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# Identification and Prioritization of Thermal Environment Regulation Hotspots in Chengdu

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**Abstract:** Temperature condition in urban areas has a substantial impact on the well-being and safety of both urban residents and the ecosystems. Green spaces are crucial for mitigating urban heat impacts, and hence, their balanced supply and demand is essential. Due to rapid urbanization, Chengdu has had a significant increase in population, which has had an impact on the dynamic changes in its green space environment, making it a suitable case for our study. This study employs the high-temperature vulnerability framework to classify urban green spaces as entities that regulate the thermal environment. This classification is based on the analysis of ecosystem service supply and demand. The approach creates an assessment framework for managing the balance between the need for and availability of thermal environment regulation in urban green spaces. The study utilizes matching and a priority index to identify places in Chengdu where there are imbalances between supply and demand for services. Our findings suggest: (1) The demand for regulating the thermal environment in Chengdu's green spaces is defined by three indices: thermal exposure, thermal sensitivity, and thermal adaptability. High-demand areas account for a relatively small proportion and exhibit a pattern of "global diffusion and local concentration". (2) The supply capacity in Chengdu is determined by both the size of green spaces and the surface temperature. High-supply capacity areas are mainly located in the southeastern part of the city, and their distribution pattern is similar to that of green spaces. (3) The level of correspondence between the supply and demand in Chengdu varies significantly and can be classified into three categories: "insufficient supply and high demand", "insufficient supply and low demand", and "abundant supply and low demand". Out of these, 32 units are located in the area with a shortage of supply, while 6 units are in the area with a significant imbalance of low supply and high demand. (4) The green space thermal environment regulation in Chengdu is categorized into four priority intervention levels: priority I, II, III, and IV zones. The priority IV zone, which has a high intervention priority level, consists of two units primarily located in the Inner Ring Qingyang, Inner Ring Jinjiang, Cuijiadian, Caotang, and Donghu, which are deemed crucial for needing prioritized regulation.

**Keywords:** urban thermal environment; green space; prioritization index; supply and demand; Chengdu

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## 1. Introduction

The combination of global climate change and increasing urbanization has worsened urban environmental problems and profoundly modified the composition and function of urban ecosystems [1–3]. The heightened urban heat island phenomenon has resulted in frequent occurrences of extreme weather conditions [4–6], increased intensity of land usage, and has negatively impacted the health and well-being of urban residents [7–9].

As near-natural biological spaces inside cities, urban green spaces (UGSs) are strategically important for raising living standards in a society growing more urbanized by the day [10–12]. They not only mitigate the urban heat island effect and offer social and psychological advantages but are also crucial for integrating urban growth with the urban ecological environment [13,14]. Urban environmental research places major emphasis on the influence and composition of ecosystem services provided by UGSs [15]. Ecosystem services serve as a conduit via which humans can obtain a wide range of advantages from the ecosystem. The association between ecological supply and societal demand relates to the production and utilization of these services [16–18]. At present, the supply and demand for environmental services play a crucial role in determining the progress of sustainable urban environmental development [19,20]. Effectively managing energy supply within the framework of sustainable ecosystem development reduces demand and ecological pressure, hence promoting urban ecosystem stability and mitigating the urban heat effect [21,22]. Moreover, multi-scale UGS studies can offer insights for future provincial and larger-scale UGS structural layout optimization, whereas study into the factors influencing UGS demand mostly focuses on environmental justice [23] or the scale of specific cities [24].

Several studies have examined the relationship between supply and demand for urban green spaces in regulating the thermal environment. These studies have found that changes in land use, impervious surfaces, and socio-ecological systems are strongly interconnected with the management of urban thermo-environmental conditions [25–27]. While Land Surface Temperature (LST) is commonly used to measure the risk of urban thermal environments [28,29], it is necessary to conduct more comprehensive studies that take into account socio-ecological systems and other aspects in order to effectively determine the actual human needs for mitigating thermal environments. Although research on urban thermal environment control has mostly focused on urban green spaces (UGSs), it has also acknowledged that Green Infrastructure (GI) plays a vital part in providing urban ecosystem services [30,31]. For meso–macro-scale analysis of the urban thermal environment, UGS is more significant than GI and is essential in minimizing urban thermal effects [32,33].

Presently, the integration of supply and demand has emerged as a popular subject in ecosystem service research [34]. Due to the intricate nature of urban environmental problems, the integration of ecosystem services' supply and demand has emerged as a significant advancement in tackling urban thermal environmental challenges [35]. Shen Sijian et al. conducted a study on the supply and demand of UGS for regulating the urban thermal environment. The researchers found that the assessment system for urban thermal environment management in UGS is constrained by data availability. They also identified geographical variations in the interaction between UGS and supply and demand. Measuring the amount of cooling effect's supply and demand can help analyze how this effect is distributed in space and is an essential requirement for reaching equilibrium in urban spaces [36]. Wilhelmi and Hayden's high-temperature vulnerability theory posits that urban thermal environmental risk is influenced by three primary factors: exposure, sensitivity, and adaptive capacity. These factors are driven by a mix of climate change and socio-economic development processes [37]. In addition, while allocating resources, it is important to take into account the requirements and preferences of various stakeholders. It should be emphasized that unequal distribution of environmental resources can result in substantial environmental and social injustice [38]. This paper examines the demand for thermal environment regulation services among urban residents and the capacity of urban green spaces to provide such services. It identifies areas where there is an imbalance between supply and demand and uses the Priority Ranking Index (PRI) to guide urban green space planning. The goal is to regulate the impact of urban green spaces on the thermal environment and improve the provision of urban ecosystem services.

## 2. Overview of the Study Area and Methodology

### *2.1. Overview of the Research Area*

Chengdu, located in the southwestern region of China, experiences a subtropical monsoon humid climate. The research area, which extends from coordinates 103°41′8.22″ E to 104°29′30.35″ E and 30°13′46.46″ N to 30°58′2.27″ N, includes the center portion of Chengdu City (as depicted in Figure 1) and has a total size of 3678 km$^2$. This accounts for around 25.87% of Chengdu's overall land area. The study region is strategically located between the eastern and western areas of Chengdu, serving as a crucial hub that connects these regions. It is bordered by Pengzhou, Dujiangyan, Suizhou, and Xinjin to the west, and Jintang and Jianyang to the east. The city consists of five primary urban districts—Jinjiang, Qingyang, Jinniu, Wuhou, and Chenghua—and six additional central urban districts, namely Xindu, Pidu, Wenjiang, Shuangliu, Longquanyi, and Qingbaijiang. In addition, the study area encompasses two directly administered districts: the Chengdu High-tech Zone and the Tianfu New District.

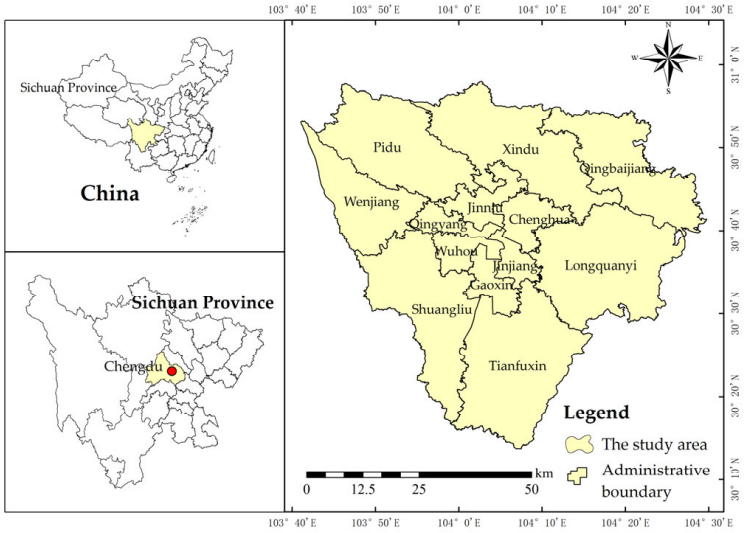



**Figure 1.** Overview of the study area.

### *2.2. Research Methods*

#### 2.2.1. Data Sources

(1) The Open Street Map website (https://www.openstreet-map.org/#map=3/36.96/104.17, accessed on 15 June 2022) provides data on the urban road network, which consists of highways, arterial, primary, secondary, and tertiary roads. The road network of each grade was consolidated using ArcMap 10.8 software. Topological errors between different road grades were manually rectified, and road line vectors were transformed into block face vectors using the line-to-face tool. This process resulted in the creation of the block parcel study unit.

(2) Remote sensing image data were obtained from the National Integrated Earth Observation Data Sharing Platform (China GEOSS-DSNET, https://chinageoss.cn/, accessed on 15 June 2022). The selected dates are from June to August 2022, with cloud cover less than 5%.

(3) Point of Interest (POI) data were predominantly gathered using the POI Kit crawler program (https://github.com/Civitasv/AMapPoi, accessed on 15 June 2022), which acquires data through the Geode map API interface. The accumulated POI data encompass 14 primary categories and 104 secondary categories. The data are sourced from Chengdu's 2022 POI data.

(4) The demographic information for this study was obtained from the seventh national census bulletin of Chengdu City and the population thermal spatial data from the Baidu LBS open platform (https://lbsyun.baidu.com/, accessed on 15 June 2022). The data collection

period spanned from 9 May 2022 to 13 May 2022, exclusively on weekdays. Averages were calculated at 10:00 a.m. and 10:00 p.m. every day. The data selection on weekdays captures the mean population level, while the inclusion of morning and evening times ensures a comprehensive representation of population distribution throughout the day.

#### 2.2.2. Evaluation System for Regulating Supply and Demand in Green Space Thermal Environments

The fundamental cause for urban thermo-environmental risk is the discrepancy between the urban population's need for thermo-environmental management and the limited availability of such regulation [39]. Examining this matter via the lens of ecosystem service supply and demand offers a valuable approach to connecting natural ecosystems with socio-economic systems [40]. This study introduces a method for evaluating the balance between the supply and demand of thermal environment regulation in urban green spaces. The system is designed based on the high-temperature vulnerability framework, as depicted in Figure 2. The system is comprised of three primary stages: ① Inversing the urban surface temperature: Through the utilization of the high-temperature vulnerability analysis framework, we constructed a model to assess the level of regulation demand for urban green spaces. This model takes into account three key dimensions: exposure, sensitivity, and adaptability. This model comprises five indicators: grid heat island temperature, grid heat island area, population density, elderly population density, and POI density. ② Green space ratio and normalized surface temperature are used as parameters in our model to assess the capacity of urban green spaces to provide regulation services. ③ Supply–demand matching and quadrating: This step involves the identification of crucial areas where there is an imbalance between supply and demand. It then determines the level of intervention required, taking into account a prioritization index.

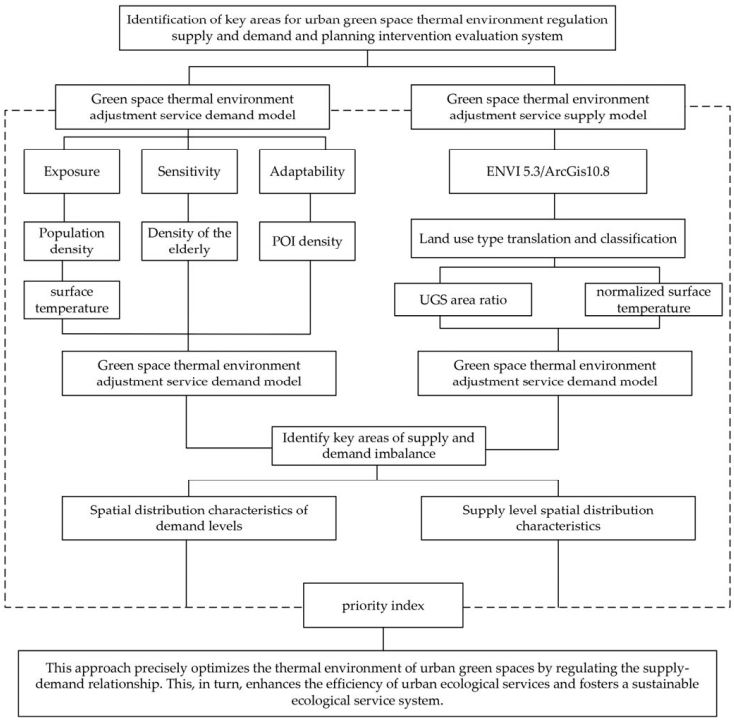



**Figure 2.** Evaluation index system for supply and demand of urban green space thermal environment regulation.

Grid plans are widely used in urban development, planning, and management. According to Hong Ge et al. (2023) [41], the average size of a planning unit in central Chengdu is approximately 25 km$^2$, and therefore, a 5 km × 5 km grid size is deemed optimal for our

purpose. Analyzing green spaces' supply and demand at the local level enhances the accuracy and practicality of research findings, making them more applicable to many contexts.

2.2.3. Modeling Thermal Environmental Regulation Demands of Green Spaces

The urban thermal environment is influenced by multiple factors, where urban green spaces play a pivotal role. The demand of urban residents for thermal environment regulation is an important concern. This study utilizes the idea of heat vulnerability as established by Wilhelmi and Hayden [42]. The framework consists of three dimensions: exposure, sensitivity, and adaptive capacity. Exposure, in this sense, refers to the frequency of high temperatures in urban areas. It is caused by a combination of hot weather conditions and the heat island effect and is influenced by population size and distribution. Sensitivity encompasses various factors, including socio-economic and socio-cultural dimensions, community-level impacts, and individual characteristics such as age and health status. Conversely, adaptability refers to the intrinsic capacity of communities to effectively manage and mitigate risks by using social capitals and lowering vulnerability. The combination of these three variables determines the level of heat vulnerability in urban areas and hence the demand for green spaces for thermal environment regulation.

This study carefully chose and standardized parameters such as population density (Pop), the percentage of the population over 65 years of age (Pos), the number of street or community hospitals (Hn), and the average surface temperature at the community level (T) to create indices that measure heat exposure, sensitivity, and adaptability. The process is outlined in a comprehensive manner as follows:

(1) The Heat Exposure Index ($E_i$) is calculated on the premise that areas with higher population densities and temperatures experience greater heat exposure, hence:

$$E_i = P_{op} \times T \tag{1}$$

(2) The Heat Sensitivity Index ($S_i$) focuses on the proportion of the elderly population typically more susceptible to heat. A higher percentage of the elderly indicates increased sensitivity to heat extremes and a greater likelihood of heat-related damages. It posits that, given similar exposure conditions, areas with a larger share of elderly residents face amplified risks during heatwaves. The risk is worsened by the increased susceptibility of elders and the burden on medical services caused by a sudden surge in demand, which could potentially compromise the timely care delivery:

$$S_i = P_{os} \tag{2}$$

(3) The Heat Adaptability Index ($A_i$) assesses the neighborhood's capacity to respond to heat events by enumerating healthcare facilities, adjusted by type-specific weight coefficients based on their ability to handle heat emergencies [43], excluding non-treatment facilities such as pet hospitals and medical examination centers. The weights are calibrated to reflect the emergency response and treatment capacity of different healthcare providers:

$$A_i = H_n \tag{3}$$

(4) The demand index for green space regulation is derived from the weighted sums of the $E_i$, $S_i$, and $A_i$ indices using the entropy weight method. After normalization, the data are inputted into the SPSS platform to assign appropriate weights. The green space regulation demand index is computed as follows:

$$H_i = P_E \times E_i + P_S \times S_i + P_A \times A_i \tag{4}$$

where $P_{op}$ represents population density; $T$ represents average surface temperature (°C); $P_{os}$ represents the percentage of the population over 65 years of age; $H_n$ represents the number of local or community hospitals; $P_E$ denotes the heat exposure's weight; $P_A$ denotes the heat adaptability weight; and, $P_S$ denotes the heat sensitivity weight. It is

important to note that while $E_i$ and $S_i$ serve as positive indicators—with higher values denoting increased demand—$A_i$ functions inversely, where greater values indicate reduced demand. This relationship is accounted for with an exponential decay function $y = e^{-0.02x}$ during the computations (as shown in Table 1).

**Table 1.** Weight parameters of entropy method.

| Index Unit | Information Entropy Value | Information Utility Value | Weight Coefficient |
|---|---|---|---|
| $E_i$ | 0.8729 | 0.1271 | 0.447 |
| $S_i$ | 0.9498 | 0.0502 | 0.177 |
| $A_i$ | 0.8929 | 0.1071 | 0.376 |

#### 2.2.4. The Model for the Thermal Environment Regulation Supply of Green Spaces

The evaluation index system for regulating the thermal environment of urban green spaces' supply and demand takes into account the attributes of Chengdu's urban green spaces and their significant influencing factors. It highlights the importance of the green space area and the normalized surface temperature as key indicators for regulating the supply level. The percentage of green space (*AR*) and its related normalized surface temperature (*NLST*) were computed for each of the 185 grid cells in the research region. The supply capacity model for urban green space regulation is based on these parameters, which are represented as follows:

$$H_s = \frac{AR}{A_u} \times \frac{1}{NLST} \tag{5}$$

where $H_s$ signifies the urban green space regulation supply index; *AR* denotes the area of green space within a grid cell; $A_u$ represents the total area of the grid cell; and *NLST* is the normalized surface temperature within the grid. A larger *AR* to $A_u$ ratio indicates a higher proportion of green space, whereas a higher *NLST* suggests increased average surface temperatures. Collectively, a larger $H_s$ value signals a more pronounced cooling effect and a robust supply capacity for urban green space regulation [44].

#### 2.2.5. Matching Supply and Demand for Green Space Thermal Environments and Quadrating

The matching of supply and demand for urban green space in controlling thermal environments establishes a fundamental structure for identifying optimization targets within urban green spaces. This framework employs standardized metrics, where the x-axis represents the standardized supply capacity of urban green spaces' regulations, and the y-axis represents the standardized demand capacity of urban green spaces' regulations. The formula used for calculating the Z-score is as follows [1]:

$$X = \frac{X_i - \overline{X}}{S} \tag{6}$$

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{7}$$

$$S = \sqrt{\sum_{i=1}^{n}(x - \overline{x})^2} \tag{8}$$

$x$ represents the composite supply index and demand index of thermal environmental regulation of green space after standardization of grid cells; $X_i$ represents the composite supply index and demand index of thermal environmental regulation of green space for a specific grid cell; $\overline{x}$ is the mean value of the entire study area; $s$ is the standard deviation of the entire study area; and n is the total number of grid cells.

The supply and demand levels of the treated green space thermal environment were divided into quadrants, with the x-axis denoting the standardized thermal environment regulation supply capacity and the y-axis denoting the standardized thermal environment regulation demand level, which constitute four quadrants. The first quadrant represents the **high supply–low demand** region, the second quadrant represents the **low supply–high demand** region, the third quadrant represents the **low supply–low demand** region, and the fourth quadrant represents the **high supply–low demand** region.

#### 2.2.6. Priority Index

The prioritization of interventions for regulating the thermal environment in urban green spaces is of great significance for further planning and implementation. In this study, we refer to Maragno [45] to construct a priority index (*PRI*) to further prioritize the identified "oversupply" neighborhood units. The calculation formula is as follows:

$$PRI = \frac{(T_h) \times (A_h) \times (D_r) \times (D_e) \times (F_x)}{H_s} \quad (9)$$

Here, $T_h$ represents the average temperature of the grid, $A_h$ denotes the area affected by the urban heat island, $D_r$ is the population density; $F_x$ is the density of Points of Interest (POI) within the grid; $D_e$ reflects the density of the elderly population; and $H_s$ is the supply capacity of urban green space for thermal regulation. A higher *PRI* indicates increased average temperatures and urban heat island effect, more active population, a larger proportion of elderly individuals, greater POI density, and diminished urban green space regulatory effectiveness. This suggests that grids with higher *PRI* values require more urgent and optimized regulatory interventions.

## 3. Results

### *3.1. Demand for Green Space Regulation's Spatial Distribution*

#### 3.1.1. Spatial Distribution of Heat Exposure

The Heat Exposure Index ($E_i$) (0.00–1.00) for Chengdu is influenced by both population density and surface temperature inversion (see Figure 3a). The spatial distribution of Chengdu's Heat Exposure Index ($E_i$) closely mirrors its population density pattern. High-value $E_i$ areas ($E_i > 0.58$), indicating greater thermal exposure include the Qingyang District, Jinjiang District, and the East Station area in Chenghua District, in total account for 3.78% of the metropolitan area. By contrast, low-value $E_i$ zones ($E_i < 0.06$) are primarily located outside the Fifth Ring, representing 57.30% of the area. This indicates that Chengdu's inner city experiences high population density, elevated surface temperatures, and significant urban heat exposure, with heat exposure decreasing outward from the Third Ring.

Chengdu's population density has a tendency of being higher in the center and lower in the outskirts (see Figure 3b). High-density areas (Dr > 13,744 persons/km$^2$), accounting for 4.32% of the city's area, mainly include Qingyang District and Jinjiang District within the inner ring, the East Railway Station area in Chenghua District, and the North Railway Station area in Jinniu District. Conversely, low-density areas (Dr < 1433 persons/km$^2$) are mostly found beyond the Fifth Ring, accounting for 57.84% of the area.

Surface temperature inversion results reveal that Chengdu's surface temperatures range from 41.10 °C to 46.58 °C, with an average of 44 °C (see Figure 3c) The distribution of surface temperatures is characterized by lower temperatures in the north and south and higher temperatures in the central region. Areas with high surface temperatures ($T > 45.15$ °C) are predominantly located within the Third Ring and in Qingbaijiang City, while low-temperature areas ($T < 42.48$ °C), such as Xindu and the outskirts of Jintang, cover 8.65% of the total area.

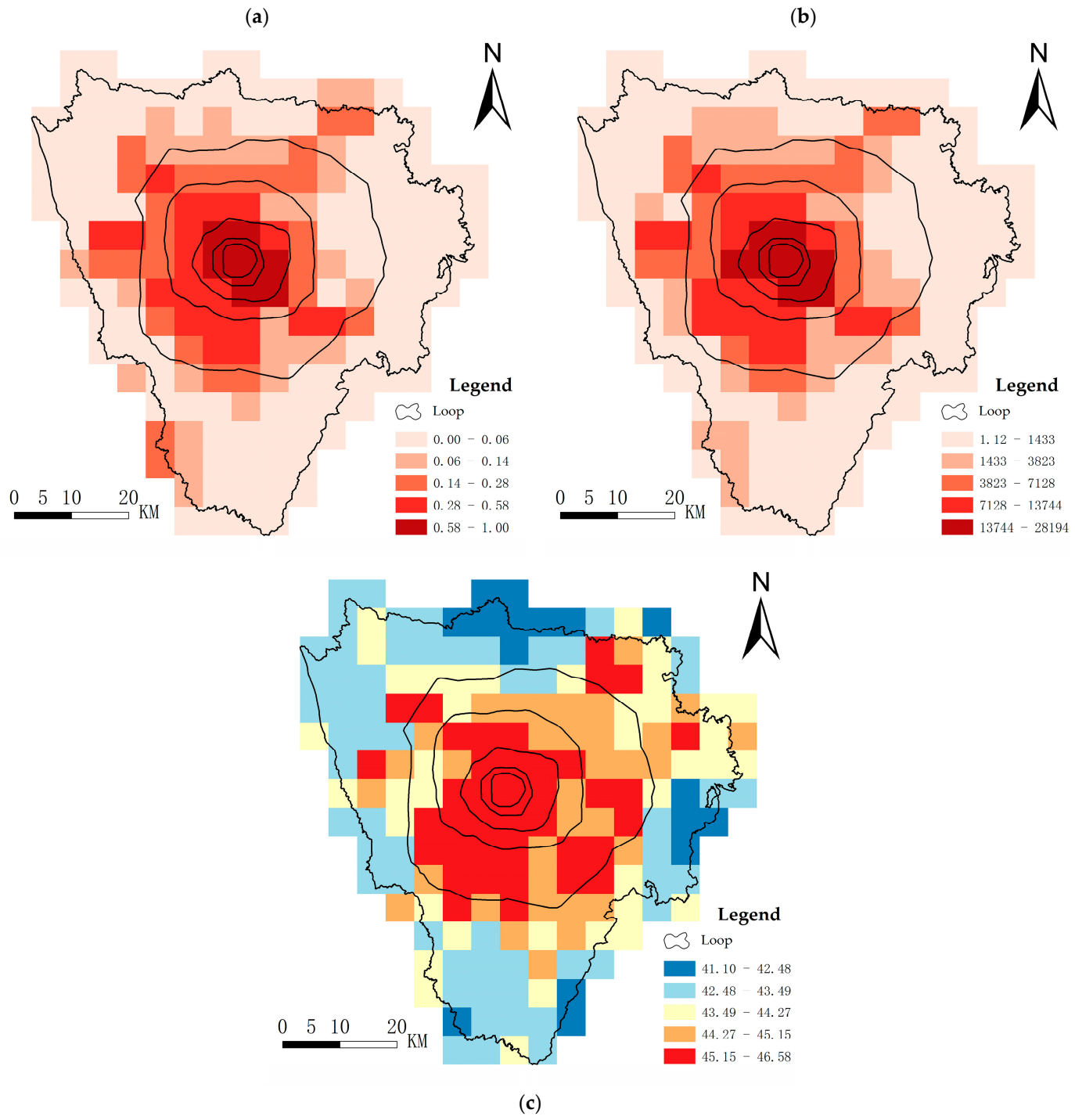



**Figure 3.** (**a**) Heat exposure distribution pattern; (**b**) Population density distribution pattern; (**c**) Surface temperature distribution pattern.

#### 3.1.2. Spatial Distribution of Thermal Sensitivity

The thermal sensitivity ($S_i$) (0.00–1.00) results reveal that the distribution of Chengdu's elderly population is predominantly concentrated in the city center and dispersed around the outskirts (see Figure 4). Areas with high thermal sensitivity values ($S_i > 0.36$), accounting for about 3.78% of the region, include the Qingyang District within the inner ring, Jinjiang District within the inner ring, and the East Railway Station area in Chenghua District. By contrast, areas with low thermal sensitivity ($S_i < 0.05$), mainly located in the eastern and northwestern parts of Chengdu, comprise approximately 58.38% of the area.

This pattern underscores that urban thermal sensitivity is elevated in central Chengdu and diminished in its eastern and northwestern sectors.

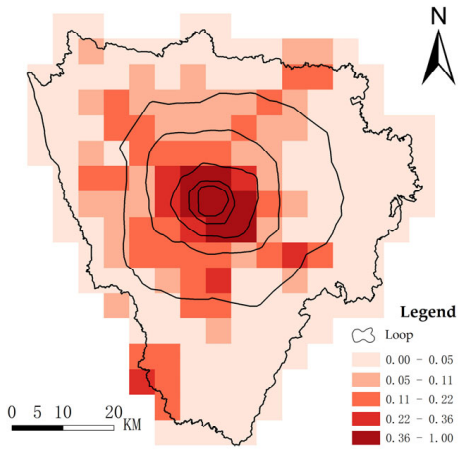



**Figure 4.** Thermal sensitivity distribution pattern.

### 3.1.3. Spatial Distribution of Thermal Adaptation

The examination of thermal acclimatization demonstrates a spatial pattern that is defined by higher temperatures in the eastern region and lower temperatures in the central region, as shown in Figure 5. Approximately 23.78% of the area has high thermal acclimation indices ($A_i$ > 0.85) (0.00–1.00). These regions include the Western Forest Park in Longquanyi District, Tianfu New District, Qingbaijiang Old Town, and the outskirts of Dujiangyan. By contrast, regions with low indices ($A_i$ < 0.11), accounting for 17.30% of the total area, include Fenghuang Mountain and the Botanical Gardens in Jinniu District, Xinchuan in Shuangliu District, Jiang'an, and Dameian in Tianfu New District. A higher thermal adaptation index implies a scarcity and inferiority of medical facilities, whereas a lower index indicates a larger abundance and superiority of medical institutions. This suggests that the outskirts of Chengdu City have a lesser number of medical facilities of lower quality, indicating a lack of ability to effectively respond to thermal environmental conditions.

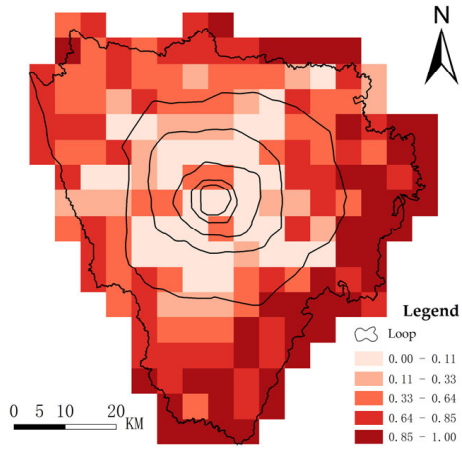



**Figure 5.** Thermal adaptability distribution pattern.

### 3.1.4. Distribution of Demand Level for Green Space Regulation

The green space regulation demand index Hi, ranging from 0.06 to 0.83, indicates that the need for green space regulation in Chengdu follows a spatial pattern characterized by "regional diffusion and local concentration" (Figure 6). The areas experiencing significant demand ($H_i$ > 0.40) are mostly situated in the Qingyang District, Jinjiang District, and the East Railway Station area in Chenghua District, collectively making up around 3.24% of

the area. Conversely, regions with a low demand ($H_i$ < 0.13) are more evenly spread out, constituting 15.68% of the total area. The distribution of these data suggests that there is a widespread demand for regulation of green spaces in Chengdu.

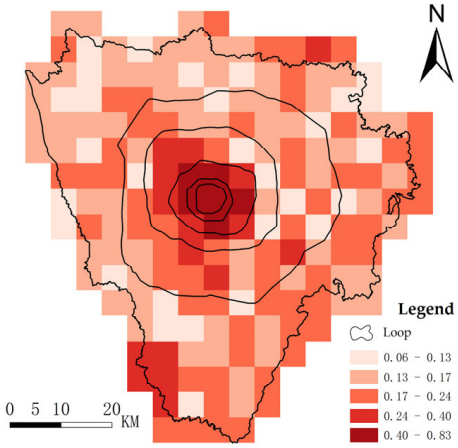



**Figure 6.** Distribution pattern of green space regulation demand level.

### *3.2. Spatial Distribution of Green Space Regulation Supply Level*

The Green Space Regulation Supply Index (Hs) in Chengdu City ranges from 0.07 to 1.00, indicating that the spatial distribution of green space's regulatory supply capacity mirrors the distribution of green space area (Figure 7c). Areas with elevated index values ($H_s$ > 0.69) encompass the Western Longquanshan Forest Park in Longquanyi District, the northern section of Xindu District, as well as the outskirts of Pixian and Wenjiang. These regions collectively make up 18.38% of the city's total area. By contrast, the low index value zones ($H_s$ < 0.22), such as Qingyang District, Jinjiang District, the East Railway Station in Chenghua District, Dameian in Tianfu New District, and Financial City in Wuhou District, account for 22.16% of the total area. The trend observed suggests that Chengdu's eastern and northern green spaces have a strong regulatory supply capacity, whereas the central areas have a weaker capacity.

Analysis of the Green Space Area (*AR*) indicates a gradual reduction in green spaces in Chengdu from the southeast and northwest towards the center, as shown in Figure 7b. The regions with the most extensive green spaces (*AR* > 87.12%) encompass locations such as Longquanshan Forest Park in Longquanyi District, Tianfu New District, and the suburbs of Dujiangyan, collectively accounting for 15.68% of the city's area. Conversely, the districts within the city's third ring, including the Qingbaijiang urban area, Wenjiang urban area, and Dameian in Tianfu New District, have the smallest green space (*AR* < 45.43%), indicating the scarcity of green spaces in central Chengdu.

The *NLST* findings reveal a spatial pattern characterized by lower temperatures in the northern and southern areas, and higher temperatures in the central region of Chengdu (as shown in Figure 7c). The high-value zones (*NLST* > 0.58) cover 23.78% of the city. These areas are mainly situated within the fifth ring, encompassing the Qingbaijiang old city in the north, the Science City in Tianfu New District, and the areas near the ecological belt in Jinjiang District. Conversely, the regions of low values (*NLST* < 0.43), which make up 8.65% of the city, are located in Longquanshan Forest Park in Longquanyi District, Tianfu New District, and the northern part of Xindu District. The data suggest that the core five-ring circle has elevated surface temperatures, whilst the cooler areas are located in the northern and southern suburbs of the city.

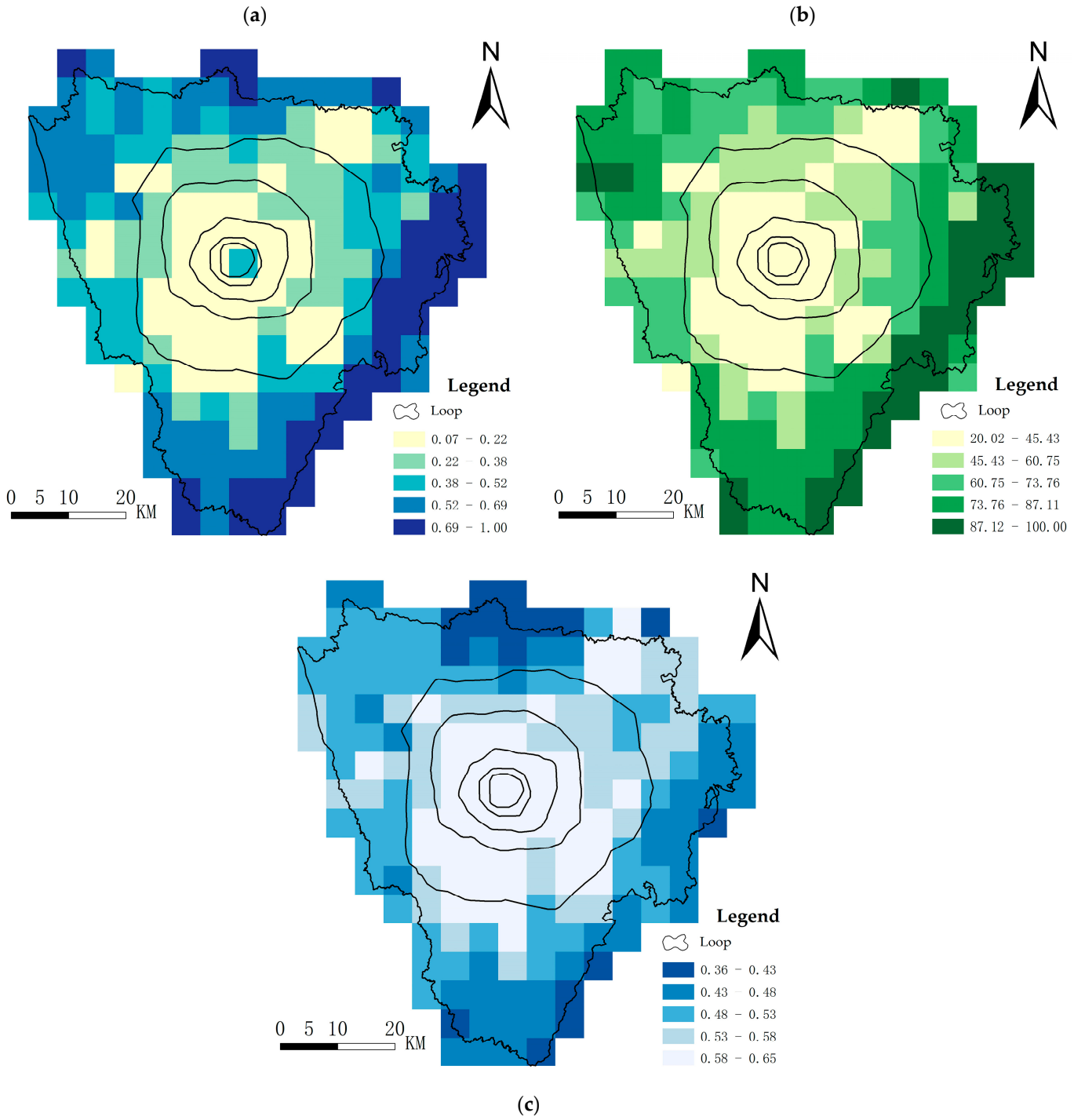
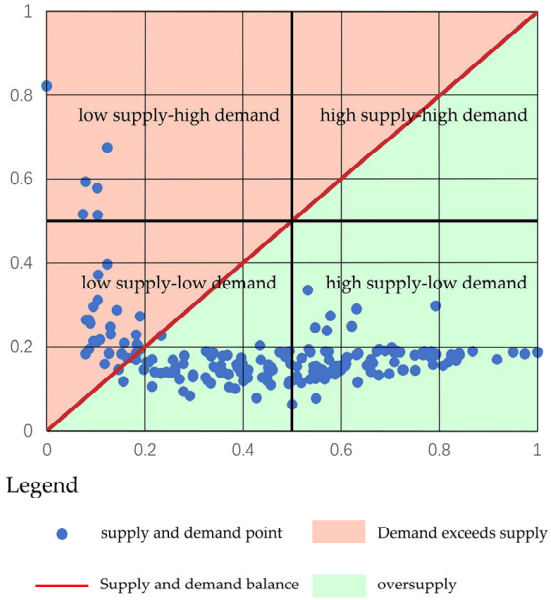



**Figure 7.** (**a**) Distribution pattern of green space regulatory supply level; (**b**) Green space area distribution pattern; (**c**) Normalized surface temperature distribution pattern.

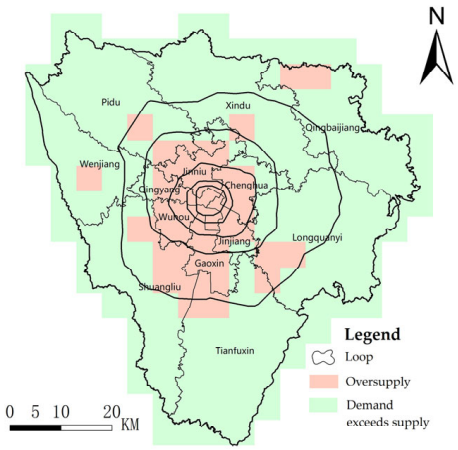
### *3.3. Green Space Regulation Supply and Demand Key Areas*

The Z-score standardized approach is utilized to determine the urban green space regulation supply and demand index, which identifies crucial zones in Chengdu. Based on the results (Figure 8a), 32 out of 185 grid cells are located in places with an excess supply and insufficient demand (Quadrants II and III), making up 17.30% of the total. The areas affected by this issue include Qingyang District, Jinjiang District, and the Cuijiadian area in Chenghua District. All of these areas are currently facing a shortage of green spaces, which needs to be addressed by specific optimization measures. By contrast, 153 grid

cells, which make up 82.70% of the total, are located in places with an excess supply (Quadrants III and IV). The main locations of these areas include Longquanshan Forest Park in Longquanyi District, Tianfu New District, the northern part of Xindu District, and the suburbs of Dujiangyan. These places have a strong capacity to provide a steady supply and are essential for preserving the city's thermal environment balance, emphasizing their importance and the necessity of their preservation (Figure 8b).




(**a**)




(**b**)

**Figure 8.** (**a**) Supply and demand matching and quadrant division; (**b**) Distribution pattern of green space supply and demand.

### *3.4. Prioritization of Green Space Regulation Interventions*

Chengdu City has utilized the Priority Ranking Index (*PRI*) and superposition analysis of supply and demand quadrant levels to effectively prioritize initiatives for improving the thermal environment. The findings, illustrated in Figure 9a, demonstrate a clear variation in the allocation of priority for urban green space interventions across the city.

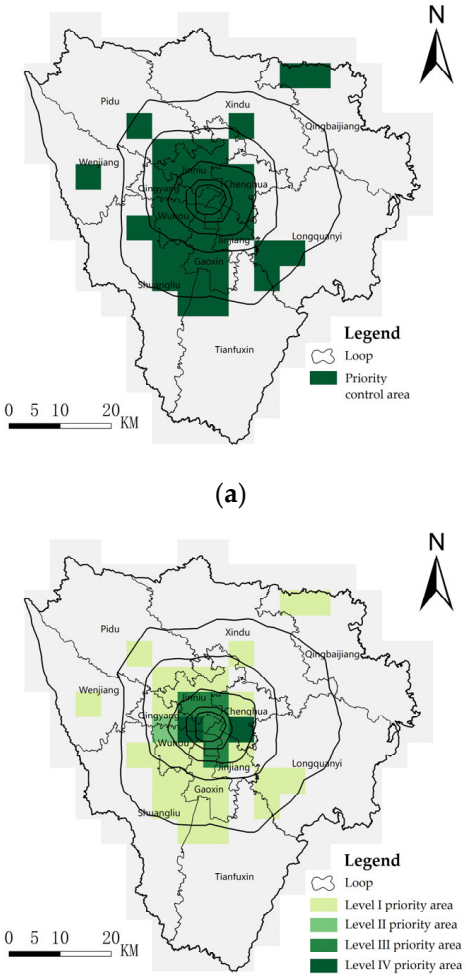



**Figure 9.** (**a**) Areas where supply exceeds demand to optimize and regulate; (**b**) Prioritization of green space regulation services.

The areas classified as Level I and Level II, which signify a lower level of urgency for intervention, mainly surround the city beyond the third ring road. Prominent places encompass Phoenix Mountain in Jinniu District, Taiping Temple in Wuhou District, Qingbaijiang District, the airport industrial park and South Lake in Shuangliu District, among others. These areas have a generally equal supply and demand of green spaces, requiring only suitable conservation measures. In contrast, Level III and Level IV areas, which necessitate immediate attention due to a significant disparity between the supply and demand of green spaces, are mainly located in the inner rings of Qingyang and Jinjiang. These areas also extend to Cuijadian, Caotang, and Donghu. Figure 9b identifies these specific areas as the focus of regulatory initiatives aimed at addressing mismatch and improving urban livability.

## 4. Discussion

Assessing the balance between both the demand and supply of green spaces and illustrating their spatiotemporal variations have been the main objectives of this research. By doing so, we have provided guidance and direction for urban green space planning and management.

### *4.1. Indicators for Thermal Environment Regulation of Green Spaces*

Thermal environment evaluation of urban human settlements involves an exhaustive list of factors including climate, social economy, urban land use, population demographics, among others. In most cases [46,47], researchers have solely focused on evaluating urban green spaces' demand by incorporating diversified indicators from social, economic, and ecological disciplines. However, there is a paucity of research on the supply side of green spaces. This study aims to combine the demand and supply aspects of green spaces to construct a thermal environment regulation evaluation system suitable for urban settings, replacing the problems of using a single or limited number of evaluation indicators in classical research. Chengdu's urban thermal condition is greatly influenced by the distribution of green spaces and population dynamics. In urban areas with high population density, inadequate green spaces hinder the efficient distribution of resources. Accordingly, the units classified as "insufficient supply and high demand" were divided into four priority intervention levels using the natural breakpoint technique, which combines the supply–demand relationship with the priority index. This approach specifically targets the areas where there is a mismatch between the supply and demand of green spaces. In this manner, the relevant departments can prioritize areas based on their deficiency level.

### *4.2. Characteristics of Green Space Regulation Areas*

The green space regulation demand index Hi indicates that green space regulation demand in Chengdu follows a "regional diffusion and local concentration" spatial pattern. The overall demand index for managing the urban thermal environment follows a similar spatial pattern as heat exposure and heat sensitivity, with high-demand zones clustering in the city's central area. Regions characterized by abundant supply are predominantly situated in sparsely populated areas, including the western section of Longquanyi District, Tianfu New District, and the outskirts of Dujiangyan. Conversely, districts located within the third ring road and heavily populated areas such as Qingbaijiang District exhibit a low supply capacity for green spaces. It has been reported that in urban central districts, concentrated development leads to the consumption of land resources, dense population, and industrial activities which could deprive the region of its green spaces [48,49]. In contrast, the outskirts of cities enjoy more green spaces, which need merely to be conserved. In specific functional areas such as airports and high-speed railway stations, intervention opportunities are limited, which aligns with the findings of this study. The ratio of green spaces to surface temperature is the primary factor influencing the uneven distribution of thermal environment regulation in Chengdu. To ensure the balance between green spaces' supply and demand, it is necessary to consider reducing the inequality in supply levels in central urban districts. In light of this, different areas could be classified from I to IV based on their priority level. In this manner, the areas with the highest priority level (IV) were found to be located in strategic positions such as Caotang in Qingyang District, Cuijiadian in Chenghua District, and Donghu in Jinjiang District. These regions displayed significant disparities in supply and demand levels and therefore require immediate optimization and management. This can be achieved by increasing the per capita green space area through measures such as vertical greening and green infrastructure, which could improve thermal environment conditions in Chengdu's central sections.

### *4.3. Limitations of the Study*

Urban green spaces regulate the thermal climate, but different indicators may yield different outcomes. The pertinent indicators in this study are influenced by multiple factors, including residents' income, cultural preferences, and occupation, which could potentially impact the demand of urban inhabitants for thermal environment regulation. This study considered only the proportion of urban green space area and did not take into account indicators such as the quality and usage rate of green spaces. This might have led to an incomplete understanding of the mechanisms by which urban green spaces regulate the thermal environment. In order to accurately analyze the supply–demand balance of green

spaces and their potential in regulating the thermal environment in urban settings, it is necessary to consider the thermal environment regulation factors of each administrative unit and study how their location, type, function, and potential impact the urban thermal environment [50,51]. This study considered a grid of 185 units, which makes it difficult to analyze finer landscape features. Additionally, studying landscape patterns can help explain the thermal environment regulation function. By utilizing landscape geometry and distribution patterns, the optimal layout of urban green spaces can be identified. The evaluation system used in this paper mainly focuses on urban and district-county scales, and hence fails to differentiate supply demand levels under otherwise diverse urban settings. However, it is recommended to refine the scale of assessments to the block level in future investigations to accommodate more accurate multi-source data sets (such as heat-related medical and health data, small-scale social survey data, etc.) to improve the results applicability.

## 5. Conclusions

Supply and demand balance in urban green spaces serves as a vital metric for evaluating urban ecological development and the well-being of its residents. This study, based on the heat vulnerability analysis and latest scientific findings, established a framework for assessing thermal environment regulation by urban green spaces. For this purpose, a grid of 185 units was established. Along with analyzing demand and supply levels, the Z-score method and the priority index were utilized to evaluate their balance and identify intervention priority levels. Assessing the balance between both the demand and supply of green spaces and illustrating their spatiotemporal variations have enabled us to provide guidance for urban green space planning and management. As far as the demand for thermal environment regulation in Chengdu is concerned, it is driven by heat exposure, heat sensitivity, and heat adaptability. High-demand areas are mainly distributed in Qingyang District, Jinjiang District, and Chenghua District, where the pressure from thermal environmental stress is significantly high. As for the supply condition, there is a scarcity of high-supply areas. Given that high-supply districts such as Longquanyi District and Tianfu New Area are located on the outskirts of the Chengdu metropolitan area, we reached the conclusion that intense human activities are the main culprit for lower green space regulatory services inside the city. Regarding the supply–demand balance, 32 units (17.30%) were found to have supply shortage. This imbalance, which directly impacts the urban ecosystem, is mainly found in the central parts of Chengdu City. However, we believe that Chengdu enjoys a suitable supply–demand situation given the negligible number of units suffering an imbalance between supply and demand of green spaces' regulatory services. In total, only two level four priority areas were identified requiring urgent intervention. These priority areas must be given special treatment in green space development, planning, and management when boosting urban well-being.

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