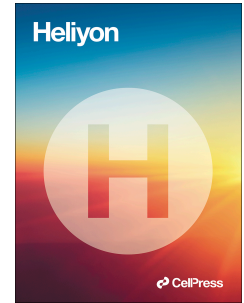


# Journal Pre-proof

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PII: S2405-8440(22)02847-X

DOI: <https://doi.org/10.1016/j.heliyon.2022.e11559>

Reference: HLY 11559

To appear in: *HELIYON*

Received Date: 12 September 2022

Revised Date: 24 October 2022

Accepted Date: 7 November 2022

Please cite this article as: Q. Zhang, D. Zhou, D. Xu, J. Cheng, A. Rogora, Influencing factors of the thermal environment of urban green space, *HELIYON*, <https://doi.org/10.1016/j.heliyon.2022.e11559>.

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# Influencing factors of the thermal environment of urban green space

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**Key Words:** Remote sensing; Fixed effect model; Urban green space; Cooling effect.

**Abstract:** Several heat records have been broken in recent years and decades. Extreme high temperature not only damages human health, but also increases the risk of wildfires. As a common urban infrastructure, urban green space has been proved to have a cooling effect. In this study, the physical indicators and temperature data of 36 green spaces in Xi'an were collected, and the influence of different physical indicators of green spaces on their thermal environment was explored through correlation analysis. The results suggest that the area of green space should be between 0.6-0.7 square kilometers or the perimeter should range from 4000 to 4500 meters in order to obtain the lowest internal temperature. When the area of water body in the green space is between 0.3-0.4 square kilometers or the perimeter is about 5000 meters, its internal temperature is the lowest. Indicators of green space in the conclusion can be directly understood and referred by urban planners and policy makers. Results of this study thus have implications for improving urban thermal comfort by controlling the physical indicators of green space.

## 1. Introduction

China's accelerated urbanization has greatly changed the underlying surface of cities. The excess heat is stored in the newly emerging impervious ground and buildings, which leads to urban heat island

(UHI) effect [1]. Scholars have proved that the extreme high temperature in summer caused by UHI has a negative impact on human health, increases unnecessary energy consumption, and even causes fires [2-4]. The heat wave that hit Chicago in 1995 caused 550 to 800 deaths [5]. In England and Wales, extreme high temperatures in 2003 and 2006 resulted in 2000 and 680 deaths, respectively [6]. In China, a projection study showed that the additional warming from 1.5°C to 2°C will lead to more than 27,900 annual extra heat-related deaths [7]. Some studies have pointed out that extreme high temperatures in cities are more harmful to the elderly and children [8-10]. For people with chronic diseases, extreme high temperature will increase the probability of suffering from other related diseases. [11] found that extremely hot weather may aggravate cardiovascular and respiratory diseases, and also lead to heatstroke and death. In a study about psychiatric patients, it was found that the incidence rate of psychosis increased significantly in extreme high temperature weather [12]. In addition to the negative impact on human health, extreme high temperature also causes the vulnerability and instability of urban infrastructure. In the face of extreme hot weather in summer, the demand for water supply is significantly increased, meanwhile, a large number of electrical equipment need additional energy for cooling. These demands cause the overload of power supply and water supply, which threatens the safety of water and electricity consumption of urban residents [13]. Although the emergency plan for the supply of water and electricity in response to extreme hot weather has been issued in major cities in China, local water and power cuts still occur every year. Therefore, it is necessary to find measures to improve the urban thermal environment in summer.

Contrary to UHI, the existence of cooling effect in urban green space has become an indisputable fact [14]. The cooling effect causes its lower internal temperature compared to surrounding urban

functional areas, providing nearby residents with a more comfortable thermal environment in summer. A study from Iran indicated that the temperature difference between the center of urban green area and its outer zone is up to 4.4 °C [15]. Moreover, some research results showed that urban green area can mitigate the UHI of its surrounding built-up areas [16]. Studies on the regulation of urban green space to the thermal environment of its surrounding area have been carried out from various perspectives. Researchers have proved that green space with different underlying surface types, including vegetation [17, 18], wetland [19-21] and water body [22-24], can effectively regulate the urban thermal environment. For the green space covered by vegetation, its cooling effect is mainly attributed to the shadow shading of trees and grass. In addition, the transpiration process of plant leaves can also form cooling effect [25, 26]. The leaf area index explained 62% of the surface temperature change [27]. An experiment from Greece showed that the vegetation near the outer wall of the building reduced direct solar radiation on the building by 80% [28]. By analyzing the implications of anthropogenic heat discharges into the urban thermal environment of Tokyo, it was concluded that the greening around buildings brought a decrease of 0.47 °C to the average indoor temperature at noon [29]. The effect of vegetation shadow to alleviate high temperature is more obvious on the road surface. A study in Bangalore, India, indicated that the difference in surface temperature between roads with or without leafy shade could be as high as 27.5 °C [30]. For the green space with the underlying surface type of wetland or water, the increased surface porosity and bodies of water play a role in increasing potential cooling through evaporation [31].

In addition to proving the cooling effect of green space, some more accurate quantitative conclusions have been drawn from previous studies. For example, increasing the tree coverage of

pocket parks in Hong Kong from 25% to 40% could reduce daytime UHI by 0.5 °C [32]. Results of a study from Philippines suggested that the urban park can provide a maximum cooling effect of 2.63 °C near the southern edge of the river [33]. Scholars from Nanjing, China proved that the greening coverage rate of 28% is the critical value for the effectiveness and economy of alleviating the high temperature in residential areas [34]. Another study in Nanjing showed that the economically optimal sizes of green space and water patch are around 0.30 ha [35]. Compared with the surrounding construction land, the surface temperature of large green space is 1 to 4 °C lower [36]. Through field measurement and numerical simulation, the research team from Chongqing University found that the littoral forest yielded 3.3 °C cooling effect than that of the separate trees [37]. What is more, the forest provided a cooling effect of up to 8.4 °C compared with urban reference sites [38]. A quantitative analysis of 60 parks in Wuhan showed that 54 of them have significant cooling effect, with average cooling intensity of  $3.5 \pm 0.2$  °C [39].

Most of the current research on the green space were carried out from the angle of environmental analysis, rather than conclusions that can be directly applied to urban planning [37, 38, 40-44]. The purpose of this study is to use remote sensing technology to analyze the influencing factors of green space cooling effect, and then propose quantitative design indicators of urban green space oriented by microclimate optimization. Compared with previous studies, we have not only verified the positive correlation between green space area and perimeter and its cooling effect, but also found the critical values for the increase of green space perimeter and area to its cooling effect, which is very important for the economy of urban green space design.

## 2. Material and methods

### *2.1. Research object*

Xi'an, also known as Chang'an, is a mega city located in the geographical center of China (Figure 1). The terrain of Xi'an is flat, with a maximum length of 204 kilometers from east to west and a maximum width of 116 kilometers from north to south. The city area is nearly 10,000 square kilometers, including an main built-up area of over 1000 square kilometers, with an average altitude of about 410 meters. The Loess Plateau in the north and the Qinling Mountains in the South surround this flat fertile soil, contributing to its basin like geographical characteristics. Xi'an has a warm temperate semi humid continental monsoon climate with four distinct seasons. The winter is dry and cold while the summer is hot and rainy. The weather is cool and changeable in the spring and autumn. The annual average temperature is about 13.7 °C, the average daytime temperature in summer is over 30 °C. According to the division of climate zones required by the Ministry of housing and urban rural development of China for building thermal design, Xi'an is classified into cold regions, however, the occurrence of intolerable high temperature event in summer here has shown an increasing trend in recent years. The main urban area of Xi'an is in a windless state most of the time due to its basin like terrain. The weak air circulation is difficult to take away the heat accumulated near the urban surface. Therefore, green space has been regarded as one of the few optimization methods for the extreme hot weather in Xi'an. The innovation of this study is to build a Xi'an urban spatial model in ArcGIS, which includes both spatial information and surface temperature information. Then the correlation between internal physical indicators of urban green space and its thermal environment is analyzed based on our previous study of the impact of external space morphology on the cooling effect of green space [45].

### *2.2. Data acquisition*

There are two kinds of data in this study: urban surface temperature data and urban physical indicator data. The surface temperature data was obtained through the inversion of the remote sensing information of landsat8 series satellite. The satellite imagery was shot on August 29, 2019 when the satellite passed over Xi'an. There are three methods to retrieve the infrared information from satellite remote sensing into surface temperature data: split window algorithm, single window inversion algorithm, and atmospheric correction algorithm, and. By comparing the temperature information obtained by these three methods with the data collected from meteorological stations, a study has proved that the data obtained by single window inversion algorithm is the most accurate [46]. Thus, it was selected in this study. Figure 2 presents the calculated surface temperature in the main urban area on the day of the selected satellite imagery.

The thermal fields were divided into 6 groups by using the mean standard deviation method. Among them, green spaces are mainly distributed in low temperature groups and sub low temperature groups. To improve the authority of the research results, green patches below  $0.01 \text{ km}^2$  were excluded. Based on the field research on the characteristics of the urban surface, 36 green spaces [45] that meet the research requirements were selected, which are shown in Figure 2. By superimposing the surface temperature map and the vector map of boundaries of green spaces in ArcGIS, the internal and external temperature map of sample green spaces were obtained. The urban physical indicators involved in this article are mainly related to the characteristics of green space. Data sources include field surveys, remote sensing images of Google Earth and Baidu street view map.





Fig 1 Location of Xi'an City

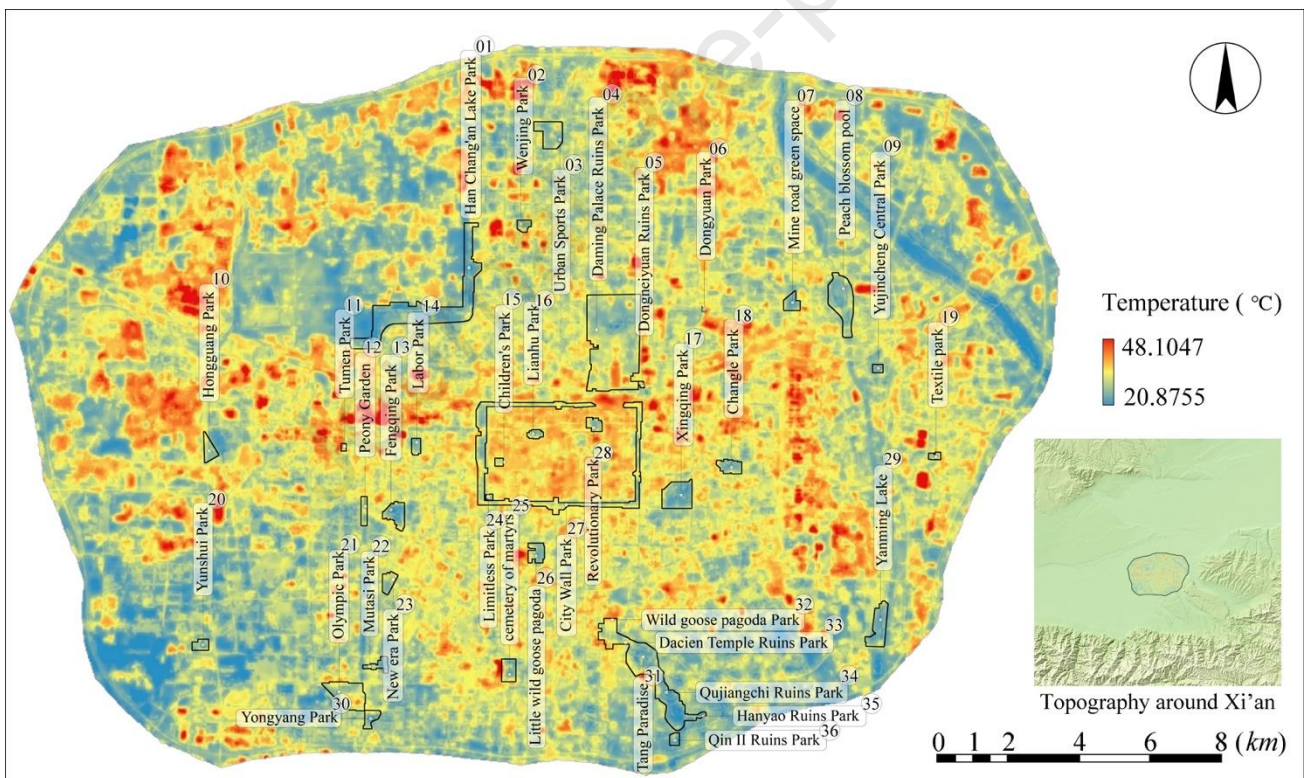


Fig 2 Distribution of retrieved surface temperature and 36 sample green spaces of Xi'an

### 3. Results and discussion

#### 3.1. Association between the form factors of green space and its internal thermal environment

##### 3.1.1. Correlation between perimeter of green space and its internal temperature



Table 1 lists the correlation result between the perimeter of green spaces and their minimum internal temperature. The correlation curve between these two variables is shown in the left part of Figure 3. As can be seen from Table 1, a negative correlation exists between the perimeter of green space and its thermal environment, with a correlation coefficient of - 0.762.

Table 1 Correlation between the perimeter of green space and its internal minimum temperature

Pearson correlation coefficient	Significance	Number of samples
-.762**	.000	33

\*\* . Significant correlation at the level of 0.01 (2 tailed). (Same below)

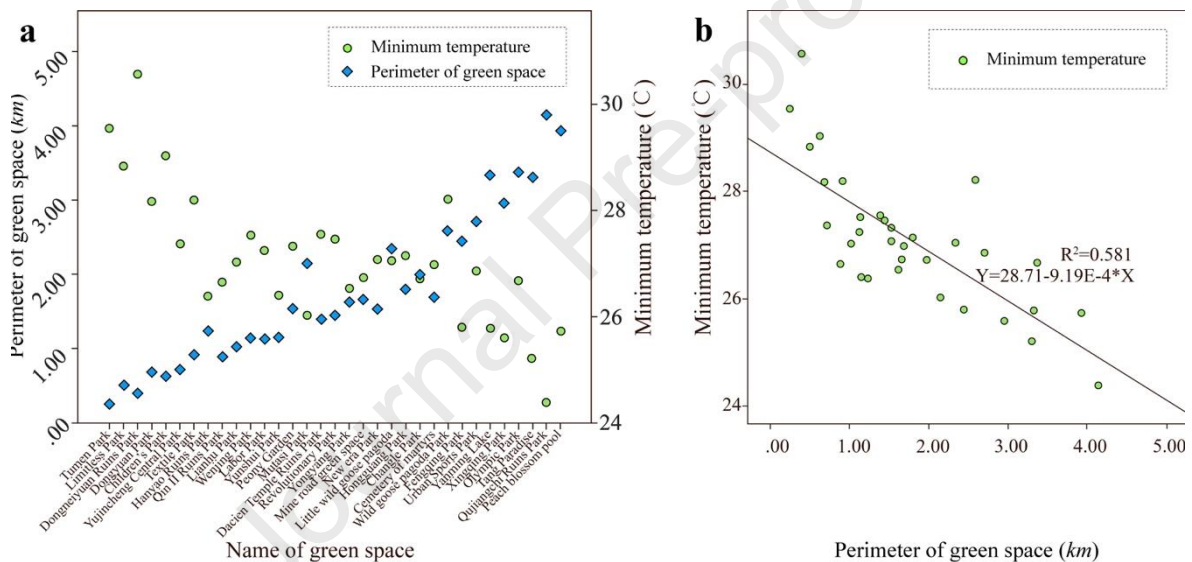


Fig 3 Data distribution and correlation fitting of perimeter of green spaces and their minimum temperatures. a) Data distribution. b) Correlation fitting.

The association between the minimum temperature of green space and its perimeter is presented in the right side in Figure 3. The perimeters of the 33 sample green spaces range from 247.07m to 4144.19m, and their minimum temperatures range from 24.38 °C to 30.57 °C. The smallest perimeter is that of Tumen Park, with a minimum temperature of 29.54 °C. The largest perimeter is that of Qujiangchi Ruins Park, and its minimum temperature is 25.73 °C, which confirms to the law that the larger the perimeter of green space is, the lower its minimum temperature is.

It is worth mentioning that the perimeters of most of the green spaces in the 36 samples are ranging from 0 to 4500m, and only three of them are far beyond this range, including Daming Palace Ruins Park, Han Chang'an Lake Park and City Wall Park. The perimeters of the three green spaces are 8952.42m, 28424.19m and 13938.94m in the order mentioned above. The lowest temperatures of their internal space are 29.25 °C, 28.85 °C and 27.10 °C respectively. By comparing all the temperature data, we found that the perimeters far above the average have not brought these three green spaces equal benefit reductions in temperature. On the whole, the minimum temperature in the green space first decreases steeply and then changes gently after exceeding a certain critical value with the increase of its perimeter.

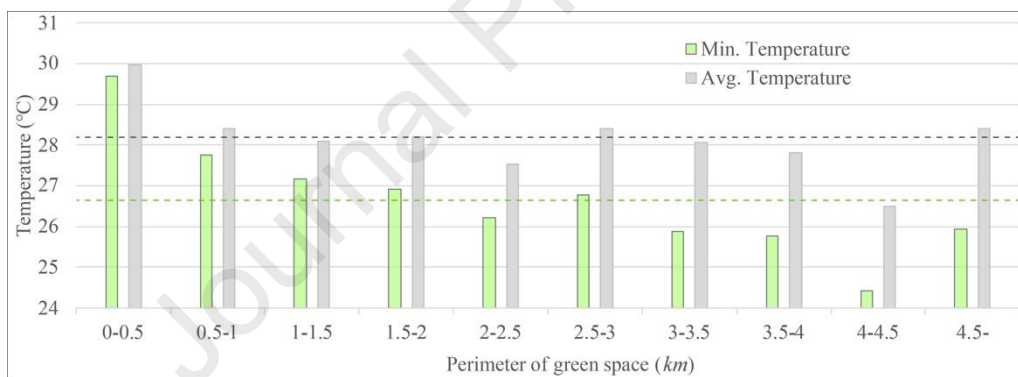


Fig 4 Average and minimum temperatures of green spaces in different groups

To further explore the economic and applicable perimeter range of urban green areas, all samples were divided into ten groups according to the length of the perimeter. The average temperatures and minimum temperatures of green space in different groups are shown in Figure 4. Combined with the above fitting results, it is natural to conclude: When the total area of the green space is constant, its internal minimum temperature and average temperature are the lowest when its perimeter is between 4000-4500m.

### 3.1.2. Correlation between green space area and its internal temperature

Table 2 reveals that a negative correlation exists between green space area and its thermal environment, with a coefficient of -0.684. The left part in Figure 5 shows the linear fitting relationship between minimum temperature of green space and its area.

Table 2 Correlation between green space area and its internal minimum temperature

Pearson correlation coefficient	Significance	Number of samples
-.684**	.000	33

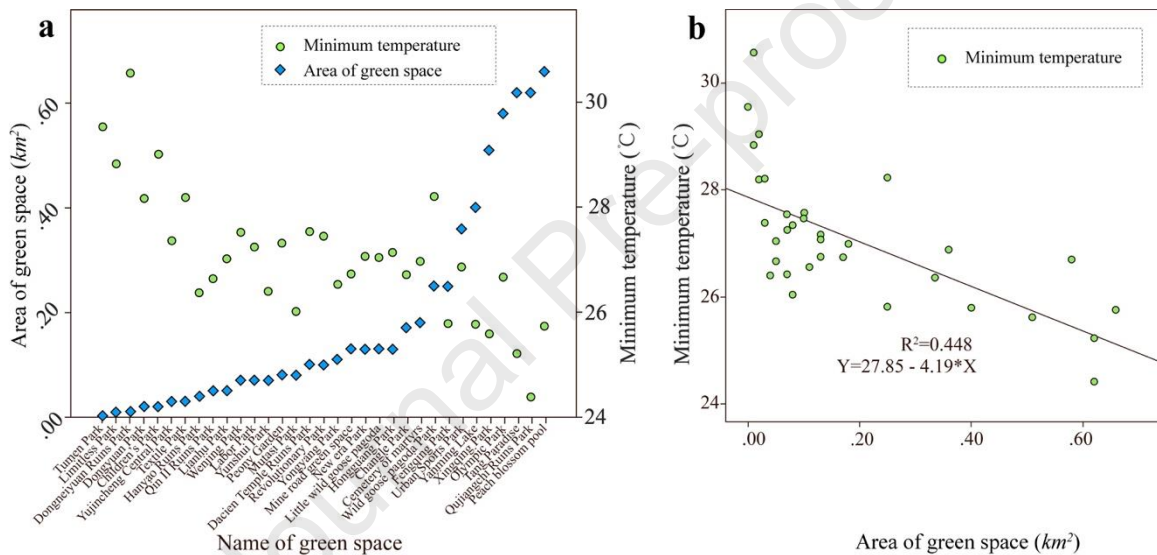


Fig 5 Data distribution and correlation fitting of area of green spaces and their minimum temperatures. a) Data distribution. b) Correlation fitting.

The right part of Figure 5 presents the association between the minimum temperature of green space and its area. It can be seen that the area of the 33 sample green spaces ranges from  $0.01 \text{ km}^2$  to  $0.66 \text{ km}^2$ . The smallest area is that of Tumen Park, with a minimum temperature of  $29.54 \text{ }^\circ\text{C}$ . The largest perimeter is that of Peach blossom pool, and its minimum temperature is  $25.73 \text{ }^\circ\text{C}$ , which confirms to the law that the larger the area of green space is, the lower its minimum temperature is.

It should be noted that, similar to the situation in the previous perimeter related section, the area

of most green spaces in this study is in the range of 0-0.7 square kilometers, except for the three with the longest perimeters. The statistical results show that the large area of these three green spaces has not brought them significant temperature reductions. Therefore, we can draw a preliminary conclusion: The temperature of green space first decreases steeply and then changes gently after exceeding a certain critical value with the increase of area of green space.

To further explore the economic and applicable area range of green space, all samples were divided into 7 groups according to the size of their area. Then temperature data of seven groups of green spaces were visualized as Figure 6. It can be concluded that the green space could achieve the lowest internal temperature and the lowest average temperature when its area is within the range of 0.6-0.7  $km^2$ . This is very different from the numerical range of 0.1  $km^2$  of green space in [16]'s research. We believe that the natural elements and qualities of the urban green spaces, as well as climate characteristics, highly inform the urban green space cooling effect.

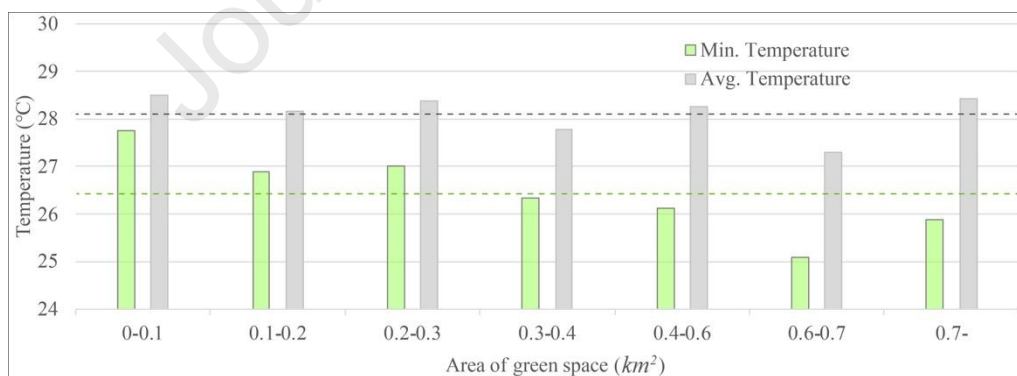


Fig 6 Average and minimum temperatures of green spaces in different groups

### 3.2. Association between the form factors of water body in green space and its internal thermal environment

As is known to all, the evaporation of water absorbs heat, which is more intense in the case of

high temperature during the day. To explore the influence of geometric indicators of water bodies on the cooling effect of green space, the correlation analysis on water bodies and temperature was carried out. We divided all green spaces in this study into two groups according to whether they contain water bodies, of which 23 are with water, and their morphological information are presented in Table 3. The average area of these water bodies is  $0.084423 \text{ km}^2$ , the smallest water body area is  $0.00071 \text{ km}^2$  in children's Park, and the largest is  $0.403829 \text{ km}^2$  in Han Chang'an Lake Park. The average perimeter of these water bodies is 3925.81m, of which the smallest is in the children's Park, 118.04m, and the largest is in the City Wall Park, 26122.74m. Table 4 lists the morphological data and temperature information of the two groups of green spaces. It can be seen that the average temperature inside the green area without water is  $28.80 \text{ }^\circ\text{C}$ , while of the green space with water is  $27.98 \text{ }^\circ\text{C}$ . The average minimum temperature of green space with and without water is  $27.91 \text{ }^\circ\text{C}$  and  $26.49 \text{ }^\circ\text{C}$  respectively. That is to say, whether the average temperature or the minimum temperature, the green space containing water is lower than that without water, which confirms the positive role of water in reducing the internal temperature of green space.

Table 3 Geometric information of the water body of 23 green spaces

No.	Perimeter	Area ( $\text{km}^2$ )	No.	Perimeter (m)	Area ( $\text{km}^2$ )
15	118.04	0.000710	20	1096.84	0.019345
02	442.12	0.001575	03	2427.04	0.025356
28	415.00	0.004508	13	1695.16	0.030601
22	410.49	0.004629	17	2856.64	0.081492
23	574.73	0.005117	29	3779.48	0.117722
35	830.16	0.005142	04	11389.32	0.139527
14	620.16	0.005302	31	7046.35	0.178855
26	777.69	0.006272	27	26122.74	0.267229
10	845.41	0.011820	08	6847.53	0.288409
18	1363.87	0.012644	34	5101.94	0.303923
30	677.95	0.013292	01	13933.01	0.403830
16	922.02	0.014870			

Table 4 Comparison of internal temperature of green space with and without water body

Pearson correlation	Avg. TEMP (°C)	Avg. min. TEMP (°C)	Avg. Area (km <sup>2</sup> )	Avg. Perimeter (m)	Number of cases
With water body	28.80	27.91	0	0	13
Without water body	27.98	26.49	0.08	3925.81	23

### 3.2.1. Influence of perimeter of water body in green space on its internal temperature

Table 5 indicates that a negative correlation exists between the perimeter of water body in green space and its thermal environment, with a coefficient of - 0.693. The left chart in Figure 7 shows the quadratic polynomial relation between the perimeters of water bodies in green spaces and their minimum temperatures. It should be noted that the perimeters of the water bodies in most green spaces are within the range of 0-15000m, and only that of the water body in the City Wall Park is far beyond this range, which is 26122.74m. Nevertheless, we found that it did not form a temperature difference that matched this perimeter difference with the other 22 cases. To eliminate the interference of this case on the fitting curve, we removed it and then fitted the other 22 groups of data again. The fitting results are shown as the right of Figure 7.

It can be seen from the Figure 7 that after excluding the City Wall Park, there is still a quadratic polynomial relationship between the perimeters of the water bodies and the minimum temperature of the green spaces. Thus, the following conclusion can be drawn: With the increase of the perimeter of water in the green space, its internal temperature decreases gradually first, and then increases after exceeding a certain critical value. In other words, when the perimeter of the water body is too long, the increase of its perimeter only brings limited cooling benefits.

Table 5 Correlation between the perimeters of water body in green space and its internal temperature

Pearson correlation coefficient	Significance	Number of samples
-.693**	.000	23

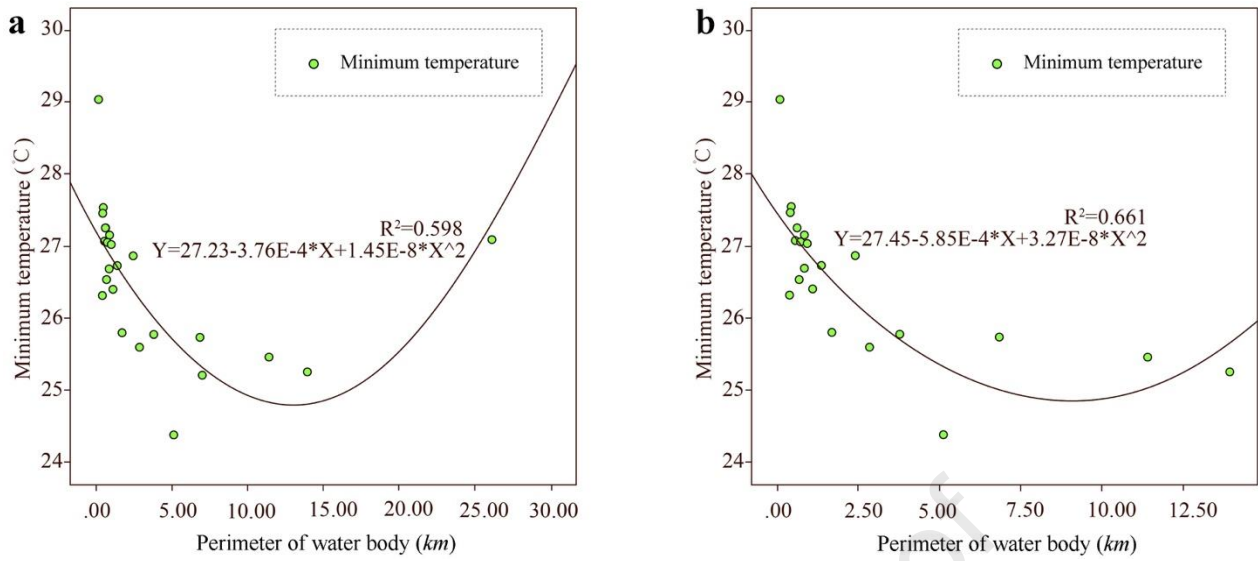


Fig 7 Correlation between the perimeters of water body in different green spaces and their minimum temperature. a) 23 green spaces. b) 22 green spaces except City Wall Park

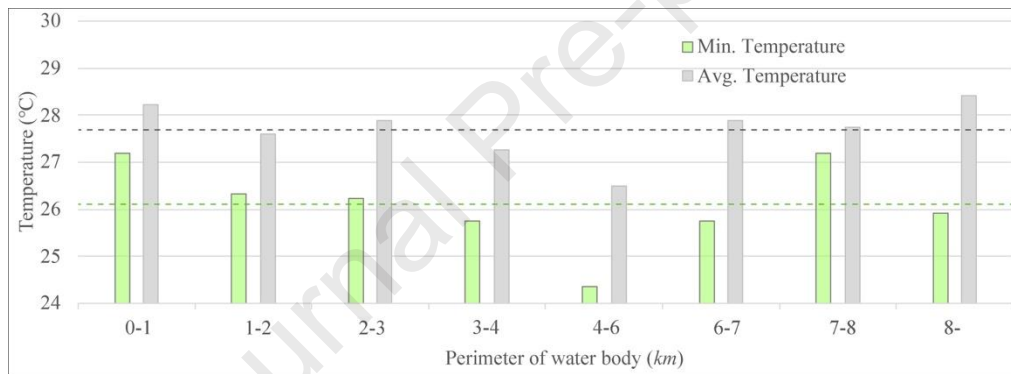


Fig 8 Average and minimum temperature of green space in different groups

To find out the economic perimeter of the water body with cooling effect, we divided the samples below the critical value into 8 groups, which are shown in Figure 8. It can be seen that when the perimeter of the water body is about 5000m, the minimum temperature and average temperature of the green space where it is located are the lowest.

### 3.2.2. Influence of area of water body in green space on its internal temperature

The correlation analysis between the area of the water body and the minimum temperature of the green space where it is located was also carried out. The results are shown in Table 6. It can be seen



that there is a linear negative correlation between these two variables, with a coefficient of - 0.778. The fitting results of the two are shown in the left part of Figure 9. Among the 23 green spaces containing water bodies, the smallest water body is located in the children's Park, with an area of  $0.01 \text{ km}^2$  and a minimum temperature of  $29.03 \text{ }^\circ\text{C}$ . The largest water body is in Han Chang'an Lake Park, with an area of  $0.40 \text{ km}^2$  and a minimum temperature of  $27.10 \text{ }^\circ\text{C}$ . In terms of the current analysis results, the larger the water area, the lower the minimum temperature of the green space where it is located. Most of the area of water bodies in the sample green spaces is no more than  $0.29 \text{ km}^2$ , except for Qujiangchi Ruins Park and Han Chang'an Lake Park. Further data analysis indicated that these two large-area water bodies do not maintain the green spaces where they are located at the lowest temperature level in all analyzed samples, which may be caused by their water bodies area exceeding the critical value. To determine the economic and effective range for the area of water body in green space, 23 samples were divided into 7 groups according to their area of the included water bodies. The average temperature and the lowest average temperature of the green space in each group are shown in the right of Figure 9, from which a conclusion can be drawn that when the area of water body is within the range of  $0.3\text{-}0.4 \text{ km}^2$ , the minimum temperature and average temperature of the green space where it is located are the lowest. This is far greater than the numerical range of the blue space area in [35]'s study, which may be caused by the difference in the complexity of water boundary.

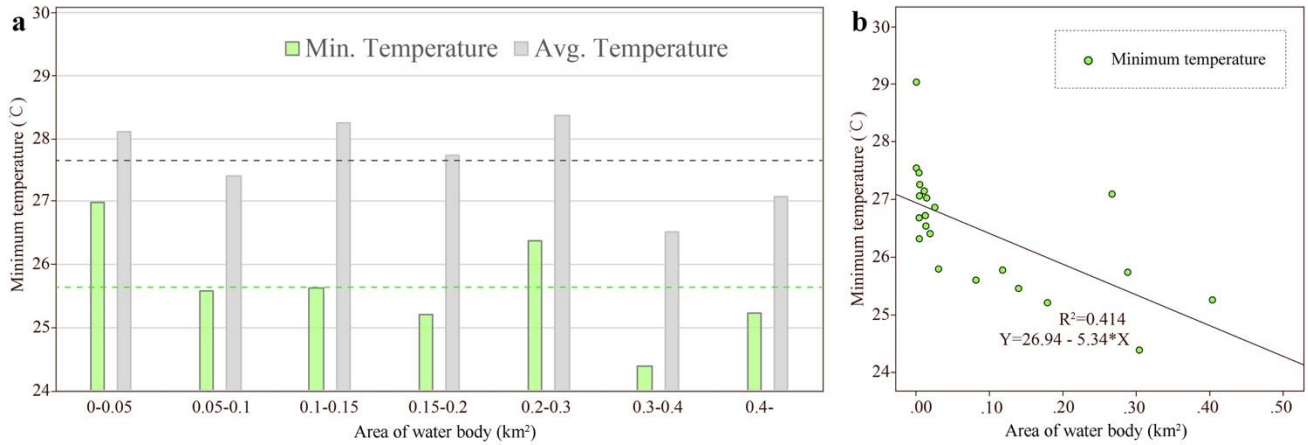


Fig 9 Data distribution and correlation fitting of water body area in green spaces and their Minimum temperature and Average temperature. a) Data distribution. b) Correlation fitting.

Table 6 Correlation between the area of water body in green space and its internal temperature

Pearson correlation coefficient	Significance	Number of samples
-.778**	.000	23

#### 4. Conclusion

In this study, the land surface temperature information in the main urban area of Xi'an was retrieved from remote sensing data, and the correlation between the physical indicators of 36 green spaces and their internal temperatures was quantitatively analyzed. The main conclusions of this study are as follows. There is a significant negative correlation between the area and perimeter of green space and its internal temperature. Nevertheless, a critical value exists for the temperature drop caused by the growth of area and perimeter. When the area of green space is ranging from  $0.6 \text{ km}^2$  to  $0.7 \text{ km}^2$  or its perimeter is between 4000-4500 m, the temperature of green space is the lowest. The area and perimeter of water in the green space also show a significant negative correlation with its internal temperature. The temperature of the green space is the lowest when the area of the water body is in the range of  $0.3 - 0.4 \text{ km}^2$  or its perimeter is about 5000m. These specific indicators of green space can be directly understood and referred by relevant practitioners of urban planning. Results of this study thus have implications for improving urban thermal comfort by controlling the physical indicators of green

space. Affected by the readability of satellite image information (such as the influence of rainy weather on satellite image), only the surface temperature data at a certain time is obtained. In the future, we plan to use handheld devices to obtain periodic temperature information and study the long-term dynamic law of cooling effect of urban green area in combination with satellite data.

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#### Acknowledgement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript.

#### Author Disclosure statement

No competing financial interests exist.

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