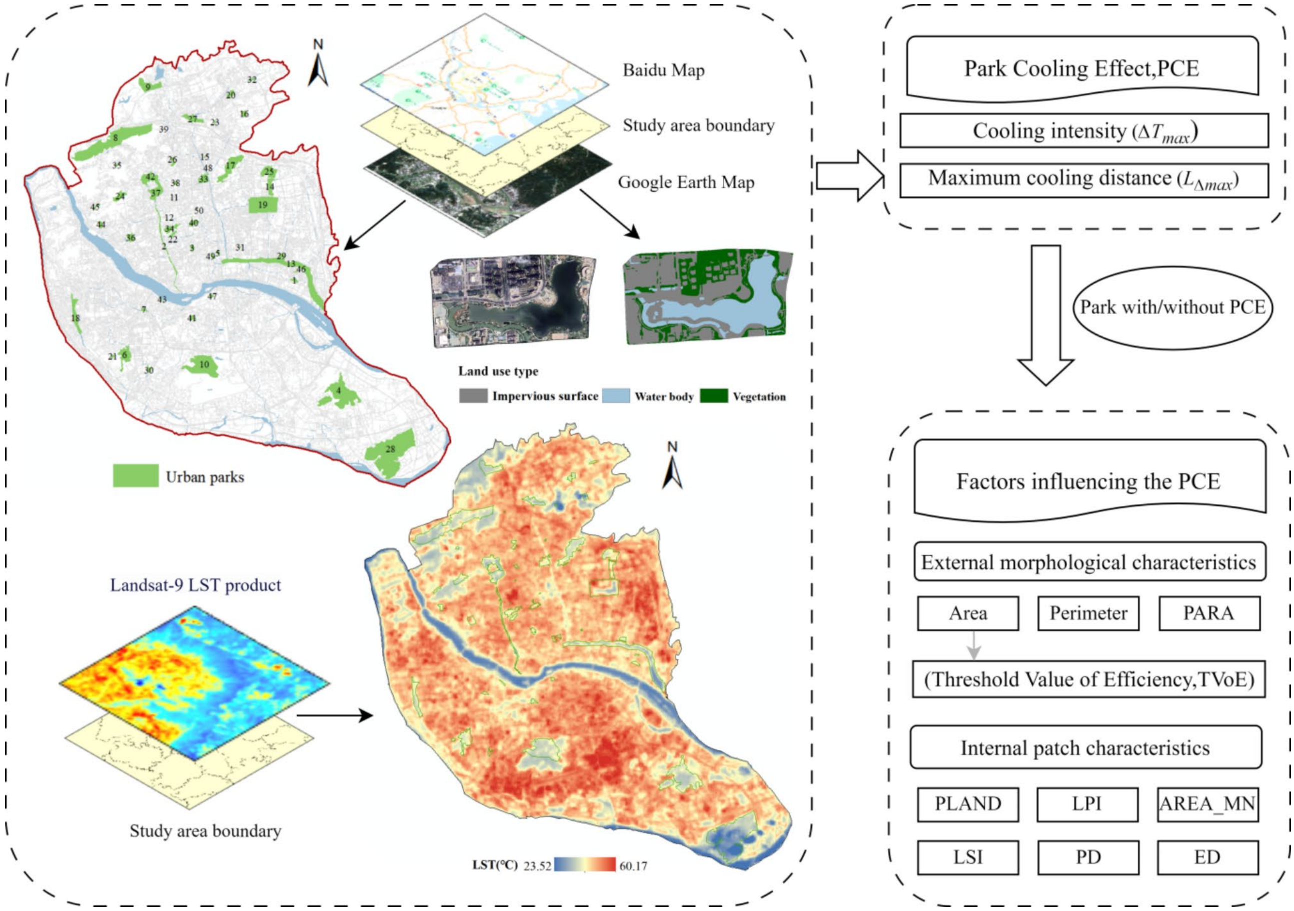

Fig. 2. Research framework of PCE. This map was created by the authors using ArcGIS software (version 9.2) (https://www.arcgis.com/). The base map was from the standard map with review number GS (2024) 0650 downloaded from the website of Standard Map Service of the Ministry of Natural Resources of the People's Republic of China, with no modification of the base map (http://bzdt.ch.mnr.gov.cn/).

Therefore, PCE is represented by the two indicators ΔT_{max} and $L_{\Delta max}$[21]. If either ΔT_{max} or $L_{\Delta max}$ is less than or equal to 0, the park is defined to be without PCE and fails to provide a cooling effect.

Threshold value of efficiency (TVoE)
TVoE is identified as the optimal threshold value in accordance with the law of diminishing marginal utility[16]. Within this research framework, it serves as a benchmark for estimating the minimum park area necessary to attain peak cooling performance[37]. Cooling performance, generally speaking, quantifies the reduction in temperature per unit area of the park, effectively capturing the park's regional cooling impact[6,7]. When the cooling efficiency trend adheres to a logarithmic pattern, the TVoE threshold for a park is discernible where the slope of the fitted logarithmic curve aligns with unity (Fig. 4). Prior to attaining this TVoE, modest expansions in park area markedly elevate cooling efficiency, rendering park enlargement economically viable. Conversely, subsequent to surpassing the TVoE, substantial enlargements in park area fail to yield notable gains in cooling performance[16]. Essentially, from a cost-benefit analysis perspective, the TVoE represents the most economically prudent park size for a specific urban setting[20,38].

Factors influencing the PCE
External morphological characteristics of parks The influence of the external morphological characteristics on the PCE is quantified using three parameters: park area, park perimeter, and the PARA. PARA efficiently assesses shape intricacy and compactness of park (Table 1)[39–41].

Internal patch characteristics of parks The influence of the internal patch characteristics on the PCE is quantified through the landscape pattern characteristics of land use types (impervious surface, water body, and vegetation). Based on previous research, the most frequently used and least correlated landscape pattern indices were selected[42–44], including Percentage of landscape (PLAND), Largest patch index (LPI), Mean of patch area (AREA_MN), Landscape shape index (LSI), Patch density (PD), and Edge density (ED) (Table 1).

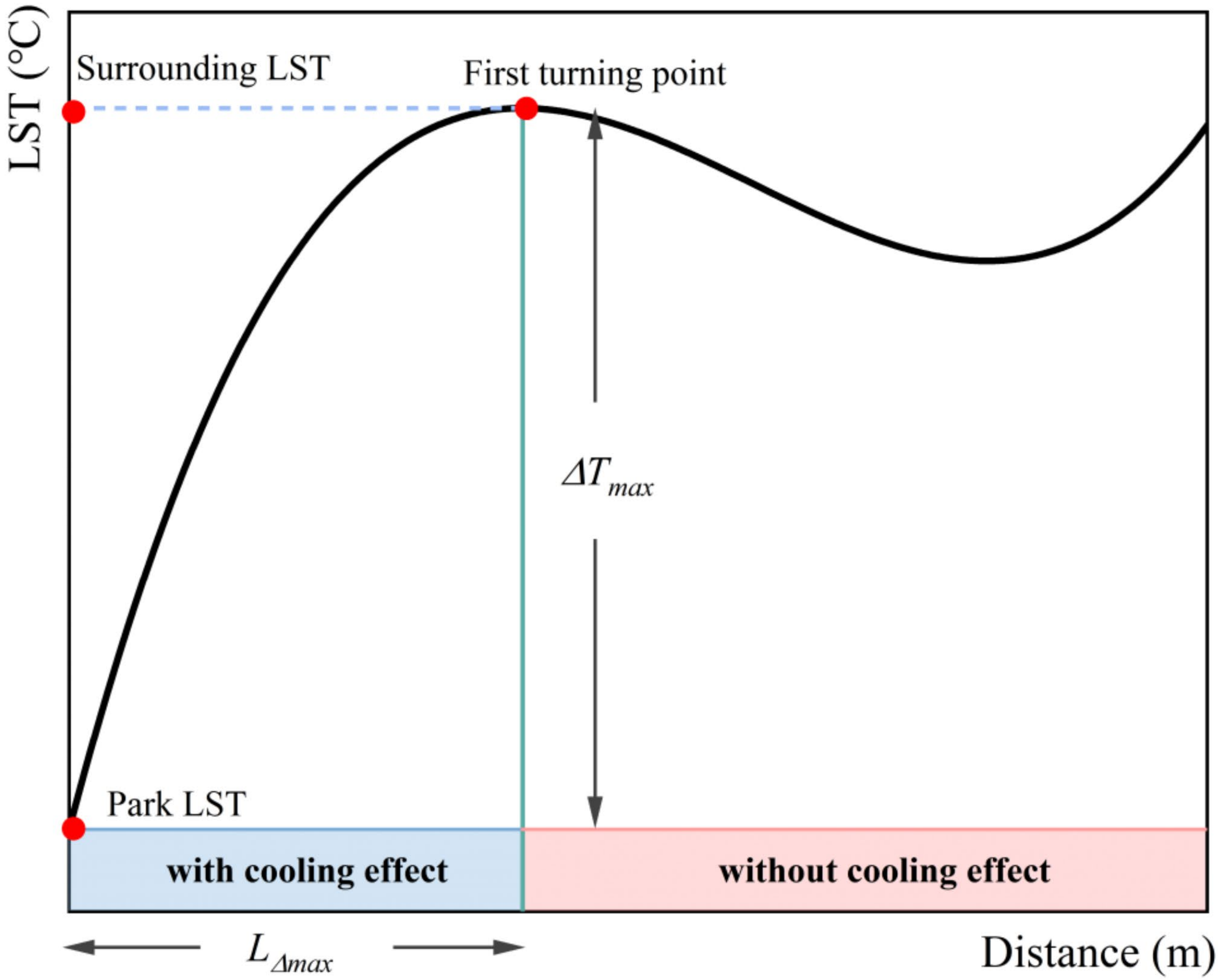

Fig. 3. Diagram illustrating the cooling curve of a park.

Statistical analysis method
The Pearson correlation analysis was used to examine the linear relationship between cooling indicators and influencing factors. This study utilized the Random Forest (RF) model to rank the importance of influencing factors. Random Forest is an ensemble learning method based on decision trees, proposed by Breiman, which effectively handles high-dimensional data and assesses the importance of various variables[45]. Collinearity among variables was detected by calculating the Variance Inflation Factor (VIF), and variables with VIF greater than 5 were iteratively removed to reduce the impact of multicollinearity on model interpretability. Subsequently, the Bootstrap resampling technique was used to generate multiple training sample subsets from the original training dataset, and multiple decision trees were constructed based on these subsets to form the Random Forest model, with performance evaluated using the Holdout cross-validation method.

Results

Characteristics of the PCE

As illustrated in Fig. 5a, most urban parks exhibit a noticeable cooling effect, such as Jinjishan Park (ID 17, Fig. 5b); however, some parks lack a cooling effect and even show a heat island phenomenon, such as Yantaishan Park (ID 47, Fig. 5c).

According to statistics (Figs. 6 and 7), out of the 50 urban parks within the study area, 42 parks exhibit a cooling effect (Parks with PCE, ID 1–42), while the remaining 8 do not have a cooling effect (Parks without PCE, ID 43–50).

The descriptive statistics for all variables are as follows:

(1) *Parks with PCE* Two indicators of the PCE (ΔT_{max} and $L_{\Delta max}$) were analyzed for these parks. The results are illustrated in Fig. 6.

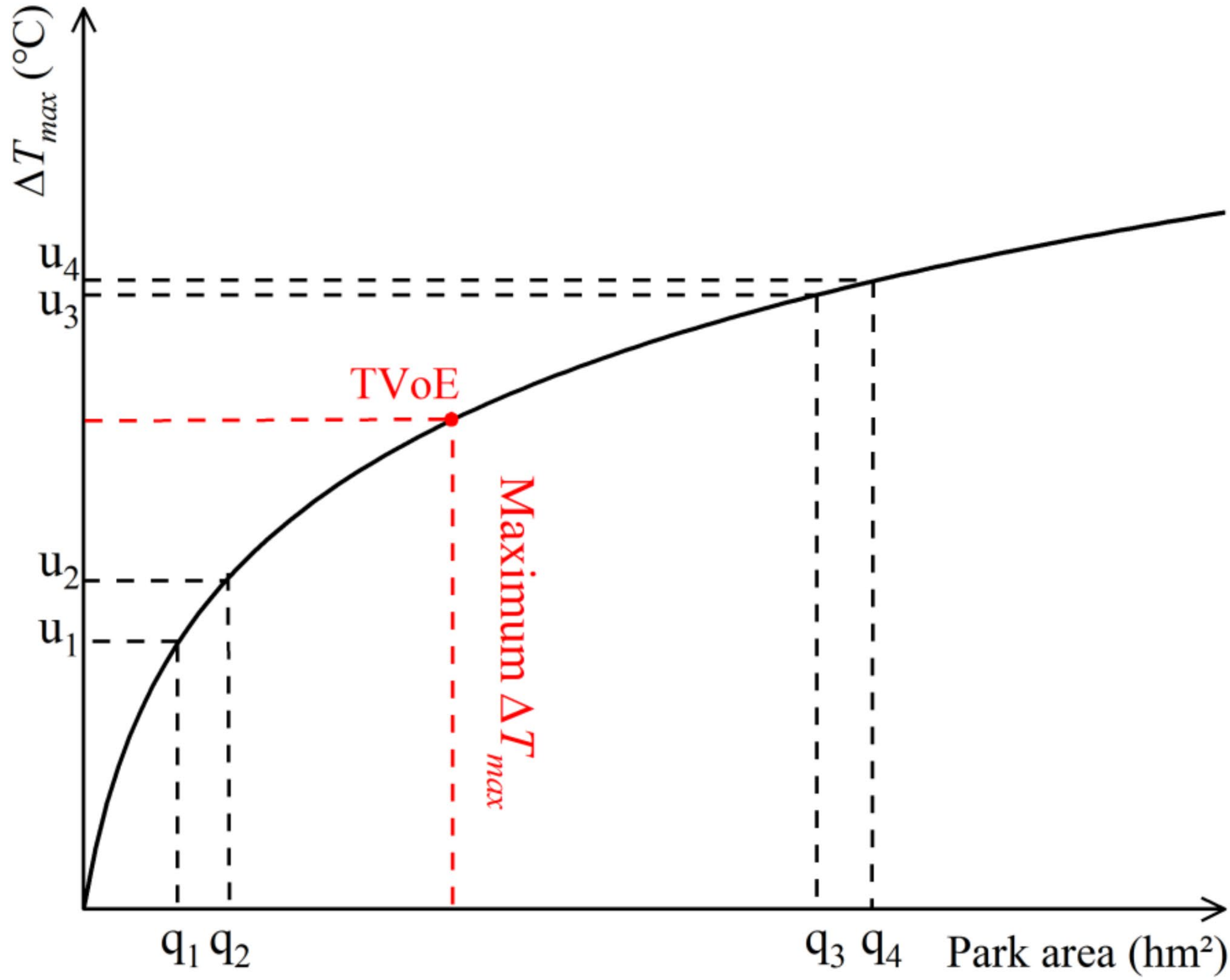

Fig. 4. Conceptual curve of TVoE (The q_1 to q_2 equal q_3 to q_4, u_2–u_1 greater than u_4–u_3).

	Landscape pattern indices	Definitions	Unit
External morphological characteristics	Area	Area of a park patch.	hm^2
	Perimeter	Perimeter of a park patch.	km
	PARA	Ratio of the perimeter to area.	–
Internal patch characteristics	Percentage of landscape (PLAND)	The proportion of a specific type of area to the total landscape area[59].	%
	Largest patch index (LPI)	The percentage of the total landscape area occupied by the largest patch; higher values indicate more pronounced dominance of the landscape by a single patch[15].	%
	Mean of patch area (AREA_MN)	The average area size of a specific type of patch [60].	hm^2
	Landscape shape index (LSI)	Reflecting the degree of regularity in the shape of patches, a higher value indicates a more complex patch shape[61].	–
	Patch density (PD)	The number of specific types of patches per unit area is a measure of fragmentation[62].	n/km^2
	Edge density (ED)	The edge length between heterogeneous landscape patches within the total unit area of the landscape[63].	m/hm^2

Table 1. Factors influencing the PCE. $PLAND_i$ Percentage of impervious surface, $PLAND_w$ Percentage of water bodies, $PLAND_v$ Percentage of vegetation, LPI_i Largest patch index of impervious surface, LPI_w Largest patch index of water bodies, LPI_v Largest patch index of vegetation, $AREA\_MN_i$ Mean of patch area of impervious surface, $AREA\_MN_w$ Mean of patch area of water bodies, $AREA\_MN_v$ Mean of patch area of vegetation, LSI_i Landscape shape index of impervious surface, LSI_w Landscape shape index of water bodies, *LSIv* Landscape shape index of vegetation, PD_i Patch density of impervious surface, PD_w Patch density of water bodies, PD_v Patch density of vegetation, ED_i Edge density of impervious surface, ED_w Edge density of water bodies, ED_v Edge density of vegetation.

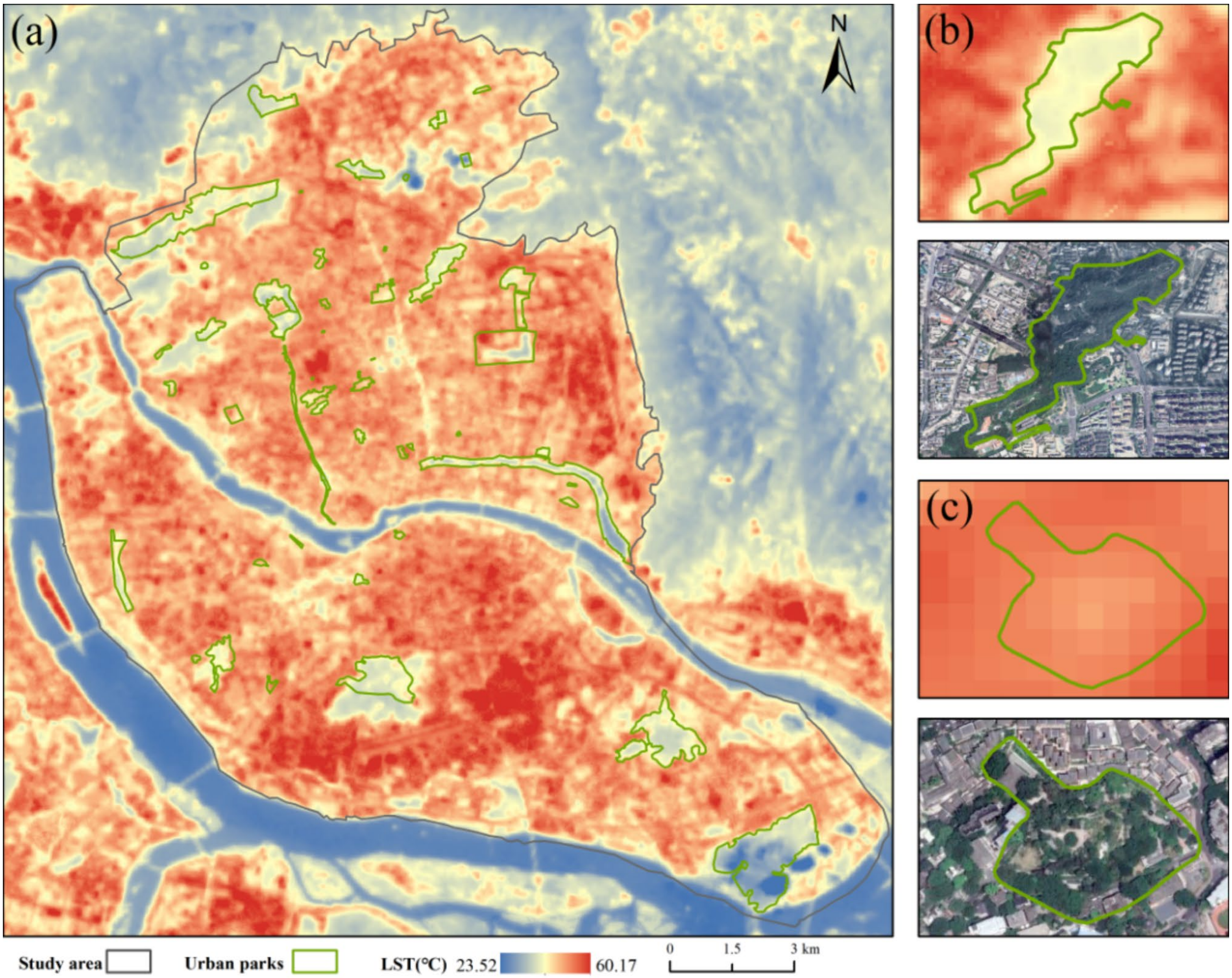

Fig. 5. (**a**) Spatial distribution of UHI; (**b**) Jinjishan Park (ID 17); (**c**) Yantaishan Park (ID 47). This map was created by the authors using ArcGIS software (version 9.2) (https://www.arcgis.com/). The base map was from the standard map with review number GS (2024) 0650 downloaded from the website of Standard Map Service of the Ministry of Natural Resources of the People's Republic of China, with no modification of the base map (http://bzdt.ch.mnr.gov.cn/).

Figure 6 indicates that ΔT_{max} ranged from 0.06 to 5.97 °C, with the highest value occurring in Qingliangshan Park (ID 28) at a maximum of 5.97 °C. $L_{\Delta max}$ ranged from 0.1 to 0.62 km, with Wushan Park (ID 34) being the park with the highest value, achieving a maximum $L_{\Delta max}$ of 0.62 km.

(2) *Parks without PCE* An analysis of the two indicators (ΔT_{max} and $L_{\Delta max}$) for these urban parks (Fig. 7) reveals that ΔT_{max} for all these parks are negative, indicating an inability to achieve effective cooling.

Parks with PCE

Relationship between external morphological characteristics of parks and PCE

A Pearson correlation analysis of PCE and park morphology is presented in Table 2.

The results indicate that ΔT_{max} and $L_{\Delta max}$ are positively correlated with area and perimeter, and negatively correlated with PARA. As the area or perimeter of urban parks increases, or as PARA decreases, the PCE becomes more pronounced. Moreover, ΔT_{max} and $L_{\Delta max}$ exhibit a strong correlation with the external morphological characteristics of parks.

Further regression analysis was conducted to study the functional relationship between the external morphological characteristics of parks and PCE (Fig. 8).

In the fitting results, the explanatory power of urban park area for ΔT_{max} reached 40.3% and for $L_{\Delta max}$ reached 51.7%. According to the fitting results, when the urban park area is within 56 hm^2, the PCE varies significantly; when the area exceeds 56 hm^2, the PCE tends to stabilize. The explanatory power of the urban park perimeter for ΔT_{max} reached 35.8% and for $L_{\Delta max}$ reached 47.3%. According to the fitting results, when the urban park

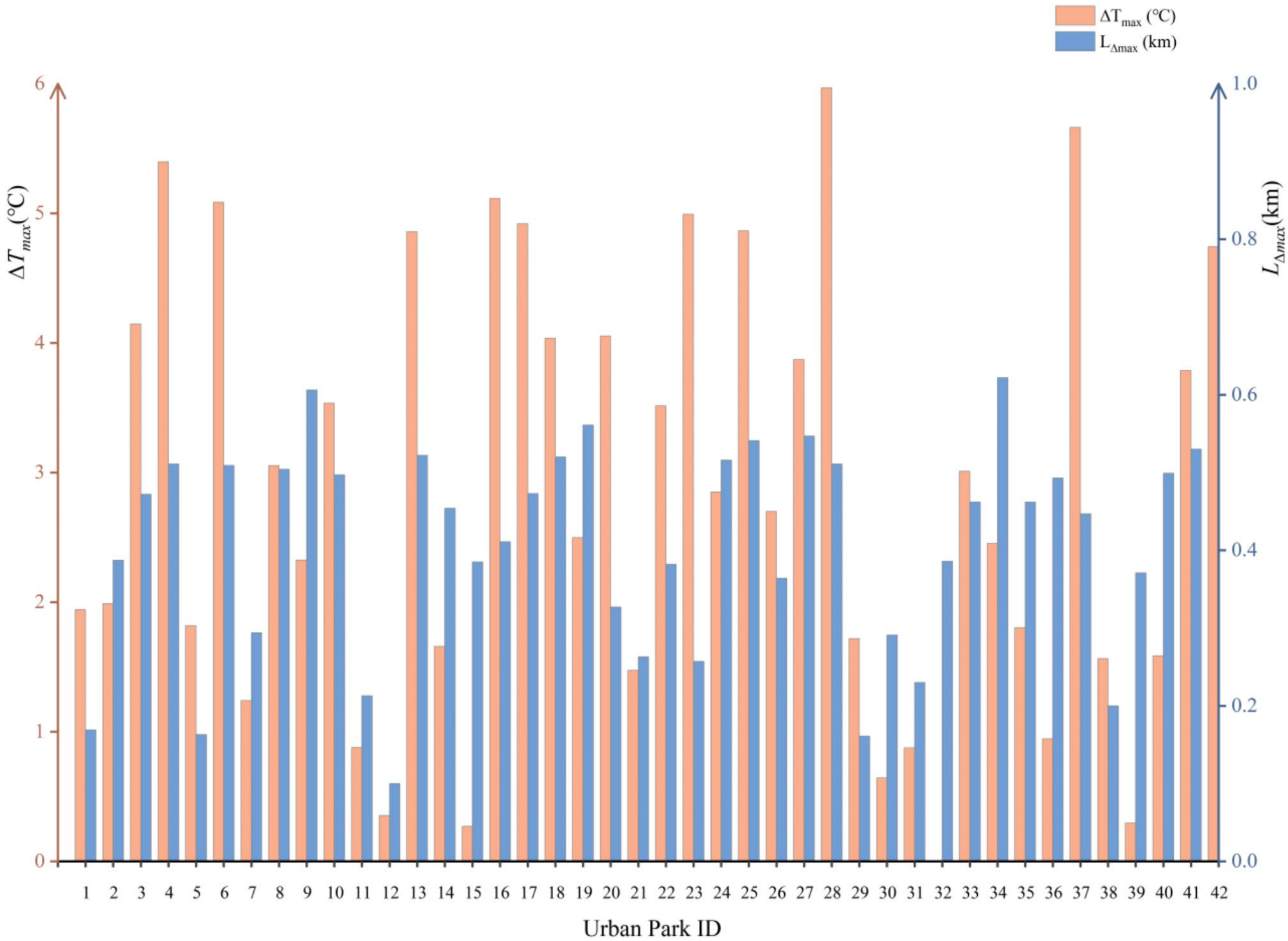

Fig. 6. The cooling effect characteristics of parks with PCE.

perimeter is within 2.5 km, the PCE varies significantly; when the perimeter exceeds 2.5 km, the PCE tends to stabilize. The explanatory power of urban park PARA for ΔT_{max} reached 38.4% and for $L_{\Delta max}$ reached 47.4%.

Logarithmic curves were adopted to obtain the TVoE (Fig. 8a), with the logarithmic function fitting equation being $y = 0.594\ln(x) + 1.493$. When the slope of the logarithmic regression function is 1, the park area is 0.594 hm^2, indicating that the minimum park area for achieving optimal cooling efficiency (TVoE) is 0.594 hm^2.

Relationship between internal patch characteristics of parks and PCE

To explore how the internal patch characteristics of parks influence the PCE, a Pearson correlation analysis was applied to scrutinize the interconnections between two cooling effect indicators and landscape pattern indices at the class level (Fig. 9). The abbreviations for the relevant indices can be found in Table 1.

The results reveal that ΔT_{max} has a significantly negative correlation with the PLAND of impervious surfaces ($r = -0.53$, $p < 0.01$) and a markedly positive correlation with LSI ($r = 0.41$, $p < 0.01$). Meanwhile, as PD and ED of each land use patches increase, ΔT_{max} significantly decreases ($p < 0.01$). $L_{\Delta max}$ is positively correlated with the LSI of impervious surfaces and water bodies within the park ($r = 0.57$ and 0.41, $p < 0.01$).

Many studies have shown that impervious surfaces are the most important factor in the UHI formation[46–48]. Therefore, regression analysis was further applied to study the relationship between the PLAND of impervious surfaces and ΔT_{max}. The results found that PLAND of impervious surfaces and ΔT_{max} is not a simple linear relationship but a logarithmic relationship (Fig. 10). By deriving the second-order derivative of the fitted relationship in Fig. 10, the proportion of impervious surfaces at the inflection point is 15%. This indicates that: (1) Impervious surfaces lead to a reduction in the park's cooling capacity. (2) This reduction in cooling capacity is not uniform. When impervious surfaces ratio in parks is low (less than 15%), even a minor expansion of impervious surfaces can remarkably decrease the park's cooling capacity.

Parks without PCE

The external morphological characteristics and internal patch characteristics of eight parks without PCE were compared and statistically analyzed with those of parks with PCE (Fig. 11).

(1) External morphological characteristics. In terms of size (Fig. 11a, b), parks without PCE are significantly smaller in both area and perimeter compared to parks with PCE, indicating that their scale is insufficient to

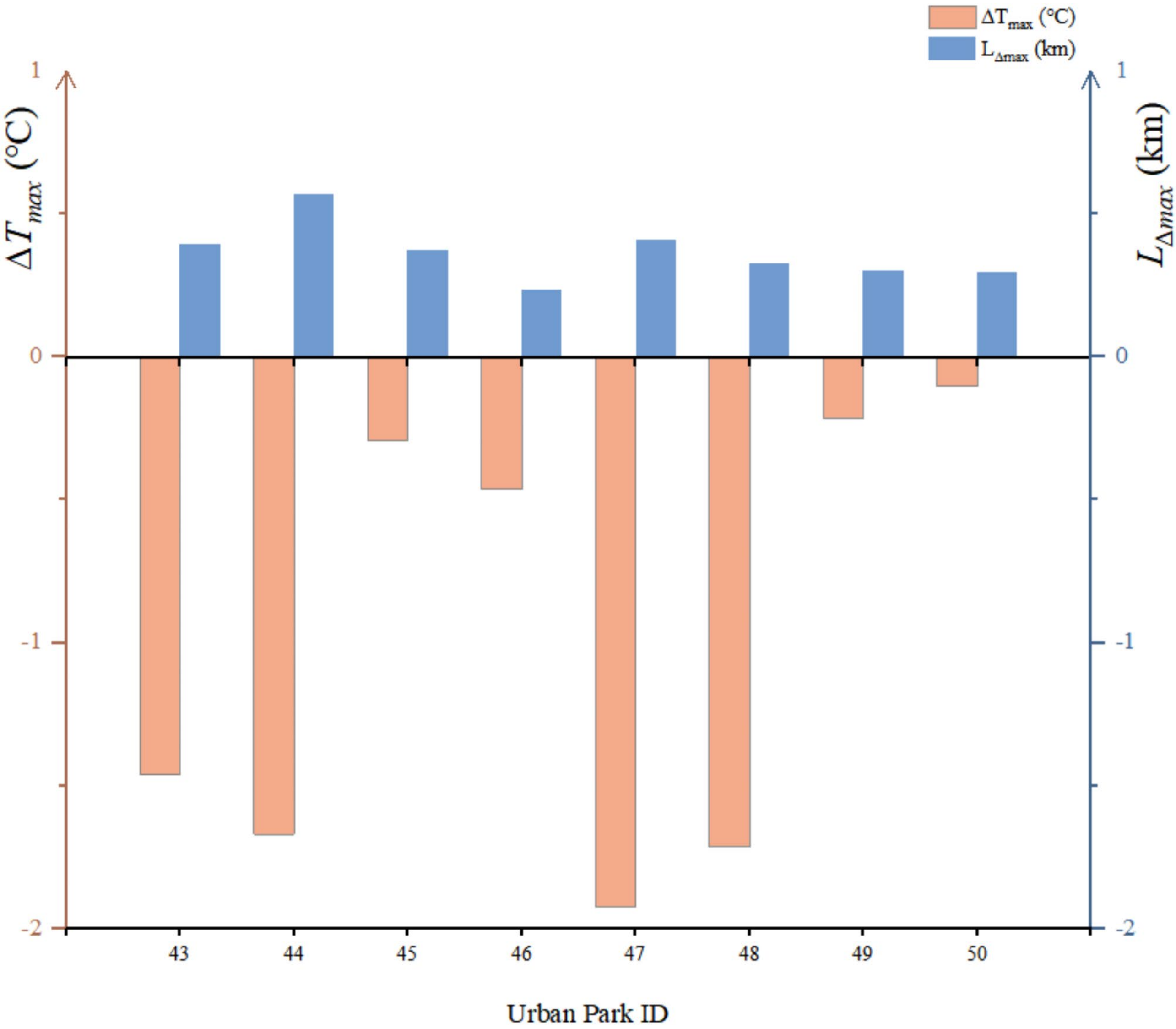

Fig. 7. The cooling effect characteristics of parks without PCE.

PCE	Area	Perimeter	PARA
ΔT_{max}	0.482**	0.512**	− 0.516**
$L_{\Delta max}$	0.422**	0.490**	− 0.669**

Table 2. Correlation coefficients between external morphological characteristics of parks and PCE. * and ** represent significance levels of $p < 0.05$ and $p < 0.01$, respectively.

form a significant cooling effect. In terms of the PARA (Fig. 11c), parks without PCE exhibit a higher PARA value (0.046), which is twice that of parks with PCE (0.023), suggesting that the outer contours of parks without PCE tend to be more complex and irregular (Fig. 12).

(2) Internal patch characteristics. Parks without PCE typically exhibit a higher proportion of impervious surfaces and lower proportions of vegetation and water bodies (Fig. 11d). Among the eight urban parks without PCE, only three contain water bodies, with proportions as low as 10%, 8%, and 1%, respectively. The higher proportion of impervious surfaces reduces the coverage of vegetation and water bodies, directly limiting their ability to form effective cooling sources. Additionally, the shapes (LSI) of land use patches in these parks are simpler (Fig. 11g), and the mean vegetation patch area (AREA_MN) is significantly smaller ($0.72\ hm^2$ vs. $12.31\ hm^2$; Fig. 11f). This indicates that parks without PCE typically have smaller vegetation patches, which are unable to form large-scale green spaces, resulting in poorer cooling effects. However,

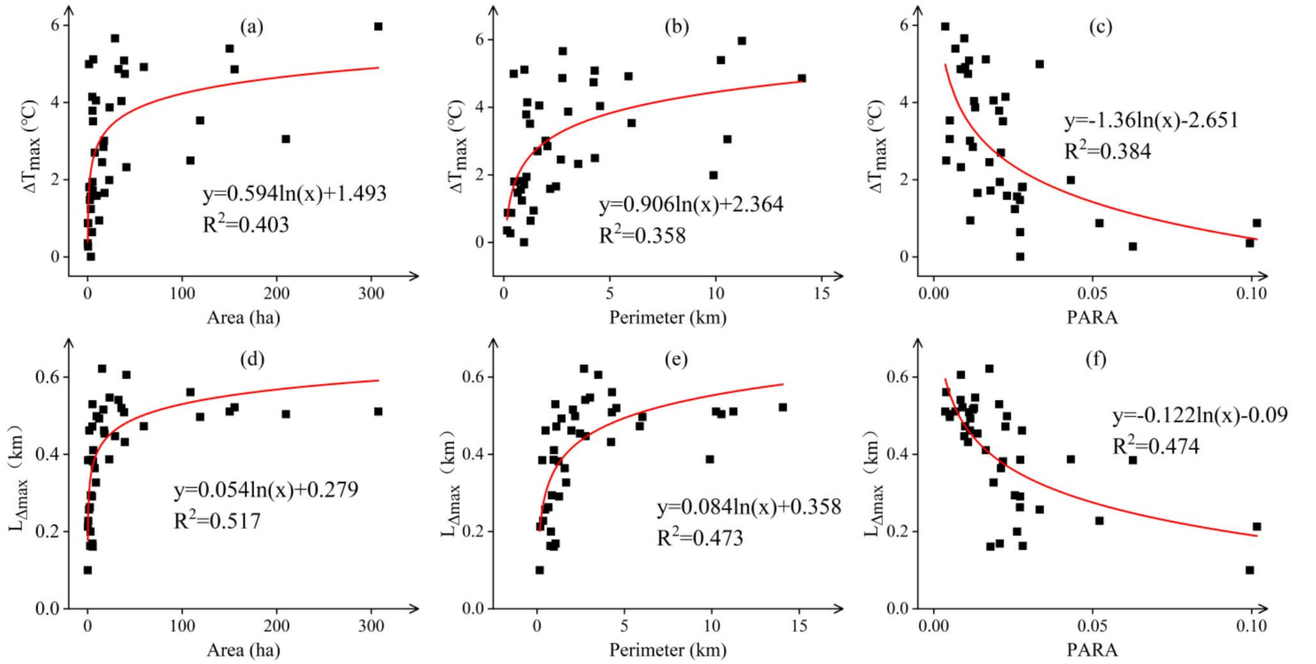

Fig. 8. Fitted curves of PCE against external morphological characteristics of parks.

no significant differences in patch density (PD) or edge density (ED) were observed between the two park categories (Fig. 11h, i).

Analysis of the importance of influencing factor

Figure 13 shows the importance ranking of influencing factors on ΔT_{max} and $L\Delta_{max}$.

For ΔT_{max}, ED_i, ED_v, and PD_v are the three most influential factors. Among them, ED_i has the highest influence, indicating that the distribution density of impervious surface edges has the most significant impact on ΔT_{max}. The high influence of ED_v and PD_v indicates that the edge density and fragmentation of vegetation patches also play an important role in the cooling effect. Overall, the landscape configuration of internal patches within parks has a relatively high impact on ΔT_{max}.

For $L_{\Delta max}$, the importance ranking of influencing factors shows that Area, Perimeter, and LSI_i are the three most influential factors. Among these, Area has the highest influence, indicating that the size of urban parks directly affects $L_{\Delta max}$. The high influence of Perimeter indicates that the length and complexity of park boundaries are closely related to heat exchange with the surrounding environment, further affecting $L_{\Delta max}$. As a landscape shape index, LSI_i reflects the shape complexity of urban parks; its high influence indicates that irregular park shapes may significantly affect the propagation of cooling distance by altering local airflow and heat distribution. Overall, the external morphological characteristics of urban parks have a higher impact on $L_{\Delta max}$.

Discussion

Impact of external morphological characteristics of parks on PCE

Larger parks tend to achieve better cooling effects[20,49], however, blindly expanding park size in cities with scarce land resources is not advisable. Additionally, larger parks do not always equate to better outcomes. As park size increases, the rate of cooling effect enhancement slows down until it stabilizes after reaching a threshold[6,17,38]. Analysis reveals a flattening of the cooling trend when parks surpass 56 hm^2 in area or 2.5 km in perimeter. According to calculation, the TVoE for urban parks in Fuzhou is determined to be 0.594 hm^2, suggesting that when the park area reaches this value, the optimal cooling effect can be achieved with the minimum park area. Therefore, the ideal size for optimizing the PCE in Fuzhou should be considered between 0.594 hm^2 and 56 hm^2 to find the optimal balance between cost and benefit.

Additionally, the PARA of parks is negatively correlated with PCE ($r = -0.516$ and -0.669), and parks with irregular outer contours tend to have lower PCE. This finding aligns with existing studies[6,18,24]: circular and squared patches featuring compactness showcase superior cooling abilities, inversely, a more intricate shape configuration results in a decrement in cooling effectiveness. Simple and regular park boundaries facilitate better natural ventilation, enabling heat to be more effectively dissipated through wind circulation, thus achieving a cooling effect[34].

Therefore, when the expansion of park size is constrained by objective conditions, reducing the complexity of park outer contours and designing regular boundaries can enhance the PCE. However, it is important to clarify that the impact of PCE is complex. Meeting the external morphological conditions of parks fails to inherently ensure a cooling effect, and the significance of the internal patch characteristics of parks in influencing their cooling effects cannot be overlooked.

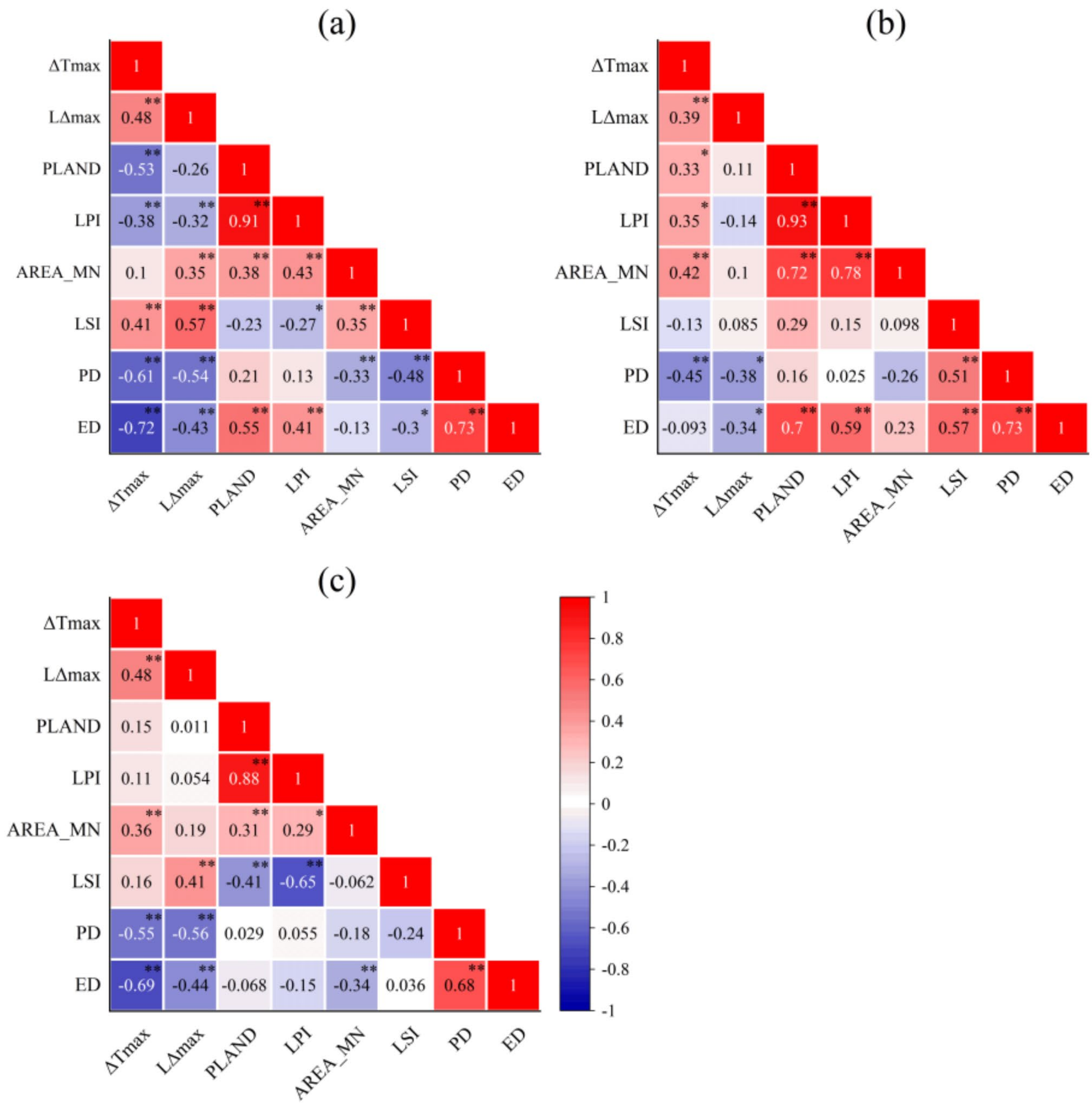

Fig. 9. Correlation coefficients between PCE and landscape pattern indices. (**a–c**) Represent impervious surface, water bodies and vegetation within the park, respectively. * and ** represent significance levels of $p < 0.05$ and $p < 0.01$, respectively.

Impact of internal patch characteristics of parks on PCE

AREA_MN of vegetation patches shows a significant positive correlation with the cooling effect ($r = 0.38$). Larger patches mean more continuous vegetation cover, which can improve evapotranspiration efficiency, i.e., release more moisture through transpiration, and form more stable shaded areas, reducing absorption of solar radiation and enhancing the cooling effect[50]. Additionally, vegetation patches with more complex shapes (higher LSI, $r = 0.41$) can provide more opportunities for heat exchange[51] and may enhance air circulation by forming ventilation channels, further promoting cooling[52]. Conversely, high PD ($r = -0.55$) and ED ($r = -0.69$) lead to fragmentation of the vegetative landscape, reducing the area of continuous vegetation cover and thereby lowering evapotranspiration efficiency and the continuity of shaded areas. Fragmented patches allow heat to transfer more easily between patches, rather than being effectively absorbed and dissipated by vegetation[53,54].

Water bodies, as essential cooling elements, have their PLAND, LPI, and AREA_MN positively correlated with ΔT_{max} ($r = 0.33$, 0.35 and 0.42), meaning that the higher the proportion and larger the size of water body

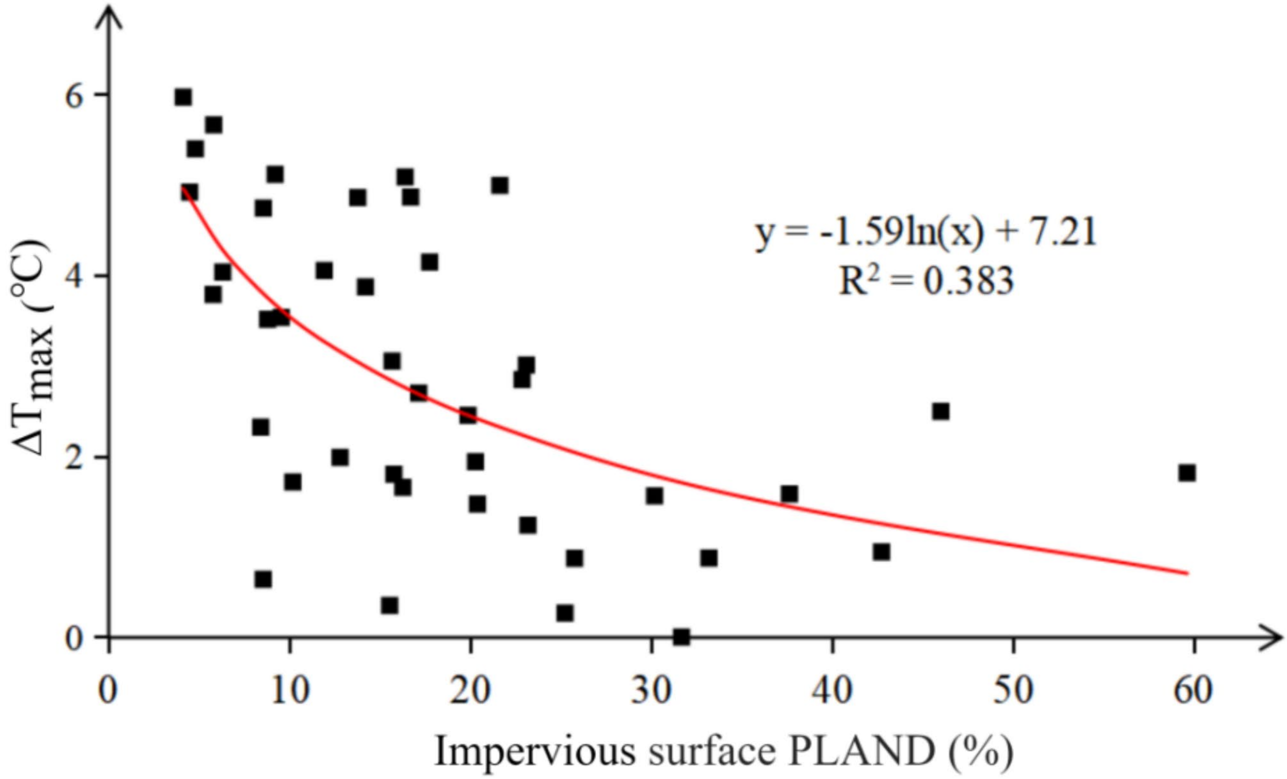

Fig. 10. The fitting curve of the proportion of impervious surfaces and the cooling intensity.

landscapes, the better the PCE. Water bodies effectively absorb and dissipate heat through evaporation, while providing a large surface area for heat exchange, thereby significantly enhancing the PCE[55].

In terms of impervious surfaces, an increase in their PLAND means an expansion of hard surfaces such as buildings and roads, which correspondingly squeeze the space for natural cooling elements like vegetation and water bodies. Additionally, due to the high heat absorption and low heat dissipation characteristics of impervious surfaces, this further exacerbates heat accumulation in local areas, thereby weakening the PCE[21,56]. When the proportion of impervious surfaces in the regional background is lower, and the coverage of vegetation and water bodies is more complete, the degree and speed of this weakening are higher (Fig. 10). Thus, as the PD and ED of impervious surfaces increase ($r = -0.55$ and -0.72), leading to their fragmentation and infiltration into originally intact and uniform vegetation or water patches, it significantly weakens the overall cooling effect of the area. Furthermore, as previously mentioned, the complexity of patch shapes promotes the exchange rate of matter and energy, so the more complex the shape of impervious surface patches (higher LSI, $r = 0.41$), the more conducive it is to the exchange of hot and cold air, thereby enhancing the cooling effect.

The composition and proportion of land use patches in Huaqiao Park (ID 43) and Luohanshan Park (ID 23) are similar. Although Huaqiao Park has a larger area and perimeter than Luohanshan Park, its cooling effect is significantly inferior (Table 3). From Fig. 14; Table 3, it can be inferred that compared to Luohanshan Park, Huaqiao Park has a greater number and more dispersed patches of impervious surfaces and vegetation, with PD values being 5.4 times and 2.5 times those of Luohanshan Park, respectively. The boundary length of impervious surfaces and vegetation patches in Huaqiao Park is also longer, with higher ED values, indicating significant edge effects and a higher degree of landscape fragmentation. This further demonstrates that more fragmented land use patches diminish the PCE.

Therefore, in the planning and design processes, the proportion and spatial arrangement of various land use patches should be comprehensively considered to maximize the PCE. By optimizing the configuration and layout of vegetation, water bodies, and impervious surfaces, as well as controlling the fragmentation degree and edge density of the landscape, the PCE can be effectively enhanced, thereby creating a more conducive living environment for urban inhabitants.

Interaction between external morphological characteristics and internal patch characteristics on PCE

To investigate the interaction between internal and external factors affecting the cooling effects of parks (PCE), four representative parks (Xichangusi Park (ID 36), Liminghu Park (ID 22), Xihu Park (ID 37), and Huannan Park (ID 15)) were selected for analysis. Table 4 summarizes the key characteristics of these parks and their cooling effects.

By comparing the data from these four parks, we can draw the following conclusions:

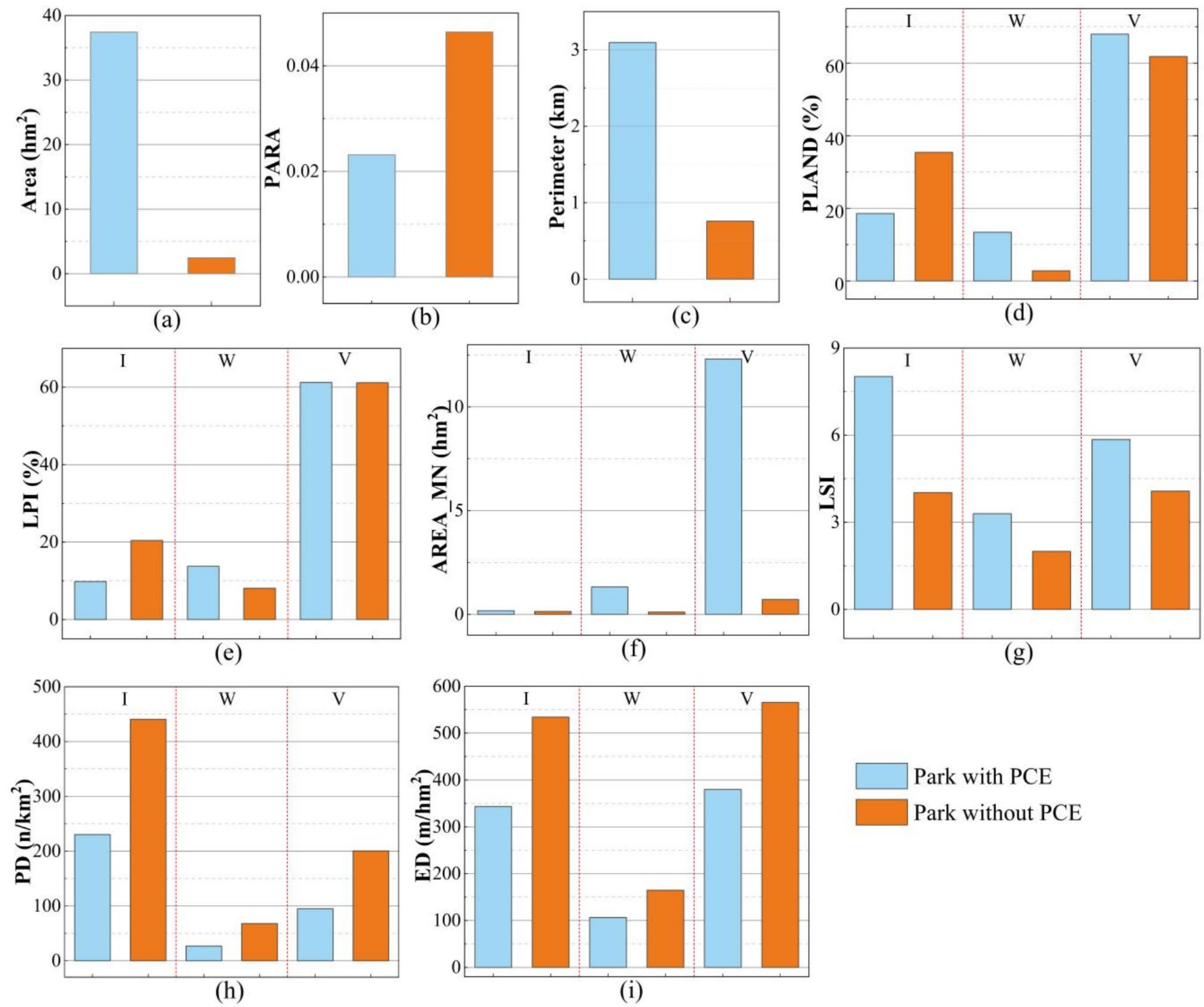

Fig. 11. Comparison between parks with and without PCE. (**a**) Area, (**b**) Perimeter, (**c**) PARA, (**d**) PLAND, (**e**) LPI, (**f**) AREA_MN, (**g**) LSI, (**h**) PD and (**i**) ED. I, W and V represented the impervious surface, water body and vegetation, respectively.

(1) Parks with good external conditions but poor internal conditions, such as Xichangusi Park: it has a larger area and a lower PARA value, indicating better external conditions. However, its internal conditions are poor (medium vegetation coverage, low water body proportion, high impervious surface ratio; high vegetation patch density and edge density), resulting in a poorer cooling effect.
(2) Parks with poor external conditions but good internal conditions, such as Liminghu Park: it has a smaller area and a higher PARA value, indicating poorer external conditions. However, its internal conditions are good (high water body proportion, low impervious surface ratio; low vegetation patch density and edge density), resulting in a better cooling effect.
(3) Parks with both good external and internal conditions, such as Xihu Park: it has a larger area and a lower PARA value, indicating better external conditions.
(4) Parks with both poor external and internal conditions, such as Huannan Park: it has a smaller area and a higher PARA value, indicating poorer external conditions. Additionally, its internal conditions are also poor (low water body proportion, high impervious surface ratio; extremely high vegetation patch density and edge density), resulting in the worst cooling effect.

These results indicate that the cooling effects of parks are not solely determined by a single factor, but rather are the result of the interplay between internal and external conditions. The influence of internal conditions on the cooling effect is significant. Even with poor external conditions, good internal conditions (such as Liminghu Park) can still provide effective cooling effects. Conversely, even when external conditions are good, parks with poor internal conditions (such as Xichangusi Park) exhibit poor cooling effects. The impact of external conditions on cooling effects is relatively minor, but under poor internal conditions, the influence of external conditions

Fig. 12. Samples of some park's outer contours. (**a–c**) Are parks without PCE; (**d–f**) are parks with PCE. This map was created by the authors using ArcGIS software (version 9.2) (https://www.arcgis.com/). The satellite imagery was obtained from Google Earth Pro, version 7.3.6.10201, with no modification of the satellite imagery (https://www.google.com/earth/about/versions/).

becomes more pronounced (such as Huannan Park). For parks with poor external conditions but good internal conditions, effective internal design can partially mitigate the adverse external conditions. Therefore, in urban planning and park design, both internal and external factors should be considered comprehensively to maximize cooling effects.

This study also found that the cooling effects of natural parks are superior to those of artificial parks, owing to the generally larger area of natural parks, as well as their higher vegetation coverage, greater green space area, and the presence of natural water bodies, which collectively contribute to a significant reduction in the surrounding environmental temperature.

Limitations

Firstly, this study was based solely on a single satellite image from a specific date (summer daytime), and future research could focus on the seasonal, diurnal, and even time-series variations of PCE and their influencing factors[38]. Secondly, various other elements, such as geographical location, socioeconomic development, human activities, and architectural patterns[31,57], may also influence the PCE and warrant further exploring in subsequent studies. Finally, the interactions between neighboring parks may also affect the study results, potentially increasing the uncertainty of the findings[58], should be further explored in future studies using more refined spatial analysis methods.

Conclusions

This study quantified the PCE using two cooling indicators: ΔT_{max} and $L_{\Delta max}$, and explored the impact of different factors on this effect from both external morphological characteristics and internal patch characteristics of parks. The principal conclusions are:

(1) Not all urban parks can provide environmental cooling. Out of a total of 50 parks, 42 exhibit PCE. Qingliangshan Park (ID 28) has the highest ΔT_{max} value, reaching a maximum cooling intensity of 5.97 °C. Wushan Park (ID 34) has the highest $L_{\Delta max}$ value, reaching a maximum cooling distance of 0.62 km. Parks with good cooling effects typically have lower PARA values, higher vegetation coverage and water body ratios, lower proportions of impervious surfaces, simpler external shapes, and lower patch fragmentation. In contrast, parks with poor cooling effects often have complex external shapes, smaller sizes, and unrea-

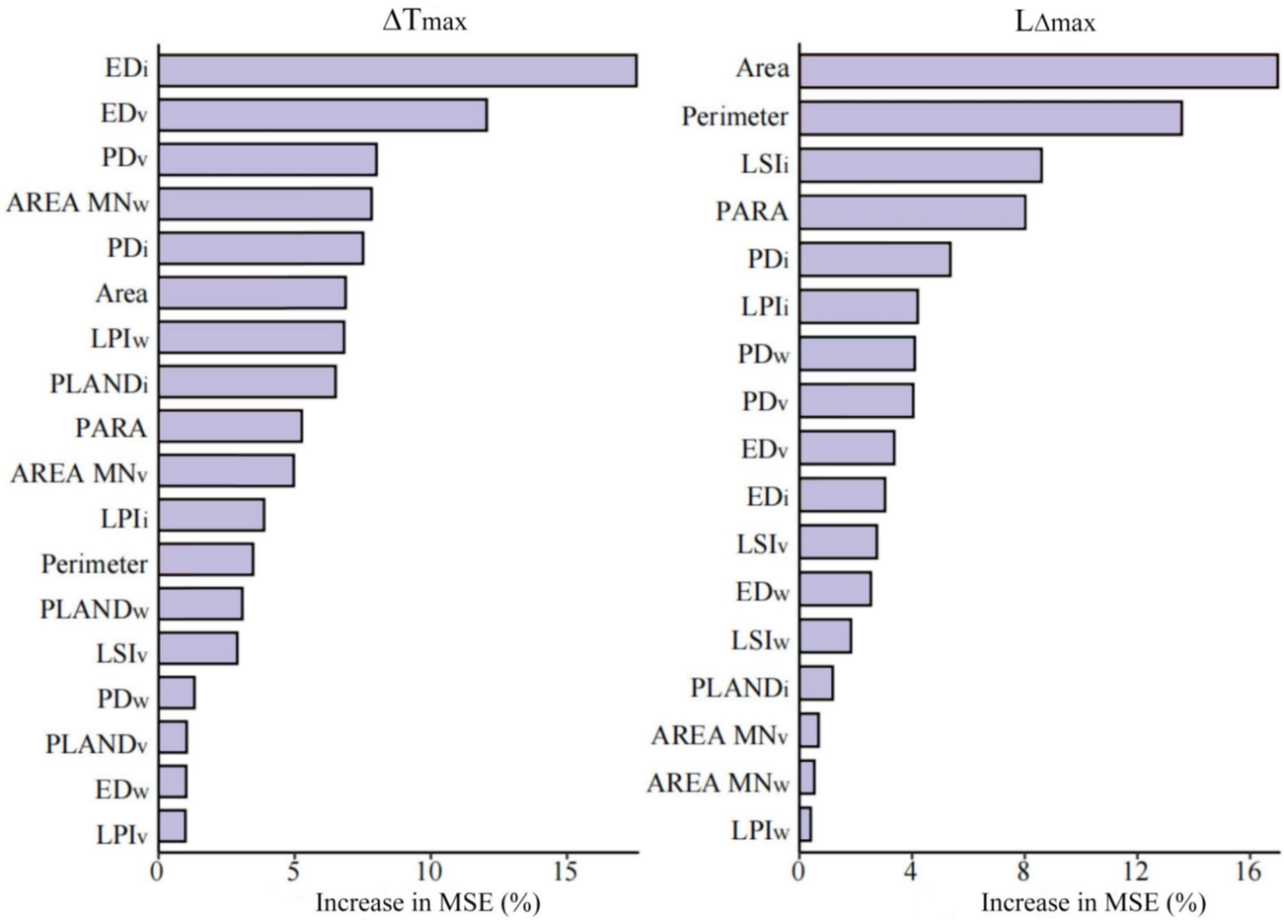

Fig. 13. The importance of influencing factors on ΔT_{max} and $L_{\Delta max}$.

Park name	$PLAND_i$	PD_i	ED_i	$PLAND_v$	PD_v	ED_v
Huaqiao Park (ID 43)	29.32	766.00	1218.67	70.68	176.77	1218.67
Luohanshan Park (ID 23)	21.62	142.56	241.47	78.38	71.28	241.47
Park name	**Area/ hm^2**	**Perimeter/km**	**PARA**	**ΔT_{max}/℃**	**$L_{\Delta max}$/km**	
Huaqiao Park (ID 43)	1.70	0.88	0.05	−1.46	0.39	
Luohanshan Park (ID 23)	1.47	0.47	0.03	4.99	0.26	

Table 3. Comparison of Huaqiao and Luohanshan parks.

sonable internal land use, resulting in higher proportions of impervious surfaces and consequently lower ratios of vegetation and water bodies.

(2) Urban parks are not necessarily better the larger they are. There exists a specific area threshold that influences their cooling effect. Statistically, 0.594 hm^2 is the most economical area for PCE in the study area. As the area increases, the cooling influence gradually expands, but beyond 56 hm^2, further increases in area do not yield greater cooling effects. When land resources are limited and park expansion is not feasible, reducing the complexity of the park's outer contour and designing regular boundaries can enhance the PCE.

(3) The proportion of impervious surfaces in urban parks and cooling intensity have a logarithmic relationship rather than a simple linear relationship. Particular emphasis should be placed on the redevelopment of parks with low impervious surface ratios (less than 15%), such as Shuishang Park (ID 29) and Gaogaishan Park (ID 10). The control of impervious surface ratio should not be relaxed due to their low baseline of impervious surfaces because even a minor expansion of impervious surfaces may significantly affect the cooling capacity of these parks.

(4) The importance ranking of influencing factors reveals that EDi, EDv, and PDv are the most significant for ΔT_{max}, highlighting the role of internal patch configuration, while Area, Perimeter, and LSI_i dominate $L_{\Delta max}$, emphasizing the impact of external morphological characteristics on cooling effects.

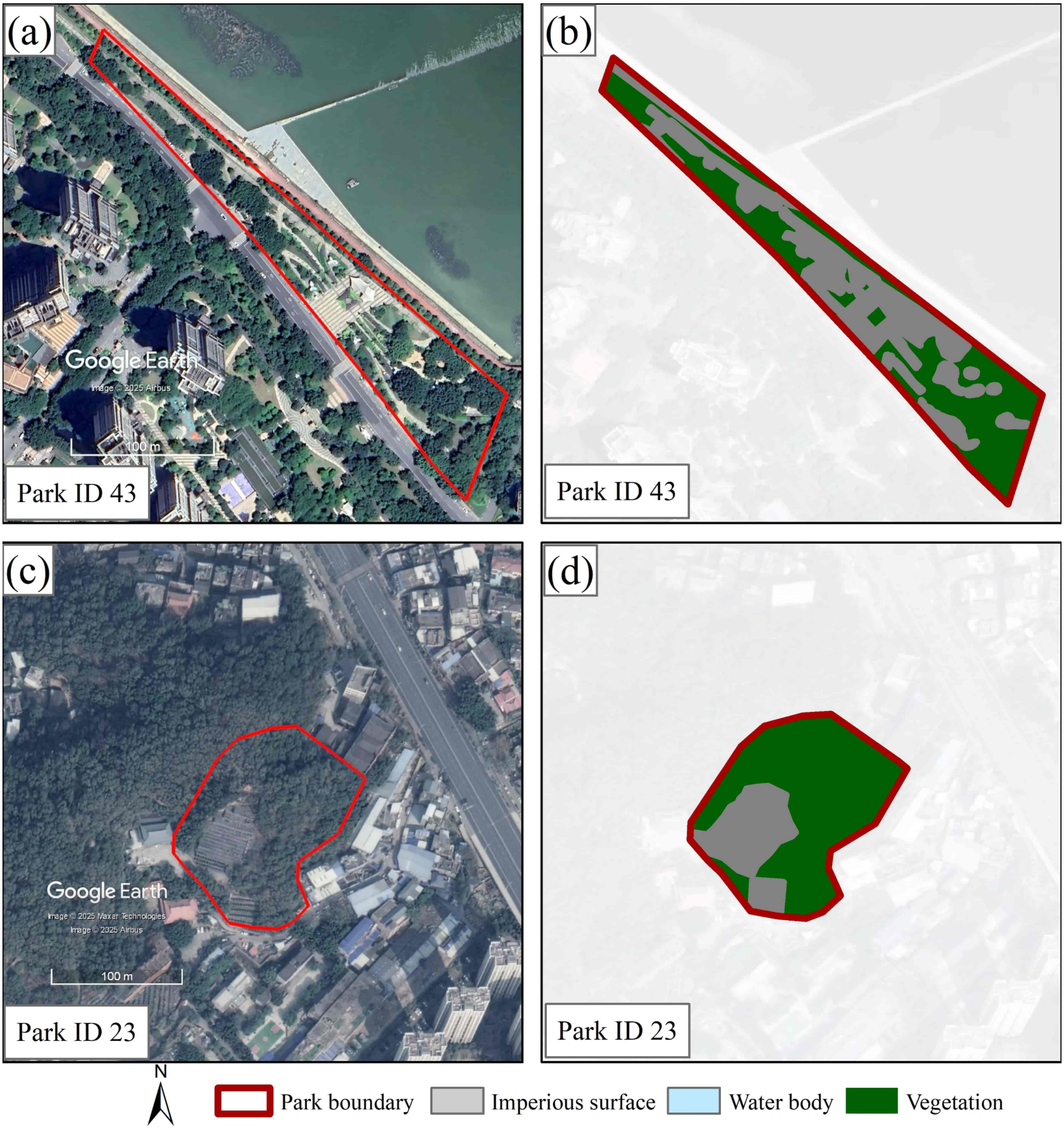

Fig. 14. Comparison of Huaqiao and Luohanshan parks. (**a**) High-resolution image of Huaqiao Park; (**b**) land use patches of Huaqiao Park, (**c**) high-resolution image of Luohanshan Park; (**d**) land use patches of Luohanshan Park. This map was created by the authors using ArcGIS software (version 9.2) (https://www.arcgis.com/). The satellite imagery was obtained from Google Earth Pro, version 7.3.6.10201, with no modification of the satellite imagery (https://www.google.com/earth/about/versions/).

(5) The cooling effect of parks is jointly determined by internal and external conditions, with internal conditions having a more significant impact. Good internal conditions can still provide effective cooling even when external conditions are poor, as seen in Liminghu Park (ID 22); while superior external conditions do not result in ideal cooling effects when internal conditions are poor, as observed in Xichangusi Park (ID 36). The influence of external conditions is relatively minor, but becomes more pronounced when internal conditions are poor, as is the case with Huannan Park (ID 15). By optimizing internal design, the adverse effects of external conditions can be partially mitigated.

(6) To maximize the PCE, in addition to traditional methods such as increasing vegetation and water bodies ratios and limiting impervious surface ratios, it is also important to maintain the continuity and integrity

	Park name	ΔT_{max}/°C	$L_{\Delta max}$/km	Area/hm^2	PARA	$PLAND_v$	$PLAND_w$	$PLAND_i$
Parks with favorable external conditions but poor internal conditions	Xichangusi (ID 36)	1.80	0.46	119.04	0.01	89.86	0.60	9.54
Parks with unfavorable external conditions but good internal conditions	Liminghu Park (ID 22)	3.52	0.38	5.67	0.02	32.76	58.45	8.79
Parks with both favorable external and internal conditions	Xihu Park (ID 37)	5.66	0.48	28.94	0.01	26.94	67.25	5.81
Parks with both poor external and internal conditions	Huannan Park (ID 15)	0.27	0.38	0.49	0.06	74.77	0.00	25.23
	Park Name	PD_v	PD_w	PD_i	ED_v	ED_w	ED_i	
Parks with favorable external conditions but poor internal conditions	Xichangusi (ID 36)	3.36	2.52	21.01	155.41	5.96	149.91	
Parks with unfavorable external conditions but good internal conditions	Liminghu Park (ID 37)	88.33	106.00	317.99	418.69	325.41	209.61	
Parks with both favorable external and internal conditions	Xihu Park	26.43	5.29	63.42	79.17	121.65	111.74	
Parks with both poor external and internal conditions	Huannan Park (ID 15)	410.64	0	1231.92	1037.89	0	1037.89	

Table 4. Key characteristics and cooling effects of representative parks.

of vegetation and water bodies coverage, design connected inner lakes and water system landscapes, and create contiguous plant landscape belts. For impervious surface coverage, it is advisable to concentrate the layout and use curves and irregular shapes to design the boundaries of impervious surfaces, such as winding walkways or small slopes and steps to add horizontal/vertical layers to the boundaries. Mimic the forms of vegetation boundaries in nature, avoiding straight lines or regular geometric shapes, instead opting for curves or irregular boundaries; designing diverse plant combinations, and planting shrubs and herbaceous plants at the vegetation boundaries to form multi-layered vegetation structures, creating more complex boundary forms.

Data availability
The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

Conceptualization, L.W. ; data curation, W.W. ; formal analysis, L.W., H.X., W.W.; funding acquisition, L.W.; investigation, F.T. and W.W.; methodology, L.W.; project administration, H.X.; resources, F.T.; supervision, H.X.;

validation, L.W., F.T., W.W. ; visualization, ; writing—original draft, L.W. and W.W.; writing—review and editing, H.X.,L.W.

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Declarations

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to H.X.