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Cooling effect and cooling accessibility of urban parks during hot summers in China's largest sustainability experiment

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ABSTRACT

The rapid urbanization process has given rise to urban heating problem and social stratification, prompting calls to evaluate and improve the quality and equity of parks' cooling service. Our study quantified cooling effect of 1,337 parks from both maximum and accumulation perspectives and investigated cooling accessibility through network analysis in 26 cities of Yangtze River Economic Belt (YREB), China's largest sustainability experiment. 1,189 (88.93%) parks showed significant cooling effect. On average, per park cooled down 2.34 ± 0.07 °C and 40.34 ± 1.17 ha, which was more than four times park area. The accumulative cooling intensity and gradient averaged at 108.55 ± 3.15 °C • m and 0.64 ± 0.02 °C, respectively. Our study also uncovered inequity in cooling accessibility in hot summers, as about 40.3% residents could not access to parks' cooling service within 30-min walk. Suburban residents had more difficulty accessing to parks' cooling services. This study can guide greater planning and design of parks to move toward a more equitable and livable direction across different urbanization hierarchy cities.

1. Introduction

The rapid urbanization has led to a population boom in urbanized area, i.e., 55% of the world population lived in cities in 2018, and the total urban population is expected to reach 68% by 2050 (Nations, 2019). The corresponding dramatic urban land expansion and increase in energy consumption were accompanied by significant climatic and environmental changes, one of which is urban heating issue (Ali et al., 2021; Ouyang et al., 2020). The urban heating directly or indirectly influences human thermal comfort and air quality, threatens physical and mental health. Heat-related morbidity and mortality have increased (Cao et al., 2016; Peng et al., 2018). To address these challenges, urban parks, the most common combination of blue and green infrastructures in cities, are suggested as a sustainable and affordable solution for urban heat mitigation (Imran et al., 2018; Kim et al., 2019; Zhang et al., 2022). However, the scarcity of urban land resources has limited the spatial allocation of urban parks (Gao et al., 2022). How to improve cities' thermal environment through exquisite park planning and design within limited urban space is a topic worth investigating for sustainable development and urban governance (Li et al., 2020).

Many studies have investigated cooling effect of parks and its main potential factors (Brown et al., 2018; Yan et al., 2018). Parks' cooling effect has been quantified using several indicators from maximum perspective and accumulative perspective. (Aram et al., 2019; Chang et al., 2007; Chen et al., 2020). Cooling indicators from maximum perspective include local cooling intensity (temperature difference between the internal park and its surroundings), maximum cooling distance and maximum cooling area (Cheng et al., 2015; Yu et al., 2017). Peng et al. (2021a) proposed park cooling intensity (PCI) and park cooling gradient (PCG) from accumulative perspective, which considered spatial continuity of parks' cooling effect. The cooling effect of a park is related to the complex interactions among factors inside and outside the park (Du et al., 2022; Yao et al., 2022). Studies have shown that park size, shape, connectivity, vegetation growth, and the proportion of water area play important roles in parks' cooling effect (Kim et al., 2019; Kuang et al., 2015; Yang et al., 2020). In order to obtain the economical cooling function, it is necessary to identify the park cooling threshold area (Yu et al., 2020). Chang et al. (2007) showed that the park threshold area in Taipei was 3 ha. And 1.08 ha was determined as the threshold area in Fuzhou (Yao et al., 2022). However, most existing studies focused on only one individual city (Chen et al., 2022; Peng et al., 2021a). Exploration for parks' cooling effect across different levels of urbanization are still needed (Gao et al., 2022).

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Nomenclature

Cwa	Köppen's subtropical monsoon humid climate
Cfa	Köppen's subtropical humid climate
LSI	Landscape Shape Index
LST	Land Surface Temperature
NDVI	Normalized Difference Vegetation Index
PCA	Park's Cooling Area
PCE	Park's Cooling Efficiency
PCI	Park's Cooling Intensity
PCG	Park's Cooling Gradient
YREB	Yangtze River Economic Belt

Furthermore, the rapid urbanization process has given rise to social stratification and inequalities, one of which is related to parks' service accessibility (Lan et al., 2022; Liang & Zhang, 2018). With the intense urban warming in summer, there is an urgent need for urban residents to improve their thermal comfort via enjoying the parks' cooling service (Nayak et al., 2019; Wang et al., 2019). There is growing evidence of positive correlation between parks' service accessibility (including cooling accessibility) and health, which has prompted calls to evaluate and improve the quality and equity of parks' service (Brown et al., 2018; Rigolon, 2016; Zhou & Kim, 2013). However, few studies have focused on urban parks' cooling access provided for different residents, especially in cross-province sustainability experimental zones (Chen et al., 2022).

Both scale and speed of China's overall urbanization process are unprecedented (Li et al., 2020). The Yangtze River Economic Belt (YREB) is China's largest sustainability experiment, faced with pronounced urban warming in summer. Due to the differences in natural resources and economic development patterns, YREB covers cities across different urban hierarchy levels (Luo et al., 2020). YREB provides vivid and distinct "natural laboratories" for climate mitigation with different urban hierarchy levels for comparative studies (Shi & Ye, 2021).

This study collated 1337 urban parks in 26 cities from different urbanization hierarchy levels in YREB. We aim to: (1) quantify cooling effect of 1337 urban parks across urbanization hierarchy levels; (2) compare different parks bundles' cooling dominance catering for specific cooling demands; (3) reveal the main factors of parks' cooling effect for cities across different urbanization hierarchy levels; and (4) assess spatial equity of parks cooling services at regional scale.

2. Materials and methods

2.1. Study area

The YREB spans the middle of China from east to west, covering 21.4% of the country's territory (Peng et al., 2021b). According to the Köppen-Geiger climate classification, the study area is dominated by subtropical monsoon humid climate (Cwa) and subtropical humid climate (Cfa) (Peel et al., 2007). Based on population data (the China Statistical Yearbook, https://data.cnki.net/), the 26 cities in this study were clustered as four megacities (ten million or more residents), nine large cities (five-ten million residents), and thirteen medium-sized cities (one-five million residents) (Fig. 1). Seven of them (Chongqing, Hangzhou, Nanchang, Changsha, Wuhan, Nanjing, and Hefei) were rated as "the Top Ten Furnace Cities" by the National Climate Center of the China

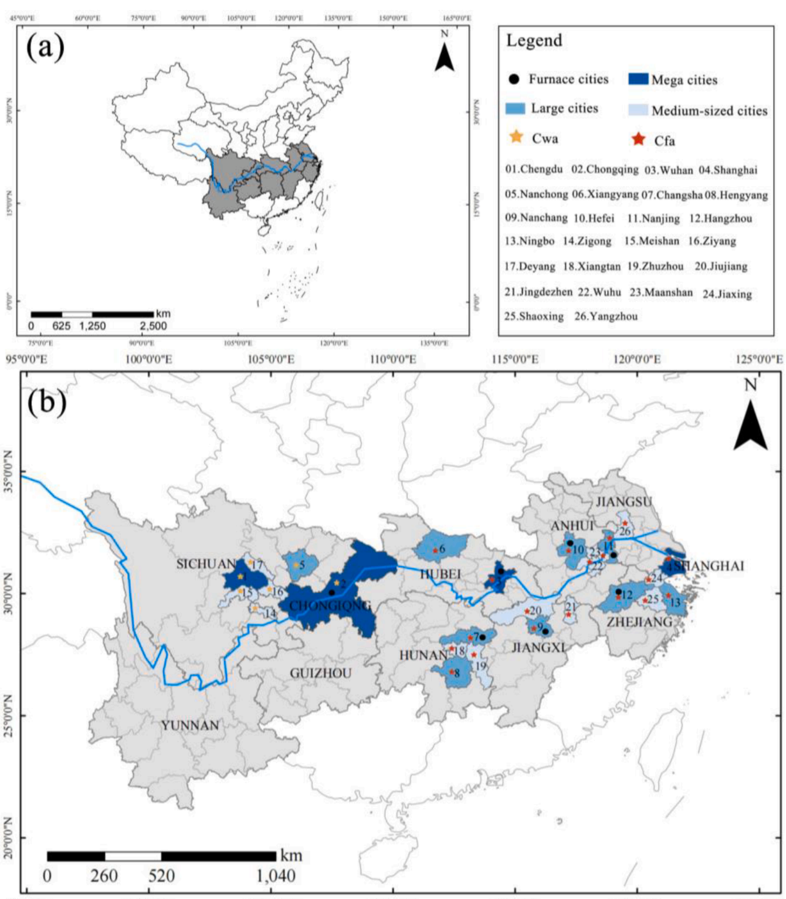

Fig. 1. (a) The location of YREB in China; (b) the selected 26 cities in the YREB across different urbanization hierarchy levels.

Meteorological Administration, according to a comprehensive analysis of historical meteorological data during year of 1981–2010 (https://www.cma.gov.cn/).

Overall, 1337 urban parks in 26 cities were collated, whose boundaries were mapped using ArcGIS 10.2 software based on AutoNavi map. There are 555 parks distributed in megacities, 474 in large cities and 308 in medium-sized cities. According to the China Standard for Classification of Urban Green Space (CJJ/T 85–2017), these urban parks are classified as 268 comprehensive parks, 256 ecological parks, 369 neighborhood parks, and 444 theme parks. Comprehensive parks are generally larger than 10 ha and have comprehensive functions catering to different groups of people. Ecological parks provide natural landscapes, aiming at nature protection. Neighborhood parks are less than 10 ha, usually serving for the surrounding inhabitants. Theme parks have specialized themes like recreation or cultural education.

2.2. Quantification of cooling effect from both maximum and accumulative perspectives

The weather in the YREB was hot from June to September. Landsat 8 TIRS satellite images (https://glovis.usgs.gov/) with little cloud during hot days in 2019 were used to retrieve the land surface temperature (LST). YREB covers large area with frequent high cloud cover due to humid climate. For regions with invalid images in 2019, we used images two years preceding or following to fill up (Table S1). The split-window algorithm was used to retrieve LST (Eq. (1)). The accuracy was better than 1.0 K (Du et al., 2015; Ren et al., 2015).

$$LST = a_0 + \left(a_1 + a_2\frac{1-\varepsilon}{\varepsilon} + a_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_1+T_2}{2} + \left(a_4 + a_5\frac{1-\varepsilon}{\varepsilon} + a_6\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_1-T_2}{2} + a_7(T_1-T_2)^2 \quad (1)$$

where a_0, a_1, …, a_7 are the coefficients from water vapor simulated dataset. ε is the average emissivity of the two channels and $\Delta\varepsilon$ is the differenced emissivity. T_1 and T_2 are the top of atmosphere brightness temperatures of band 10 and band 11 in Landsat 8 respectively (Du et al., 2015).

Cooling effect of urban parks were measured using four indicators, including two maximum indicators (i.e., park cooling area, PCA; park cooling efficiency, PCE), and two accumulative indicators (i.e., park cooling intensity, PCI; park cooling gradient, PCG) (Du et al., 2022; Peng et al., 2021a). Considering the 30 m resolution of the retrieved LST and the limited cooling distance of urban parks, thirty continuous buffer rings of 30-m wide were made from park's boundaries (Peng et al., 2021a). Then LST at various distances of 300 m, 600 m and 900 m were analyzed to determine the most accurate relationship. The relationship between LST and distance was fitted with cubic curve. Usually, the cooling effect would decrease along the rising cooling distance outskirt from park boundary, then reach a turning point (Fig. 2). The maximum cooling distance was determined with this turning point. PCA was the maximum area that a park can cool within the maximum cooling distance. PCE was the proportion of PCA to park area, representing the cooling efficiency per unit of park area. Considering the spatial continuity of the park cooling effect, we also selected PCI and PCG as accumulative cooling indicators. PCI was the accumulated LST reduction along the maximum cooling distance (Eq. (2)). PCG was quantified as the proportion of PCI to the maximum cooling distance (Eq. (3)).

$$\mathrm{PCI} = L \times TL - \int_0^L f(x)d(x) \quad (2)$$

$$\mathrm{PCG} = \frac{L \times T_L - \int_0^L f(x)d(x)}{L} \quad (3)$$

where L is the maximum cooling distance. T_L is the temperature at the turning point. $f(x)$ is the fitted cooling curve function.

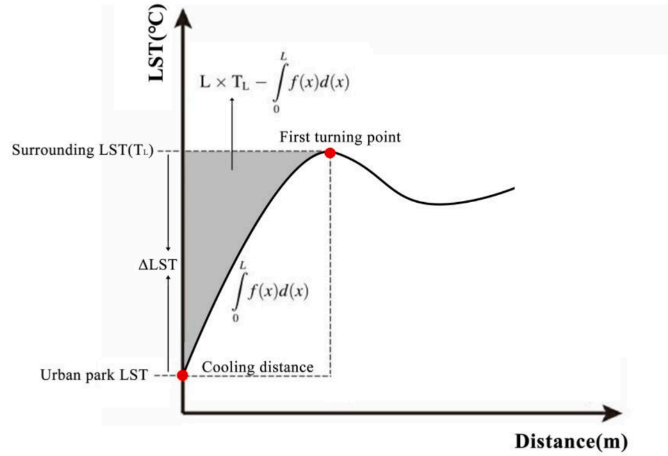

Fig. 2. The curve fitting of park cooling.

Then parks were clustered into several cooling bundles based on similar cooling performance using K-means clustering method. According to the normalized four cooling metrics, the clustering number "k" was determined using the silhouette, the gap, and the elbow statistic method (Litardo et al., 2020). The silhouette score reached largest when "k" equaled five. The gap value was highest when "k" was ten and five. The decrease of within-cluster distortion was marginal when "k" was five or greater (Fig. S1). Finally, the parks were grouped into five clusters. The clustering analysis was performed in SPSS version 25.0 (SPSS Inc., Chicago, IL, USA).

2.3. Identifying the influencing factors of cooling effect

This study analyzed five potential factors so as to investigate how to maximize urban parks' cooling effect via urban planning and design. These factors included park area, park perimeter, shape complexity (LSI, Eq. (4)), vegetation growth and water area ratio inside the park. Vegetation growth is indicated by the Normalized Difference Vegetation Index (NDVI). Pearson correlation was analyzed for these potential factors.

$$\mathrm{LSI} = \frac{\mathrm{P}}{2\sqrt{\pi \times S_{park}}} \quad (4)$$

where P is park perimeter, S_{park} is park area. A larger LSI denotes a more irregular park (Sun & Chen, 2012).

2.4. Cooling accessibility analysis

Cooling accessibility of urban parks helps evaluate the equity of cooling benefits provided to residents (Chen et al., 2022). Network analysis was used to calculate the cooling accessibility (Khaza et al., 2020; Oh & Jeong, 2007). Accurate road networks of the 26 cities were derived from Open Street Map (http://www.openstreetmap.org) and Google Earth images. Residential data of the 26 cities were from AutoNavi map (https://ditu.amap.com/). A set of entrances were assumed every 200 m along the cooling boundary per park. The average walking speed was set as 1 m/s (Oh & Jeong, 2007) and the waiting time at each intersection was set as 30 s. Then via road network analysis tool in ArcGIS 10.6 platform, we derived 10-min and 30-min walking accessibility to park cooling areas. A more than 30-min walk was considered as inaccessible to cooling service of parks.

3. Results

3.1. Cooling effect of urban parks in the 26 cities from the YREB

There were 1189 of 1337 parks (88.93%) cooler than the surrounding areas, whereas 148 of those showed no significant cooling effect. Two maximum-perspective cooling indicators (PCA and PCE) and two accumulative-perspective cooling indicators (PCI and PCG) were analyzed to explore cooling effect of urban parks across different urbanization hierarchy levels. From the maximum perspective, the urban parks cooled down 2.34 ± 0.07 °C, ranging from 0.02 °C to 7.12 °C. The cooling distance averaged at 151.43 ± 4.39 m, ranging within 6.37 ~ 514.88 m. PCA covered 40.34 ± 1.17 ha, ranging within 0.54 ~ 367.36 ha (Fig. 3). And PCE averaged at 4.29 ± 0.12, i.e., the cooling area was more than four times of park's area. The large ranges of these cooling indicators suggested the great potential of cooling. Also, there were vivid examples for us to learn, e.g., Xuanwu Lake Park in Nanjing city cooled 7.12 °C for surroundings, Xinqiao Park in Chengdu city was with the largest cooling distance, Senlan Park of Shanghai city was with the largest PCA, and one neighborhood park (Qu Park) in Ningbo city was with the highest PCE of 31.23. From the accumulation perspective, PCI averaged at 108.55 ± 3.15 °C • m, and PCG averaged at 0.64 ± 0.02 °C. Dafeng park of Chengdu city was with the largest PCI and PCG of 835.65 °C • m and 2.37 C°, respectively.

The urban parks in the 26 cities from YREB behaved differently. The averaged PCA in Wuhan city was the highest with 54.11 ± 6.05 ha, whereas Deyang city was the lowest with 15.68 ± 1.99 ha (Table S2). The average PCE in Shaoxing city was the highest at 7.84 ± 2.02, whereas Meishan city was with the lowest average PCE of 1.73 ± 0.23. The averaged accumulative PCI in Wuhu city was the highest PCI with 158.01 ± 31.87 °C • m, while Meishan city was with the lowest value of 29.01 ± 4.23 °C • m. Wuhu city was also with the highest averaged PCG (0.94 ± 0.13 °C), while Meishan city was with the lowest PCG (0.27 ± 0.04 °C).

3.2. Different cooling bundles of urban parks

Based on K-means method, the 1189 urban parks with cooling effect were clustered into five bundles according to similar cooling performance (Fig. 4). Bundle 1 had fifty parks dominated by large PCG and PCI, 45.5% of which were theme parks. They were usually irregularly shaped, with dense vegetation and large water area ratios. Bundle 2 parks behaved well in PCG, but poor in other three cooling indicators. They had 351 parks in total, 31.4% and 33.2% of which were ecological parks and theme parks respectively. They were with the lowest LSI, larger water area ratio and denser vegetation, suggesting the efficient cooling benefit from blue and green infrastructure. Bundle 3 parks were dominated by PCA and PCG. They had 136 parks and 64.7% of which were comprehensive parks. These parks had the largest area, perimeter, LSI and water area ratio. The average area of them was 112.57 ha, suggested that parks with large PCA were mostly large parks, equipped with a certain area of water body. Bundle 4 parks were dominated by PCE. They had a total of 115 parks, 84.7% of which are neighborhood parks usually with the lowest area but high LSI, indicating that small parks with complex shapes were economical in heat mitigation. Bundle 5 parks performed poor in four cooling indicators. They had 537 parks, almost half of the collated 1189 urban parks, indicating the YREB urban parks still had great potential to improve cooling function in hot summers. Most of Bundle 5 parks were theme parks (37.9%) and neighborhood parks (32.8%), which were with sparse vegetation and little water body.

3.3. Factors analysis of cooling effect

PCA in cities across different urbanization hierarchy levels showed positive correlation with all the five potential factors, and the correlation with park area and perimeter was larger, suggesting the dominant contribution of size effect on PCA ($p < 0.001$, Fig. 5a). We further discovered threshold area for the ideal land resource investment by the critical point (when slope of the logarithmic function equaled 1). The threshold area to promote PCA for megacities, large cities, and medium-

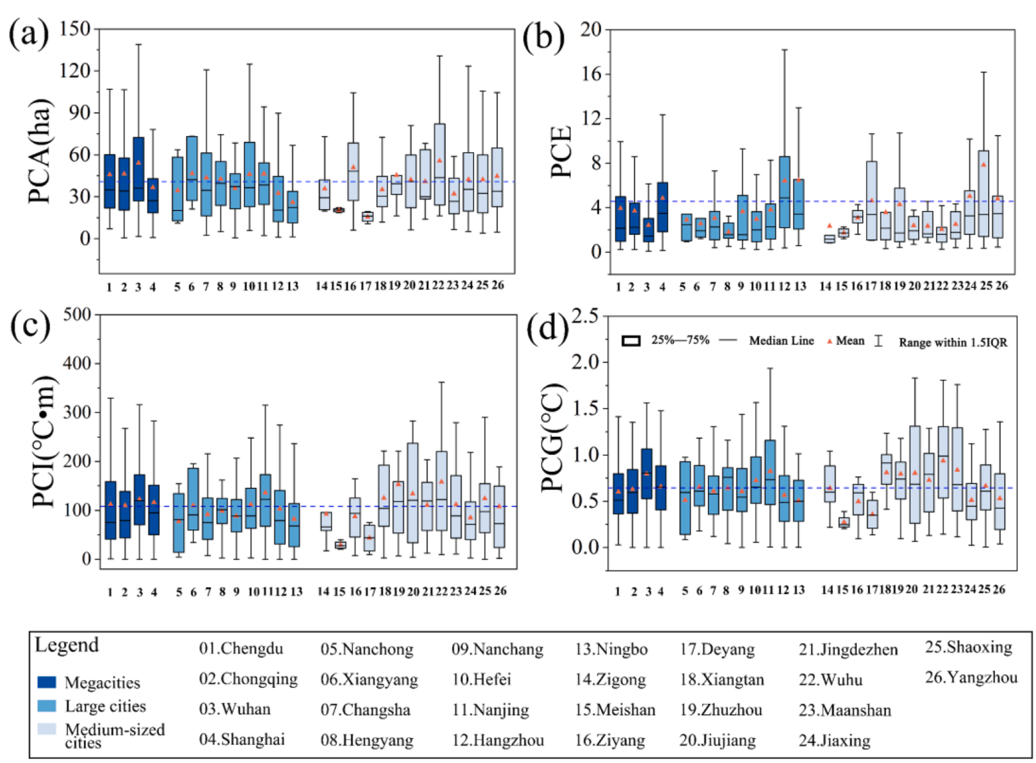

Fig. 3. Box plots of urban parks' cooling indicators in the 26 cities from the Yangtze River Economic Belt. Blue dashed lines represent the overall average values.

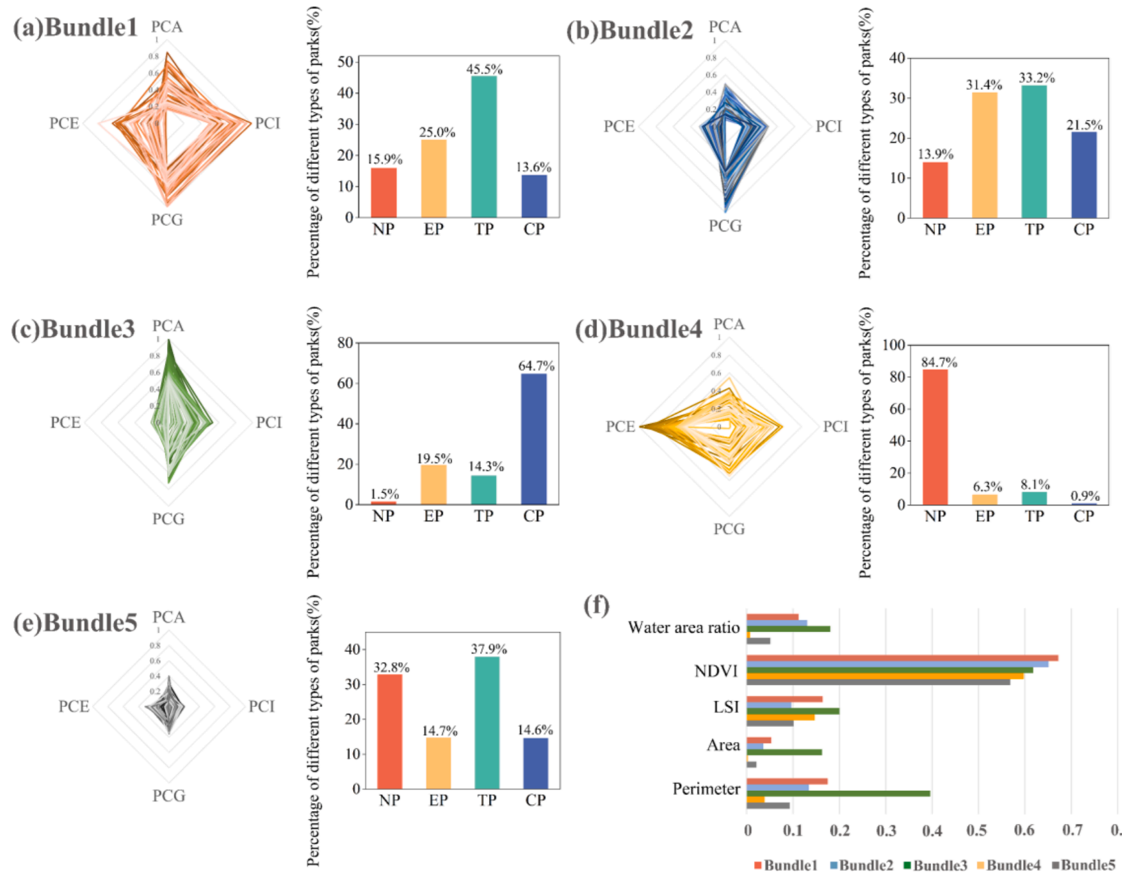

Fig. 4. (a-e) Five cooling bundles of urban parks and (f) their characteristics. (NP: neighborhood parks; EP: ecological parks; TP: theme parks; CP: comprehensive parks).

sized cities were 19.4 ha, 14.3 ha, and 13.3 ha, respectively (Fig. 6). Large parks were often with small PCE, and vice versa. To promote PCE, the threshold area for megacities, large cities, and medium-sized cities were 2.2 ha, 2.1 ha, and 2.3 ha, respectively. PCE was also positively correlated with LSI and NDVI for megacities and large cities, indicating that shape complexity and lust vegetation growth would enhance the parks' cooling efficiency.

As to two accumulative cooling indicators, PCI was positively correlated with NDVI across three urbanization hierarchy levels ($p < 0.001$), indicating that the more vigorous the vegetation growth in parks, the greater PCI was. Also, we found that the correlation between PCI and NDVI was higher in megacities than that in large cities and medium-sized cities. Notably, PCI was not correlated with park area, suggesting that some small parks also had large cooling potential to reach the accumulative cooling intensity comparable to larger ones. PCG was positively correlated with perimeter and area ($p < 0.001$), and most correlated with NDVI and water area ratio, addressing the efficient cooling gradient of coupled blue and green infrastructures.

For both climates, PCA showed significant positive correlations with all factors (Fig. 5b). PCI and PCG were positively correlated with NDVI for both climates ($p < 0.001$), suggested that increasing green infrastructure in both climate zones could improve the cooling performance of parks. PCG was positively correlated with water area ratio on Cfa ($p < 0.001$), but not correlated in Cwa. It indicated that the increase of blue infrastructures in Cfa was more effective than that in Cwa.

3.4. Cooling accessibility of urban parks during hot summers

Within 30-min walk, 1189 urban parks with significant cooling effect served for 59.7% residents during hot summers (Fig. 7). About 4.9% residents lived within cooling range, thus had direct access to parks' cooling service. About 18.5% and 36.3% residents could access park cooling services within 10-min walk and 10~30-min walk, respectively. There were still 40.3% residents inaccessible to the parks' cooling service within 30-min walk.

For cities across different urbanization hierarchy levels, 62.8% residents in megacities could access the cooling services within 30-min walk, higher than that of large cities (55.9%) and medium-sized cities (55.3%). Among the four megacities, Chongqing city and Shanghai city had higher levels of cooling accessibility, providing cooling services to 78.5% and 62.0% residents within 30-min walk, respectively. Among large cities, parks in Hengyang city provided 82.2% residents cooling services within 30-min walk, which was the highest percentage. Among medium-sized cities, 79.1% and 70.1% community residents in Wuhu city and Jiaxing city could access to parks' cooling services within 30-min walk, respectively, while only 19.4% residents in Meishan city could access to cooling services within 30-min walk.

Furthermore, Fig. 8 showed the inequality of cooling accessibility in urban core and suburbs for ten cities with definite urban-suburbs boundaries. Overall, 72.9% residents dwelling in the urban core area could access to cooling services from parks within 30-min walk, whereas only 42.8% residents in the suburbs had access to parks' cooling services within 30-min walk. Shanghai city was with the largest inequality, i.e., 81.5% residents in urban core were accessible to cooling services, whereas only 41.6% in the suburbs were accessible to parks' cooling services. Chongqing city set an example with equitable cooling accessibility due to the construction of "National Forest City" and scattered distribution of urban parks.

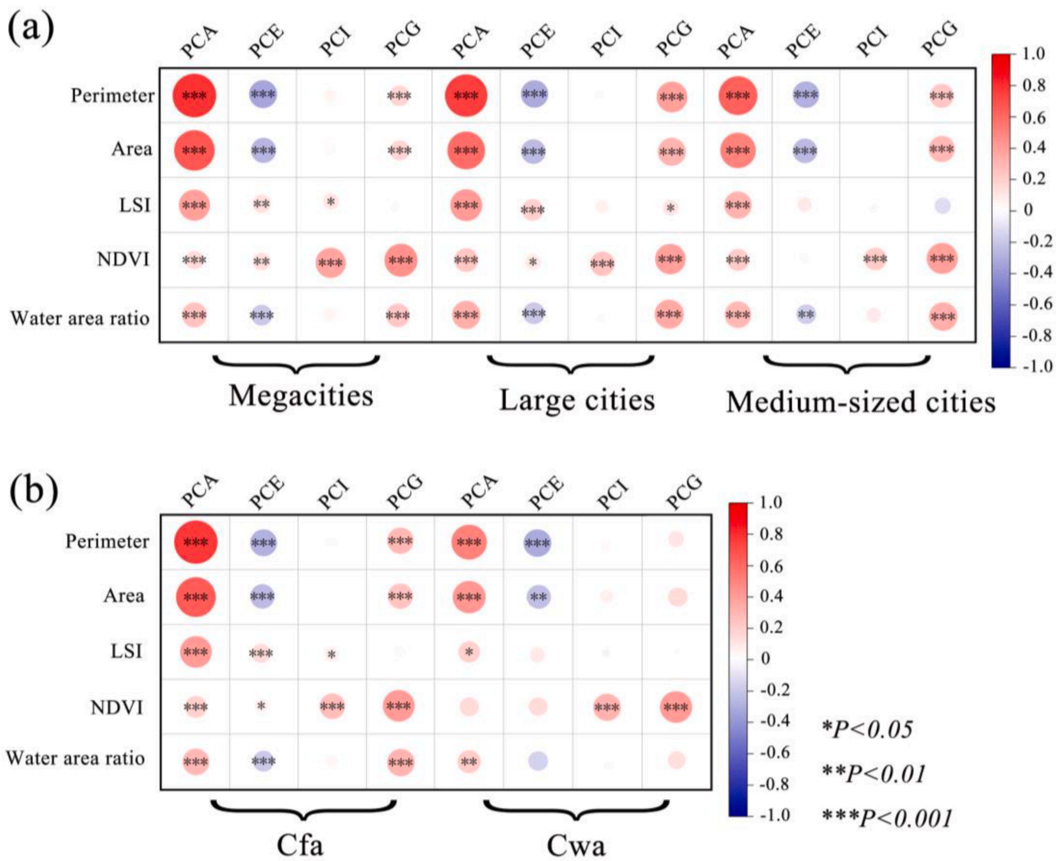

Fig. 5. Correlation analyses for the factors of cooling effect across (a) three urbanization hierarchy levels and (b) two climates.

4. Discussion

4.1. Urban parks' cooling effect in 26 cities of YREB

To scrutinize the heat mitigation function of parks from different urbanization levels, we conducted a hierarchical study on a regional basis. The 1189 of the 1337 parks in the 26 cities showed cooling effect. The cooling area of these individual parks averaged at 40.34 $\pm$ 1.17 ha, and PCE averaged at 4.29 times of parks' area. PCA of individual parks in our study was lower than 81.30 ha in Peng et al. (2021a), and PCE was higher than 1.36 in Peng et al. (2021a). PCI of individual parks in YREB averaged at 108.55 $\pm$ 3.15 °C • m, and the PCG was 0.64 $\pm$ 0.02 °C, both lower compared with PCI of 153.87 °C • m and PCG of 0.78 °C in Du et al. (2022). The disparities might be related to the different background climate and various green development strategies.

With the implementation of China's economic strategy, urban agglomerations are growing, coincided with various environmental problems and climatic changes (Liang et al., 2019). Thus, exploring heat mitigation strategies at regional level would potentially yield insights that may extrapolate beyond singular city research (Geng et al., 2022; Yu et al., 2020). Cities with higher urbanization hierarchy levels displayed a greater cooling intensity. Despite urban heating caused by cities with high urbanization hierarchy levels was more intense, their parks functioned well in local cooling systems (Manoli et al., 2019). This demonstrated cities with high urbanization hierarchy levels held more well-developed park systems and superior policy implementation. For cities of lower urbanization hierarchies, the planning department should also improve applicable policies in the planning and construction of parks.

4.2. Tradeoff among cooling indicators

This study identified the potential factors of cooling effect from parks, in an effort to furnish references for urban park planning at varying urbanization hierarchy levels. Park size was widely considered to be a dominant factor influencing PCA (Algretawee et al., 2019; Gao et al., 2022). Parks with larger area generally had larger cooling area, which could provide cooling services to a larger number of urban residents. However, it was not feasible to enlarge parks without limit due to the urban land resource scarcity (Jia & Zhao, 2020; Yan et al., 2021). The threshold area for park land investment varied for different urbanization hierarchy levels, with 19.4 ha for megacities, 14.3 ha for large cities, and 13.3 ha for medium-sized cities, suggested different practical strategies of park planning for cities with different urbanization hierarchy levels. The park threshold area in our study was higher than Geng et al. (2022) (0.66–0.81 ha) and Yao et al. (2022) (1.08 ha). We used PCA which was different with previous delta LST to identify the threshold. Also, the sample size in our study was larger, i.e., megacities with 502 parks, large cities with 421 parks, and medium-sized cities with 266 parks.

The cooling intensity could be enhanced by increasing vegetation cover in parks across all three urbanization hierarchy levels, and by building irregularly shaped parks in megacities. Water bodies in parks were found significantly correlated with PCA, PCE, and PCG, indicating that the combination of blue and green infrastructures was an effective heat mitigation solution. Also for Cfa climate zone, both blue and green infrastructures were suggested to improve the parks' cooling performance, whereas for Cwa climate zone, it was more effective to increase green infrastructures than blue infrastructures. Also, complex-shaped parks enhanced heat exchange with surroundings, thus boosted their potential for cooling gradient (Cao et al., 2010; Yao et al., 2022).

With the limited available area in cities, tradeoff should be

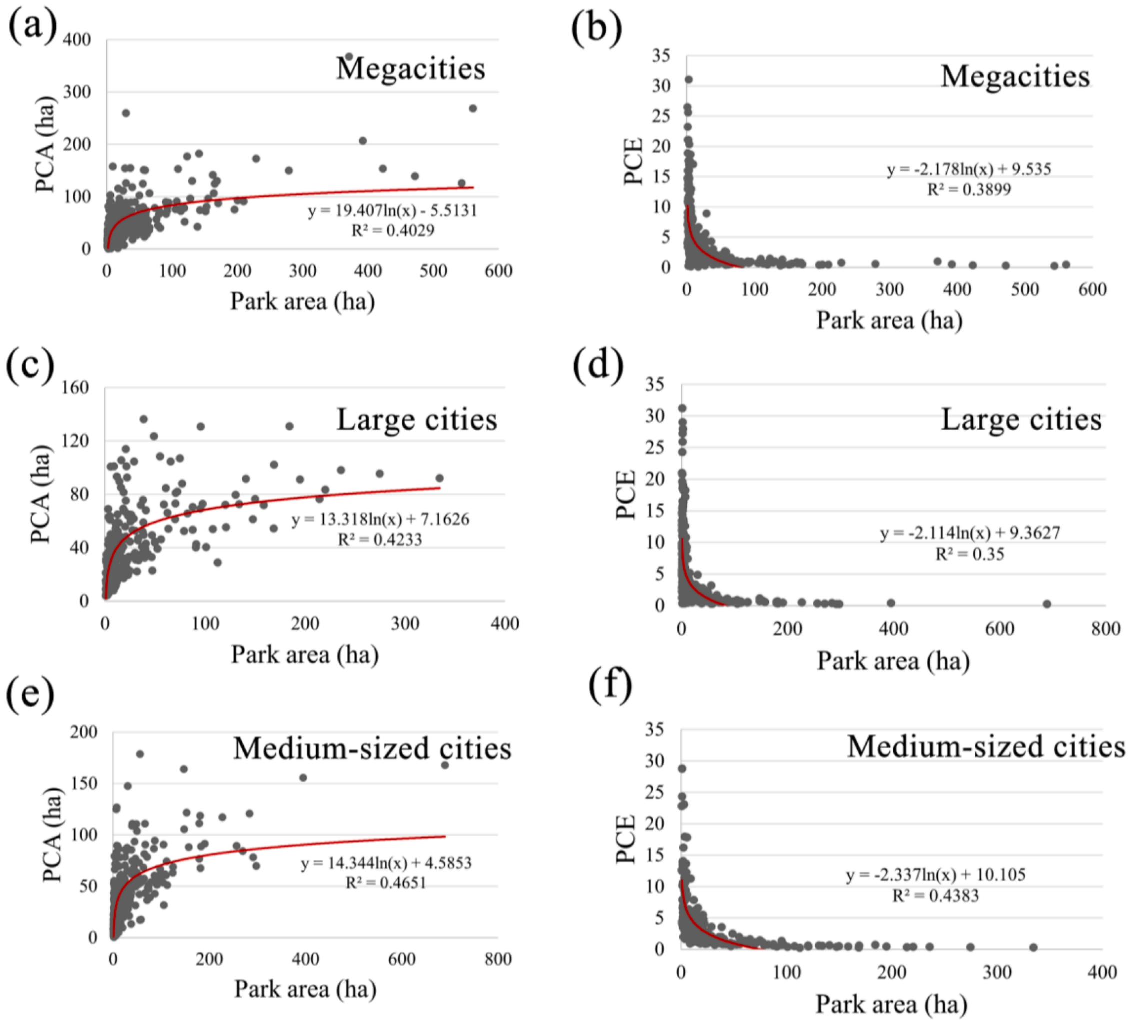

Fig. 6. The threshold area of parks in different urbanization hierarchy levels.

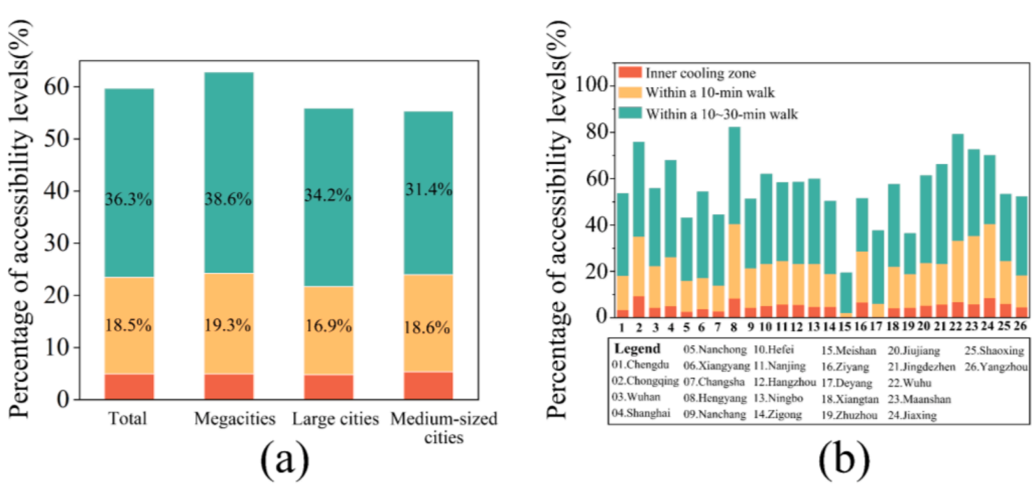

Fig. 7. Cooling accessibility of 1189 urban parks in YREB.

considered for the specific cooling demand when making decisions in urban parks' planning and designing. Different cooling needs should be matched with specific cooling solutions (Gao et al., 2022; Peng et al., 2021a; Yao et al., 2022). Smaller parks tended to have higher cooling efficiency with limited space especially in high-rise area, which coincided with relevant studies (Du et al., 2022; Yao et al., 2022). Studies have proven that pocket parks can mitigate urban heating (Lin et al., 2017; Ma et al., 2022).To cater for cooling efficiency demand, pocket parks (< 2.3 ha) in irregular shapes with high vegetation cover were suggested in megacities and large cities.

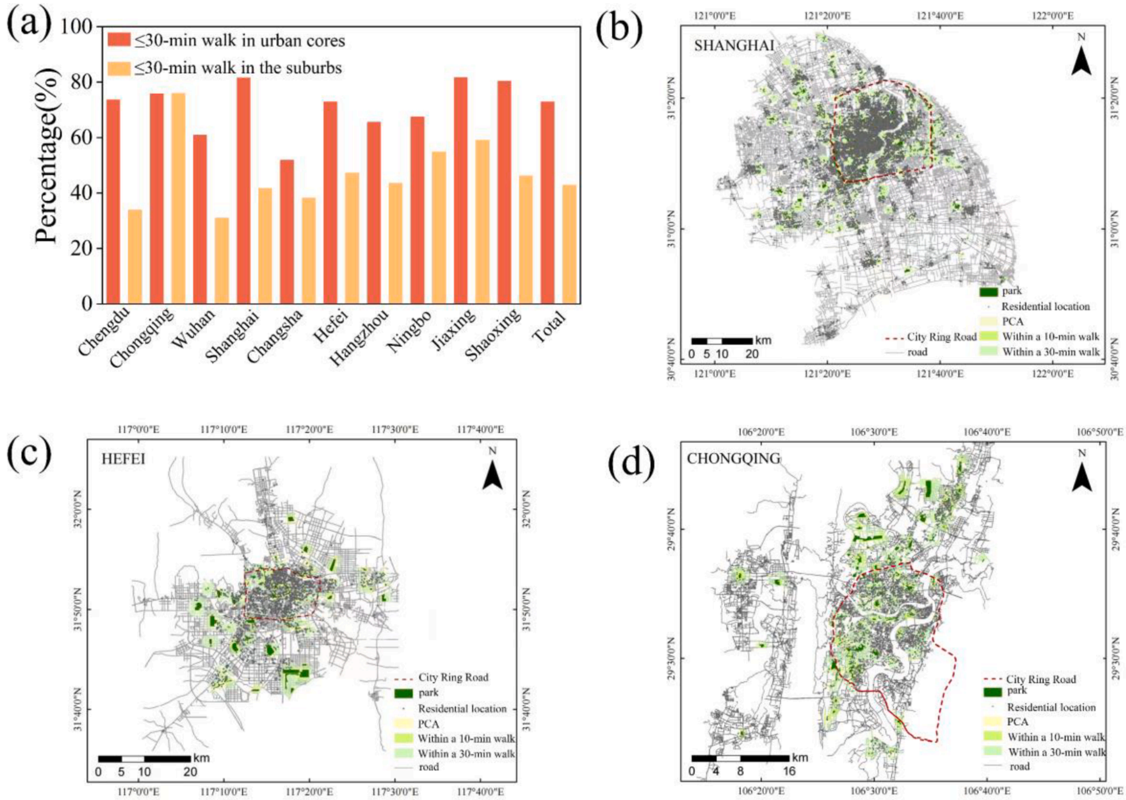

Fig. 8. (a) Cooling accessibility of parks in urban cores and suburbs; (b-d) Spatial distribution of cooling accessibility in example cities (Shanghai, Hefei city and Chongqing).

4.3. Residential accessibility to urban parks' cooling services

As of yet, few studies have been conducted regarding the accessibility of park cooling services. In the context of social stratification and increasing cooling demands, it was also important to evaluate the equity of cooling accessibility of urban parks at regional scale. This study revealed the inequality in access to cooling services in hot summers. There were still 40.3% of residents inaccessible to cooling service within 30-min walk in hot summers. As to different urbanization hierarchy levels, 62.8% of residents in megacities were accessible to parks' cooling services within 30-min walk, higher than large cities (55.9%) and medium-sized cities (55.3%). This might be related to the fact that megacities had more developed transportation, which granted residents convenient access to cooling service. Our research also revealed that residents living in suburbs had more difficulty to access to parks' cooling service.

To improve the equity of cooling accessibility for all groups of people, we propose the following planning implications: (1) For medium-sized cities, government should allocate additional investment for the construction of parks and transportation systems; (2) Improve the transportation system in suburb and add certain parks near the newly developed area; (3) Construct pocket parks in densely populated areas so as to utilize limited urban space to its fullest potential and provide more residents with cooling services. This research will guide toward a more equitable and livable city though greater planning and design of parks.

4.4. Limitations

This study had limitations. First, the application of satellite images from different dates might affect the consistency of LST retrievals. Since cooling effect of the parks was quantified using the LST difference compared with the surrounding local background temperature, this uncertainty should not change our results much. Also, the temporal resolution of satellite images limited the exploration of cooling effect with diurnal changes. In addition, the surface temperature inversion from remote sensing images could simulate sensible heat fluxes, but could not capture latent heat fluxes, thus limited the investigation on thermal comfort (Yu et al., 2020). Some studies have shown that urban moisture island has a synergistic effect on urban heat island, which should be investigated in the future study (Chew et al., 2021; Huang et al., 2021; Wang et al., 2021). Moreover, thermal comfort brought by different urban parks could be elucidated in subsequent studies. Furthermore, other potential factors of cooling effect should be considered in future studies, such as leaf area index, evapotranspiration, vertical plant communities and ground albedo, etc. (Gao et al., 2022; Gunawardena et al., 2017; Zhang et al., 2013). In addition, our study ignored the effects of traffic conditions and the layout of facilities within the PCA on cooling accessibility. In subsequent studies, uncertainty of cooling accessibility could be further validated if fine-grained land use images and population data are available.

5. Conclusions

In this study, we used satellite image to analyze cooling effect and cooling accessibility of 1337 urban parks in 26 cities across three urbanization hierarchy levels in YREB, the China's largest sustainability experiment. The main conclusions are as follows.

(1) A total of 1189 Urban parks had significant cooling effect. Parks in higher urbanization hierarchy cities had better cooling performance. Tradeoff should be considered for the specific cooling demand. The threshold investment area to maximize cooling area was 13.3 ha ~ 19.4 ha for different urbanization hierarchy cities. To cater for cooling efficiency demand, small parks (< 2.3 ha) in irregular shapes with high vegetation cover were suggested in megacities and large cities.

(2) There existed inequity in cooling accessibility of urban parks. About 40.3% residents could not access to parks' cooling service within 30-min walk. Suburban residents had more difficulty accessing to parks' the cooling services. To improve the equity, government should make effort in the suburb transportation network and park construction near the newly developed area.
(3) This study had limitations. Satellite approaches with high temporal and spatial resolution should be pursued in future study. Thermal comfort brought by different urban parks could be also elucidated. Other potential factors like leaf area index, evapotranspiration and vertical plant communities should be considered in future study. Finer land use images and population data can further improve the accuracy of cooling accessibility.

Declaration of Competing Interest

The authors declare that they have no financial or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.104519.

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