ABSTRACT

Cities have suffered from urban heat island (UHI) effect due to rapid urbanization, which can be effectively adjusted by urban green space. Taking the community parks in central area of Nanjing, Jiangsu Province as an example, this paper explored the size and shape of small-scale parks to mitigate the UHI effect. Land surface temperature was retrieved from Landsat 8-OLI remote-sensing image of 2019. The 52 studied community parks were identified with ArcGIS 10.4, and classified by kernel building density. The threshold-size and optimal shape of community parks to mitigate UHI effect were then discussed. The results showed that 1) with the increase of buffer ring distance around the community parks, the cooling intensity decreased and the cooling extent were mostly less than 180 m; 2) area, shape, and NDVI of the parks were important factors affecting the cooling intensity; 3) the cooling intensity of community parks under a high kernel building density was better, with a higher threshold-size (0.848 hm$^2$) than that of the low ones (0.384 hm$^2$); and 4) the optimal cooling intensity would occur when the park in a shape of circle or square. In conclusion, it is suggested that small green space should be planned in the areas under a high building density. Through renewal design and refined management measures in the urban green space system planning, giving full play to the ecological benefits of urban green spaces in mitigating the local UHI effect can also be expected.

KEYWORDS

Community Park; Nature-Based Solutions; Urban Heat Island Effect; Microclimate Adjustment; Empirical Study

MITIGATION OF URBAN HEAT ISLAND EFFECT WITH SMALL-SCALE PARKS—AN EMPIRICAL STUDY ON COMMUNITY PARKS IN NANJING, JIANGSU PROVINCE

小尺度公园对于城市热岛效应的缓解作用
——基于南京市中心城区社区公园的实证研究

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1 Introduction

In 2018, 55% of the world population reside in cities, and the predicted number will reach 68% by 2050 as the urban population of China will reach 1.086 billion, reported in the World Urbanization Prospects 2018[1]. Rapid urbanization has impacted the evolution of cities’ landscape pattern, sharply shrinking urban green spaces and accompanying severe ecological problems such as the exacerbated urban ecosystem damage and urban heat island (UHI) effect[2]. Moreover, traditional costly approaches that aim to resist natural disasters are no longer effective in coping with today’s environmental challenges[3].

In response, “Nature-Based Solutions” (NBS) has attracted increasing attention of researchers and planning decision-makers over recent years. Leveraging and facilitating the delivery of ecosystem services, NBS can contribute to the sustainability of economy, environment, and society[4][5], and is widely regarded as ecological measure of a sound cost-effectiveness[6].

A large number of studies have proven that urban green space can effectively regulate urban microclimate (e.g., UHI effect mitigation)[7], being a critical component to a city’s resilience to future climate changes[8]. For example, Zhang Changshun et al. examined the central area, satellite towns, and suburbs of Beijing City and attempted to reveal the inner-relations between the cooling intensity of green space with its type (include grass, shrub, and bamboo forest), structure, and management measures[9]; Majid Amani-Beni et al. found that the cooling effect of urban parks has a significant correlation with the urban green space type (farmland, waterbody, and urban green space) and its landscape level index[10]; Du Hongyu probed into the cool island effect of green-blue spaces and their optimal distributions based on landscape pattern index, i.e. spatial and temporal pattern of land surface temperature, and proposed associated planning strategies[11]. Studies have also proven that the size and shape of urban green space are key factors to its cooling effect[12]~[14]. Zhou Dongying et al. quantified the correlations between the size and temperature of urban parks in cooling effect[15]; Du Hongyu probed into the cool island effect of green-blue spaces and their optimal distributions based on landscape pattern index, i.e. spatial and temporal pattern of land surface temperature, and proposed associated planning strategies[11]. Furthermore, Chang Chi-Ru et al. found that there may be a non-linear relation in urban green space area and the cooling effect[16]; Yu Zhaowu et al. defined a threshold value of efficiency (TVoE), i.e. the cooling efficiency will decrease when the size of urban green space exceeds a critical value—This finding bridges urban ecological research and landscape planning and design practice[17]~[19], and the mitigation on UHI effect by parks is broadly explored (especially in size and shape) in urban land planning and urban green space system planning.
总体来看，已有研究多集中于现有景观组成和空间配置对案例城市热岛效应的缓解作用，亦有少数学者开始着眼于量化水体、绿地等不同景观类型的面积阈值，以便获得绿地最佳降温效果，有利于进一步的城市管理和气候适应性规划的制定。但是，针对小尺度的绿地面积和形态与降温效果之间的量化研究尚且不足。因此，本文以南京市中心城区社区公园为例，旨在1) 探究社区公园对周边环境降温效果的影响因素；2) 量化、讨论社区公园的最佳面积、形状；3) 为绿地规划在城市微气候调节功能上提出可行建议，帮助更有效地缓解城市热岛效应，并提供数据支撑与方向指引。

2 研究区域与研究方法

2.1 研究区域

南京市地处长江下游，属于典型亚热带季风性气候，年平均气温15.4℃。随着近年多个城市中心的快速发展，城市热岛效应加剧，素有“火炉”之称的南京已成为中国夏季最炎热的城市之一。2019年

In general, current literature mainly studies the composition and configuration of existing urban landscapes to the mitigation on UHI effect. Also, a few of studies quantify the threshold-size in different landscape types (e.g., waterbody and green space) to the optimal cooling effect of green space to better supply urban management and climate adaptation planning. However, there are few documents on quantizing the relation between the cooling effect with the area and shape of small-scale green spaces. The authors selected the existing community parks in the central area of Nanjing as an example to 1) identify the causal factors of community parks on the urban cool island (UCI) effect to surrounding environment; 2) quantify the threshold-size and optimal-shape of community parks; and 3) offer references to urban green space planning on mitigating UHI effect and improving microclimates with quantitative evidences and guidance on adaptive strategies.

2 Study Area and Research Methods

2.1 Study Area

Located in the lower reach of the Yangtze River, Nanjing has a typical subtropical monsoon climate and its annual average temperature is 15.4℃. In recent years, with the rapid expansion of several urban centers that have aggravated the UHI effect,
2.2 Data Sources and Pre-Processing

Remote-sensing images of central area of Nanjing used in this study include Landsat-8 OLI one (30 m in resolution) and high-resolution satellite one (0.5 m in resolution) obtained from the USGS Earth Explorer® and BIGEMAP data software®, respectively. The former one was taken on July 11th, 2019 when the weather was sunny and cloudless, and the detected temperature was 23 ~ 30°C; all bands except the thermal infrared one were processed in ENVI 5.3 for radiometric calibration and atmospheric correction, then obtained the image of central Nanjing by mask extraction with ArcGIS 10.4. The latter one was obtained through the coordinate transformation and geographical registration by ArcGIS 10.4.

2.3 Study Methods

Based on the remote-sensing image and the high-resolution satellite image, the study attained land surface temperature (LST), community park location, kernel building density, and other data with ArcGIS 10.4 and ENVI 5.3. The relations between the UCI of small-scale urban parks with their size and shape factors were explored through the statistical analysis with SPSS 24.0 and Excel.

2.3.1 Land Surface Temperature Retrieval

Due to the unstable parameter settings in band 11 of the Landsat 8-OLI satellite, and the single-channel algorithms suitable for the situation of low atmospheric water vapor content being not applicable for the rainy weather of Nanjing[,] the study introduced the radiative transfer equation (RTE) to retrieve a highly accurate land surface temperature (LST) using band 10 in ENVI 5.3.
2.3.2 社区公园识别与缓冲区划定
通过2019年的南京市卫星影像、《南京市公园布局规划（2017-2035）》以及现场调研，进一步精确获取社区公园信息，借助ArcGIS 10.4识别社区公园，并计算社区公园面积。此外，考虑到Landsat 8-OLI图像的最小分辨率为30米（30m），分别沿社区公园边缘每隔30米向外生成缓冲带，得到总距离为600米的20个缓冲带，即设定0-600米为社区公园缓冲区⑤，以便提取各缓冲带的地表温度，计算每个社区公园的降温效果强度。

2.3.3 核建筑密度估计
地表温度是区域土地利用和人为热的综合体现，因此，社区公园周围的建筑分布情况对于降温强度具有一定影响。本研究采用了黄焕春等人提出的“核建筑密度”概念与算法⑥。其概念来源于“核密度估计法”⑥，指空间上某点的建筑密度是以该点为圆心的一定距离内，周围的建筑分布情况对于降温强度具有一定影响。

根据研究需要，将建筑密度的计算思想，基于栅格数据格式，运用移动搜索法对面域单元空间进行逐个像素计算，具体而言是以某点（i点）为中心画一个圆形作为滤波

2.3.2 Community Parks Identification and Buffer Zone Parameter Delineation
According to the high-resolution satellite image, the schemes of Nanjing Park Layout Planning (2017-2035), and field surveys, the location and area of the 52 community parks were identified with the ArcGIS 10.4. Moreover, considering the 30 m as the minimum resolution of Landsat image④, 20 buffer rings (each with a width of 30 meters) were set for each community park, i.e. the width of the total buffer zone of each park ranged from 0 to 600 m⑤. The average LST in each buffer zone was retrieved to quantify the cooling extent and intensity.

2.3.3 Kernel Building Density Estimation
LST is subject both to local land use and anthropogenic heat. The cooling intensity of a community park is affected by the building environment around it. This study adopted the concept and algorithm of “kernel building density,” proposed by Huang Huanchun et al.⑥ based on the theory of kernel density estimation⑥. The building density of a certain place is the ratio of the total building area to the land area within a certain distance centered from the place. Applying the kernel density function, the method of floating catchment area (FCA) is used to calculate the unit space of the area one by one on the raster data format. Specifically, a circle can be drawn centered on one point (i) as the

| 指数名称 | 定义 | 数值范围 |
|---------|------|---------|
| 贴块面积 | Patch area | A ≥ 0 |
| 贴块紧凑度指数 | Patch Compactness Index (CI) | 0 ≤ CI ≤ 1 |
| 景观形状指数 | Landscape Shape Index (LSI) | LSI ≥ 1 |
| 地表温度 | Land Surface Temperature (LST) | LST ≥ 0 |
| 归一化植被指数 | Normalized Difference Vegetation Index (NDVI) | -1 ≤ NDVI ≤ 1 |

表1: 阶段尺度下组织特征指数及其生态学意义
Table 1: The characteristic indexes of landscape pattern and their ecological implication at the patch scale
window (A), using the average value in the window A as the kernel building density to point i. Finally, a kernel building density diagram with continuous spatial changes was obtained. The calculation formula is as follows:

\[ f(x) = \frac{1}{n h^d} \sum_{i=1}^{n} K(w_i x_i) \]

where, \( K(\ ) \) is the kernel density function; \( w_i \) is the weight value of place i, \( x_i \) is the kernel building density of point i, \( A \) is the size of filtering window, \( h \) is the threshold range of spatial effect, \( n \) is the number of points in the threshold range, and \( d \) is the dimension of data.

In addition, in order to identify the threshold-size and optimal shape of community parks under different kernel building densities, this study quantified the kernel building density within the buffer zone (0~600m) around the community parks by the natural breaks in ArcGIS 10.4. Finally, 38 community parks were identified under a low kernel building density (kernel building density values 0~17,923) and 14 under a high kernel building density (kernel building density values 17,924~81,613).

2.3.4 Quantification of Cooling Intensity and Urban Green Space Characteristics

The UHI effect mitigation is related to the area, shape, and other factors of the green space[10][31], but the mechanism leading to the optimal cooling effect has not been clearly understood, as well as the relations between the cooling intensity and the size and shape of green space[22][32]. Accordingly, assisted with SPSS 24.0, the study quantified these relations in community parks by examining green space indicators both on typological characteristics—
including the Area (AREA), Compaction Index (CI), and Landscape Shape Index (LSI), calculated with the ArcGIS 10.4 and FRAGSTATS—and the biological characteristics—including LST and Normalized Difference Vegetation Index (NDVI), calculated with ENVI 5.3 (Table 1).

2.3.5 Optimal Cooling Intensity and Threshold-Size

SPSS 24.0 was used to estimate the threshold-size for optimal cooling intensity of community parks. An assessment

3. Variation characteristics of surface temperature in each buffer ring of the community park. The fitting curve shows a trend of rising first and then falling, and the park have obvious cooling effect on the surrounding area at a certain distance.
3 Results and Analyses

3.1 The Cooling Effect of Community Parks on the Surrounding Areas

With the zonal statistical tool of ArcGIS 10.4, community parks, buffer zones, and LST were overlapped to obtain the average LST inside each park and of each buffer ring. The research used SPSS 24.0 to probe into the curve fitting degree, where the buffer ring distance was independent variable, and the average LST of buffer ring was the dependent variable. The result showed that the fitting effect of cubic polynomial was optimal, where $R^2$ valuing 0.6 ~ 1 accounted for 94%, and $R^2$ valuing 0.8 ~ 1 accounted for 69%.

4 community parks with a high fitting degree are illustrated here. All the fitting curves in the Figure 3-1 rise first and then decline, which indicates that those community parks have a significant cooling effect on the surrounding area within a certain distance. In this study, the $x$-axis value in accordance with the cooling extent of each community park was defined as the $E_{\text{max}}$, marked in red on the curve. Existing studies have proven that the local climate conditions (precipitation, wind speed, relative humidity, etc.) may impact the cooling effect of urban green space to some extent[33]. The LST within the buffer rings is also subject to the orientation, light, wind direction and speed, etc. Specifically,
| 编号 | 公园名称 | 面积（hm²） | 降温范围（m） | 编号 | 公园名称 | 面积（hm²） | 降温范围（m） |
|-----|---------|-------------|--------------|-----|---------|-------------|--------------|
| 7   | 光华游园 Guanghua Garden | 2.58 | 390 - 420 | 30  | 蓝山山头广场 Xiaoshan Mountain Plaza | 2.43 | 30 - 60 |
| 8   | 大行宫市民广场 Daxinggong Civic Plaza | 1.57 | 0 - 30 | 31  | 蓝山社区公园 Shuangshan Community Park | 3.04 | 120 - 150 |
| 9   | 铁路北街广场 Railway North Street Plaza | 1.57 | 300 - 330 | 32  | 优寓家园游园 Hengmao Home Garden | 1.69 | 30 - 60 |
| 10  | 积善广场 Moriyoshi Plaza | 1.37 | 0 - 30 | 33  | 贝尔森市民广场 Beiersen Road Civic Plaza | 1.03 | 30 - 60 |
| 11  | 月光广场 Moonlight Plaza | 2.13 | 120 - 150 | 34  | 田龙桥社区绿地 Tianlong Bridge Community Green Land | 1.74 | 360 - 390 |
| 12  | 曲水荷公园 Chunshuiheyu Park | 1.64 | 150 - 180 | 35  | 州达社区公园 Xingda Community Park | 1.12 | 30 - 60 |
| 13  | 永和仙居社区公园 Youhengxianju Community Park | 1.58 | 120 - 150 | 36  | 黄山桥公园 Huangshan Bridge Park | 1.56 | 150 - 180 |
| 14  | 紫藤山社区公园 Zitengshan Community Park | 1.47 | 40 - 90 | 37  | 春华街广场 Chunhua Street Plaza | 1.50 | 120 - 150 |
| 15  | 南湾营广场 Nanwanying Plaza | 1.04 | 0 | 38  | 月华楼公园 Yuehuavilow Park | 1.47 | 0 - 30 |
| 16  | 华电西苑山体公园 Huadianxiyuan Mountain Park | 9.66 | 180 - 210 | 39  | 五洲山社区公园 Wuozhou Mountain Community Park | 6.48 | 120 - 150 |
| 17  | 瓜洲广场 Guaizhou Plaza | 1.36 | 30 - 60 | 40  | 将军大道桥头公园 General Avenue Bridgehead Park | 1.02 | 0 |
| 18  | 优风广场 Yufeng Plaza | 1.03 | 150 - 180 | 41  | 新城路社区公园 Xincheng Road Community Park | 2.98 | 90 - 120 |
| 19  | 百家湖花园 Baijiahu Garden | 1.07 | 120 - 150 | 42  | 龙华路中央公园 Longhua Road Central Park | 1.21 | 90 - 120 |
| 20  | 竹山公园 Bambo Mountain Park | 3.04 | 270 - 300 | 43  | 美和路社区公园 Meihuo Road Community Park | 1.08 | 0 - 30 |
| 21  | 嘉华门市民广场 Jiahuamen Civic Plaza | 3.06 | 40 - 90 | 44  | 嘉熙路社区公园 Jiaxi Road Community Park | 1.13 | 30 - 60 |
| 22  | 嘉善国际城公园 Cuiping International City park | 1.39 | 0 - 30 | 45  | 龙湖湾社区公园 Longhuwan Community Park | 1.84 | 0 - 30 |
| 23  | 古龙路社区公园 Gulong Road Community Park | 2.45 | 0 | 46  | 龙湖湾西社区公园 Longhuwan West Community Park | 1.50 | 90 - 120 |
| 24  | 龙华台商区公园 LonghuTai Business Park | 3.51 | 180 - 210 | 47  | 嘉瑞社区公园 Jiarui Community Park | 1.74 | 30 - 60 |
| 25  | 泰神山公园 Taishenshan Park | 3.45 | 0 - 30 | 48  | 黄山山头社区公园 Huangshan Mountain Head Community Park | 1.58 | 0 |
| 26  | 永和家园西区公园 West Side of Eternal Home Park | 1.12 | 120 - 150 | 49  | 黄山社区公园 Huangshan Community Park | 5.19 | 90 - 120 |
| 27  | 永和家园东区公园 East Side of Eternal Home Park | 1.82 | 0 - 30 | 50  | 城市澜湖社区公园 Urban Oasis Community Park | 3.13 | 30 - 60 |
| 28  | 永和家园西区公园 West Side of Eternal Home Park | 2.02 | 30 - 60 | 51  | 吴江澜湖社区公园 Wujiang Luhan Community Park | 1.03 | 0 - 30 |
| 29  | 九龙公园 Nin Dragon Park | 2.16 | 150 - 180 | 52  | 紫东路社区公园 Zidong Road Community Park | 1.23 | 30 - 60 |
4. It is found that the cooling intensity decreases with the increase of buffer ring distance and approaches 0℃ in the end.

3.2 Cooling Intensity and Urban Green Space Characteristics

The cooling intensity of the 52 community parks ranged from 0℃ to 2.612℃, with an average of 0.604℃, — the significant cooling effect verifies the spatial heterogeneity shaped by the typological characteristics of landscapes. The correlation coefficients between the 5 typological indicators and cooling intensity were calculated with SPSS 24.0 (Fig. 5), where individual outliers were eliminated (for instance, the shape index of No.25 park was far larger shape than the others). The results showed that the cooling intensity was positively correlated with NDVI (R = 0.354, p < 0.01), AREA (R = 0.467, p < 0.001), CI (R = 0.403, p < 0.001) and LSI (R = -0.393, p < 0.001) with the land surface temperature of park (P_LST) (R = -0.683, p < 0.001) and LSI (R = -0.393, p < 0.001). In other word, within the thresholds, the cooling effect of a community park can be optimized with a larger size, a higher NDVI, and in a more regular shape, which is consistent with other research findings. Originally, this research further examined the threshold-size and optimal shape of community parks under...
表3: 不同核建筑密度下社区公园降温强度与相关影响因素分析

| 类别 | 数量（个） | 平均面积（hm²） | 平均降温强度（℃） | 平均形状指数 | 平均归一化植被指数 | 平均紧凑度指数 |
|------|-----------|----------------|-------------------|--------------|------------------|-----------------|
| 社区公园 | 52 | 2.114 | 0.654 | 0.736 | 1.481 | 0.253 |
| 高核建筑密度的社区公园 | 14 | 1.773 | 0.741 | 0.738 | 1.409 | 0.229 |
| 低核建筑密度的社区公园 | 38 | 2.239 | 0.532 | 0.721 | 1.508 | 0.258 |

注：*表示P<0.01，**表示P<0.001。

NOTE: *: P < 0.01; **: P < 0.001.

5. 利用SPSS 24.0计算了5个社区公园的形状特征因子与降温强度之间的相关系数，结果表明，降温强度与NDVI、AREA、CI三个因素显著相关。

5. The correlation coefficients between 5 typological characteristic factors of community parks and cooling intensity were calculated by SPSS 24.0. The results showed that cooling intensity was positively correlated with NDVI, AREA, and CI.

步计算了高、低核建筑密度类型的社区公园的相关影响因素的平均值（表3）。其中，低核建筑密度的社区公园平均降温强度为0.554℃，高核建筑密度的社区公园平均降温强度为0.741℃，两者相差0.187℃；高核建筑密度的社区公园具有较为规整的形状特征，但公园面积和NDVI略小于低核建筑密度的社区公园。

不同核建筑密度类型（Table 3）: the average cooling intensity of community parks under a low kernel building density was 0.554℃, and 0.741℃ for the ones under a high kernel building density—the intensity difference was 0.187℃; Compared with the community parks under a low kernel building density, the parks under a high kernel building density were found in a more regular shape, but slightly lower in AREA and NDVI.
3.3 The Threshold-Size of Community Parks

The size of the 52 parks ranged from 1.019 to 9.663 hm². Although this research found that the size of the parks was positively correlated with their cooling intensity, the insignificant cooling intensity observed in smaller parks was also resulted from location reasons or the impacts by their surrounding environments. For instance, the No.45 park (1.84 hm²) has a high impervious surface ratio and is adjacent to a large-scale green space (a scenic area). In addition, this correlation was strongly impacted by the kernel building density of the community parks (Fig. 6, 7). The linear fitting analysis (outliers removed) revealed that the slope of community parks under a low kernel building density was 0.12 ($R^2 = 0.369$, $p < 0.001$), and 0.51 ($R^2 = 0.501$, $p < 0.01$) for the parks under a high kernel building density, evidencing that the latter ones had a more significant cooling effect on the surrounding areas.

Through a simple linear regression to analyze the size and the cooling intensity of community parks with SPSS 24.0, the logarithmic function relation between those two was identified (Fig. 8). As the area of the parks increases, the cooling intensity under the both density...
(\(R^2=0.316\), \(p<0.05\))的降温强度随着公园面积的增大而逐渐趋于平缓、稳定。但对应的最佳公园面积阈值存在显著差异：低核建筑密度的社区公园，阈值为0.384hm\(^2\)；高核建筑密度的社区公园，阈值远大于前者，为0.848hm\(^2\)。

### 3.4 社区公园的最优形状规律

紧凑度指数被用于度量景观空间形状特征，研究选择圆形率紧凑度分析社区公园形状规律。经测算发现，社区公园的紧凑度指数与降温强度为指数函数，呈正相关（\(R=0.434\), \(p<0.05\)），当CI值接近1时，即公园趋于圆形或正方形时，降温效果最显著，该结论与多数既有研究结论一致\(^{[36][37]}\)。如图9所示，低核建筑密度的社区公园拟合性较弱（\(R^2=0.318\), \(p<0.01\)），高核建筑密度的社区公园拟合性较强（\(R^2=0.602\), \(p<0.001\)）。但受限于较少的研究样本数量，难以对该关系形成有效验证，如图9-1中，有较多散点分布于拟合曲线下方。研究进一步发现，这些散点对应的社区公园多是由于自身NDVI值过小，或社区公园受周边环境影响较大。如37号社区公园的CI值为0.881，而其降温强度仅为0.267℃，多由于其自身下垫面硬质率较高且NDVI值较低（仅为0.169，远小于平均值0.239）所致；18号社区公园的CI值和NDVI值均较高，但其降温强度也仅为0.301℃，这是由于该公园类型多的社区公园的降温强度随着公园面积的增大而逐渐趋于平缓、稳定。但对应的最佳公园面积阈值存在显著差异：低核建筑密度的社区公园，阈值为0.384hm\(^2\)；高核建筑密度的社区公园，阈值远大于前者，为0.848hm\(^2\)。

### 3.4.1 The Optimal Shape of Community Parks

The circularity ratio of CI, a metric to the shape characteristic of a landscape, was selected to analyze the shape factor of community parks. It showed that the CI and their cooling intensity of the studied parks was an exponential function with positive correlation (\(R = 0.434\), \(p < 0.05\)), and the optimal cooling effect would occur when CI value was close to 1 (i.e. the park in a shape of circle or square), being consistent with most existing studies\(^{[36][37]}\). As shown in the Figure 9, community parks under a low kernel building density had a lower fitting degree (\(R^2 = 0.318\), \(p < 0.01\)), compared to the ones under a high kernel building density (\(R^2 = 0.602\), \(p < 0.001\))—However, these fitting correlations need to be further verified because of the limited samples in this study, most of which were scattering below the fitting curve (Fig. 9-1). The reason for this fitting pattern was that the NDVI value of the corresponding parks was extremely low, or those parks were affected by the surrounding environments. For instance, the CI value of No.37 park was 0.881 and its cooling intensity was only 0.267℃, might resulting from its high impervious surface ratio and low NDVI value (NDVI = 0.169, far less than the average level); The No. 18 park had both high CI and NDVI values but a very low cooling intensity (0.301℃), probably because of the park's...
adjacency to a large scenic area in the north and a bigger urban park (covering water bodies) in the south, which two impacted the park’s cooling intensity considerably. Besides, relevant studies on urban blue-green spaces have also demonstrated that when a park’s size exceeds 1 hm$^2$, its cooling effect would be little subject to whatever the park’s shape is\cite{38}, which is deviated from the findings of this study. Compared to larger blue-green spaces that can form a relatively local micro-climate, community parks (mostly being 1 ~ 4 hm$^2$) would have a poorer cooling effect if they are in an irregular shape, due to the increased inner-outer interface would lead to more diffuse thermal flows\cite{32,39}. In this sense, the shape irregularity has greater impact on the cooling effect of smaller community parks.

4 Discussions

4.1 Causal Factors to the Cooling Extent of Community Parks

In this research, the main findings on the cooling extent and intensity of community parks in central area of Nanjing—including the cooling extent of the 52 studied community parks was mostly less than 180 meters, the average cooling extent of 114.23 meter, and the average cooling intensity was 0.604℃—verify existing research outcomes. Remarkably, the cooling extent of the No.7, No.9, and No.34 community parks exceeded 300 meters, all of which were under a high kernel building density (Table 4). Specifically, the No.34 community park was mostly occupied with woodland and it had the highest NDVI value among the parks under a high kernel building density. This conclusion explained that green spaces’ structure can largely define their UCI effect: the more healthy and denser vegetation an urban landscape is occupied, a more significant
cooling effect it has, where woodland landscapes show a better cooling effect than grasslands\[40\]. The parks of No. 3, No. 7, and No. 9 are close to water areas, but the cooling intensity and extent of both the latter two parks were far higher than the No. 3 park. The possible reasons are as follows: 1) compared with No. 7 and No. 9, No. 3 park covers a smaller area and is in more complex shape, which would weaken the cooling intensity of the park; 2) No. 3 park is covered by grasslands, and No. 7 and No. 9 parks by woodland which can not only cool the air more efficiently but also provide other ecosystem services such as improving air quality\[31\]\[41\]; and 3) No. 7 and No. 9 are connected with surrounding water and green spaces together forming a larger green space that would perform a stronger cooling intensity and a wider cooling extent\[11\]\[13\], this also corroborates the study conclusions that water body is an important causal factor to UCI effect\[38\]\[42\].

### 4.2 Community Park under Different Kernel Building Densities

The 52 studied community parks were identified under different kernel building densities. Most parks under a low kernel building density locate around the central area of the city, and the threshold-size of such parks was 0.384 hm$^2$ and the average cooling intensity was 0.532 ℃. The parks under a high kernel building density are mostly sitting within the central area of the city, with the threshold-size as 0.848 hm$^2$ and 0.741 ℃ for the average cooling intensity. The disparity of threshold-size was caused by the fact that the heavier UHI effect of urban built-up areas under a high kernel building density can only be efficiently mitigated by a green space that covers a large-enough area\[14\]\[39\].

It was found that the cooling intensity of the parks under both kernel building densities were easily impacted by the environmental factors from the surrounding areas. An across-examination on the NDVI value of 0 – 600 m buffer zone of each park indicated that

| 编号 | 公园名称 | 面积 (hm$^2$) | 降温强度 (℃) | 形状指数 LSI | 归一化植被指数 NDVI | 降温范围 (m) |
|------|----------|-------------|--------------|--------------|-----------------|------------|
| 3    | 刘伯承广场 | 1.336       | 0.328        | 2.079        | 0.249           | 0 ~ 30     |
| 7    | 光华游园  | 2.585       | 1.978        | 1.260        | 0.227           | 390 ~ 420  |
| 9    | 铁路北街广场 | 1.573       | 0.660        | 1.316        | 0.259           | 300 ~ 330  |
| 34   | 回龙桥社区绿地 | 1.738       | 1.143        | 1.263        | 0.292           | 360 ~ 390  |

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| 9    | 铁路北街广场 | 1.573       | 0.660        | 1.316        | 0.259           | 300 ~ 330  |
| 34   | 回龙桥社区绿地 | 1.738       | 1.143        | 1.263        | 0.292           | 360 ~ 390  |
该结论可能是受限于高核建筑密度的公园样本量过少，且公园面积集中在1.2~2.6hm²所致（表3）。

### 4.3 城市绿地系统规划层面的指标调整建议

本研究试图探讨最佳降温效果下社区公园的面积阈值和形状规律。研究发现，南京市社区公园的面积、形状、NDVI和降温强度显著相关，且低核建筑密度和高核建筑密度的社区公园最佳面积阈值分别为0.384hm²和0.848hm²，均小于《城市绿地分类标准（2017）》对社区公园“宜超过1hm²”的规定。因此，建议根据各地区城市的实际情况，在城市绿地系统规划层面适当调整社区公园绿地面积指标，有助于在高核建筑密度地块内见缝插针地规划小面积绿地，利用精细化的存量设计与管理，发挥城市区域的最佳生态效益，进一步缓解局部热岛效应。同时，将基于自然的解决方案和生态设计等理念纳入城市规划和管理体系，有利于在快速城镇化过程中有效应对环境压力与挑战。

针对本研究范围而言，低核建筑密度的社区公园具有面积较大、NDVI平均值较高等特征。为了营造更加舒适的公园内部热环境，在绿地布局时，应注重对现有植被生境的保护和恢复，合理构建新的植被群落。条件允许时，可通过丰富公园内植被层次与规模来获得最佳冷岛效应，并将零散的绿地进行整合。城市核心区内的社区公园多为高核建筑密度，且易受周边灰色基础设施的影响。因此，在用地有限的情况下，应在城市核心区内增加社区公园等小面积绿地，同时增加社区公园

the average NDVI value of the parks under a high kernel building density was 0.149 and 0.184 for the parks under a low kernel building density (Fig. 10). Under the same factor conditions of the community parks and their surrounding environments, the parks under a high kernel building density expect a relatively larger size to support the optimal cooling effect, compared with the ones under a low kernel building density. However, this finding needs to be further verified because the number of the studied samples for the high kernel building density type is inadequate and the spectrum of park size is relatively narrow (mostly 1.2 ~ 2.6 hm²) (Table 3).

4.3 Suggestions on Index Adjustment in Urban Green Space System Planning

This paper delved into the threshold-size and optimal shape of community parks that support the best cooling effect, and found that the area, shape, and NDVI of the parks were significantly correlated with their cooling intensity, wherein the threshold-size of parks under a low and high kernel building density were 0.384hm² and 0.848hm² respectively. Both of them are smaller than the expected size of community parks (no less than 1 hm²) by the Standard for Classification of Urban Green space (2017). Proper adjustments on the green space index in community parks of urban green space system planning should be taken according to locality conditions. Particularly, it is conducive to plan small green spaces in the areas under a high kernel building density, giving full play to the ecological benefits of urban green spaces in mitigating the local UHI effect through renewal design and refined management measures. Embracing the ideas such as Nature-Based Solutions and ecological design, urban planning and management will perform a stronger capacity to address the challenges in the rapid urbanization.

In this research, the studied community parks under a low kernel building density have a larger average size and a higher average NDVI value. To create a more comfortable micro-climate in urban parks, park designers and managers should pay attention to the protection and restoration of existing vegetation habitats and the establishment of new plant communities. The best UCI effect can be obtained by enriching the vegetation structures and scales and improving the connectivity of the green spaces within the park. Community parks within central urban areas are often under a high kernel building density and prone to the environmental impacts by grey infrastructures in the surroundings. In this sense, under the inventory planning background, the cooling effect of community parks in central areas can be improved by adding more small-scale green spaces, increasing the compactness of parks—making the parks in a more regular shape—and enhancing the
的紧凑度，使公园形状更为规则，并适当提高植被郁闭度和连续性，提升公园的降温效果。

4.4 研究贡献与展望

本研究分析了南京市中心城区52个社区公园对城市热岛效应的缓解作用，探究了小尺度公园在最佳降温效果下的面积阈值与形状规律，研究成果具备一定的普适性。

研究尚有一定不足。首先，受限于研究样本与方法，本文以林地为主的社区公园占80%以上，缺少对包含水体社区公园的研究，尚未进一步展开探讨草本地被、灌木、乔木等具体覆被类型对于热岛效应缓解作用差异；其次，虽然本文在数据来源和研究对象的选择上尽量避免了气象等因子对温度的影响，但根据以往研究发现，气象背景条件（降水、风速、相对湿度等）对绿地的降温效果有显著影响[17][40]，因此，研究对以上气象背景条件的综合效应探论仍显不足；再次，对于社区公园降温强度的季节和昼夜差异，不同气候带和人文地理特征下的空间分异等问题也有待进一步研讨。因此，基于不同城市的研究还需考虑地域、季节、气象等背景因素的影响。

5 结论

本文基于遥感影像、ArcGIS及统计学工具与方法，通过分析南京市中心城区社区公园与降温强度的相关影响因素，探讨缓解城市热岛效应的最佳社区公园面积阈值和形状规律。研究得到如下结论：

1) 通过对样本社区公园建立缓冲区，构建公园与周边环境温度变化的三次多项式模型，发现随着缓冲带距离的增加，降温强度逐渐减小，并最终趋于0℃。

2) 在社区公园降温强度的影响因素中，降温强度与NDVI（R = 0.354, p < 0.01）、AREA（R = 0.467, p < 0.001）和CI（R = 0.403, p < 0.001）呈正相关，与公园温度（R = -0.683, p < 0.001）和LSI（R = -0.393, p < 0.001）呈负相关。表明当社区公园在一定范围内具有更大的面积、更高的NDVI以及更规则的形状时，其降温效果最佳。

3) 在不同核建筑密度的社区公园最佳降温强度方面，低核建筑密度的社区公园面积阈值为0.384hm²，高核建筑密度的社区公园面积阈值为0.848hm²。
4) Analyzing the shape characteristics of community parks with circularity ratio of CI, it showed that the relation between CI and their cooling intensity can be expressed as an exponential function, the optimal cooling effect would occur when CI value was close to 1 (i.e., the park in a shape of circle or square). LAF

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4) Using circularity ratio紧凑度分析社区公园的形状特征，其紧凑度指数与降温强度的关系符合指数函数，公园趋于圆形或正方形（CI趋于1）时，降温效果最为显著。LAF

4) Analyzing the shape characteristics of community parks with circularity ratio of CI, it showed that the relation between CI and their cooling intensity can be expressed as an exponential function, the optimal cooling effect would occur when CI value was close to 1 (i.e., the park in a shape of circle or square). LAF

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