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Spatial and Temporal Evolution of Multi-scale Green Space Environments and Urban Heat Islands: A Case Study of Beijing Sub-center

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With the rapid development of global industrialization and urbanization and the aggravation of climate warming, the urban heat island (UHI) effect has become an important environmental problem affecting human survival and development. In 2020, China clearly set a "dual carbon" target. Because the location and layout of urban green space are related to the function of carbon sink, the study of the relationship between the construction of urban green spaces and the heat island effect is of great significance. This study was based on Landsat 8 remote sensing images of the Tongzhou District, Beijing, from 2013 to 2019 and examined the effect of urban green space construction and the heat island effect in the Tongzhou District at three scales: the macro level of the overall construction environment, the meso level of the urban area, and the micro level of the individual park. The results show that: (1) when the vegetation coverage was increased by 10% in the Tongzhou District, the temperature decreased by 0.58–0.68 ℃; (2) the change in the heat island in the Tongzhou District had a circular layered structure, the degree of mitigation produced by green space in different circles differed, and the effect of urban and rural transition areas was obvious; and (3) parks have different effects on the temperature drop inside and outside the park. The cooling benefit was higher when the area of an individual park was 105 ha or less, and a park including both forest and wetland had better cooling ability. This study clarifies the direction of urban space cooling and carbon control at different levels and proposes a multi-scale planning decision–making process for urban green space based on temperature orientation, thereby providing a theoretical reference for macro policy, standards, planning, and park design of urban green spaces.

1. Introduction

Because of rapid urbanization and industrialization, global carbon emissions have increased sharply, and climate warming has become an increasingly prominent problem. The

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intensification of the urban heat island (UHI) effect has brought great challenges to urban sustainable development. Under the "double carbon" goal of "carbon peak by 2030 and carbon neutrality by 2060", the implementation of low-carbon strategies in cities has become the main path to achieve reduction in carbon emissions.(1) Establishing a system of urban green spaces is important for creating urban carbon sinks, carbon emission reduction, and mitigation of the heat island effect. Multi-scale comparison of the relationship between urban green space construction and heat island effect is of great significance for optimizing the spatial layout of carbon sinks in urban green space.

The UHI effect refers to the phenomenon that the temperature in cities is significantly higher than that in the suburbs.(2) The concept of the UHI was first proposed by Manley in 1958.(3) Since then, research on the effect has attracted extensive attention from scholars around the world, and a large number of relevant studies on the impact of urban green space on the heat island effect have been conducted.(4) In terms of measuring the heat island effect, surface UHI intensity based on remote sensing images,(5) cooling intensity of urban green spaces,(6) the cooling capability of green space cool islands,(7) and other indicators have been used. A large number of studies have shown that, among the factors having a significant impact on the UHI effect, the spatial scale of urban green spaces,(8) the landscape patterns of green spaces,(9) and the scale and intensity of land use(10) are important.

A close relationship exists between the urban thermal environment and urban planning.(11) At the macro level, the surface temperature of natural land, such as green space and bodies of water, is lower than that of land with construction.(12) The proportion of landscape area occupied by green patches is significantly and negatively correlated with land surface temperature (LST).(13) Increasing the area of urban green patches can effectively reduce the surface temperature.(14) At the meso-level, urban ecological and construction spaces have different green space configurations and structural layout requirements.(15) Urban functional layout is closely related to the spatial distribution of the heat island effect.(16) At the micro level, the main factors affecting the temperature inside a park include the ratio of the park's perimeter to area, vegetation coverage, and green area.(17) Reasonable adjustments in the area, the perimeter, and the shape of urban green space can alleviate the heat island effect.(18) In terms of relevant studies on UHIs in the Tongzhou District of Beijing, Fu *et al.*(19) explored the spatio-temporal variation and factors affecting the UHI effect in the Tongzhou District and found that the effect of the heat island in Tongzhou District weakened when the urban cold island strengthened; Xie *et al.*(20) found that the distribution pattern of a sub-central heat island in Beijing had a polycentric structure.

At present, most studies on the UHI effect and green space construction start at a single scale. Research on the Tongzhou District lacks a multi-scale perspective, and the relationship between urban green space and the heat island effect at different scales has not been extensively explored. Therefore, we studied the heat island effect in the Beijing sub-center at three levels: the macro scale (Tongzhou District), the meso scale (subdistrict), and the micro scale (park green space), to explore the relationship between the construction of urban green space and the spatio-temporal evolution of the heat island effect in the Tongzhou District. The correlation between the overall constructed environment and heat island intensity in the Tongzhou area was explored at the macro scale. We probed the effect of green space changes in different urban circles on the heat island effect within the smallest administrative and statistic unit – the town (subdistrict) – at the mesoscale. The effects of spatial characteristics of individual parks on the mitigation of the heat island effect were studied at the micro scale. The relationship between urban green space systems and the spatio-temporal evolution of the heat island effect was systematically studied by connecting the three scales: urban green space system planning, green space construction in different urban areas, and park planning and design. The conclusions provide a scientific basis for the Tongzhou District to further optimize the layout of urban green space resources and build a green, healthy, and sustainable territorial space and to serve as a significant reference for other cities to cope with the heat island effect in the future.

2. Research Object and Methods

2.1 Study area and data sources

The planning of the Beijing sub-center was proposed to adjust the spatial pattern of Beijing and expand new development space. The planning area is the original planned construction area of Tongzhou New Town, and the peripheral control area is the other area of the Tongzhou District. We took the Tongzhou District as the research object; it is located at 116°32’–116°56’ east longitude, 39°36’–40°02’ north latitude, with a total area of 906 km² (Fig. 1). With the rapid urbanization of Beijing, the Tongzhou District has experienced the development process from a small county in Hebei to Beijing’s suburb area, then to Beijing’s sub-center.

Currently, the Tongzhou District, which is a key area for green development of urban and rural construction, focuses on eco-oriented planning of the new town. To alleviate the heat island effect caused by the rapid urbanization in the Tongzhou District, relevant government departments have issued a series of plans for green space construction to promote sustainable development, such as “Beijing Green Space System Planning (2004–2020)”(21) and “Beijing Urban Master Plan (2016–2035)”.(22)

The data source for this study is the remote images from the Landsat 8 Operational Land Imager–Thermal Infrared Sensor (OLI–TIRS) satellite. Since the satellite was put into use in 2013 and the heat island effect is most obvious in summer, satellite images from September 1, 2013, August 22, 2015, September 12, 2017, and September 2, 2019 were selected for analysis under the condition that the temperature was similar and the cloud cover was less than 5% at the shooting time. The spatial resolution of the remote sensing images is 30 × 30 m^2.

2.2 Acquisition of surface built environment information

The ENVI5.3 platform was used to perform radiometric calibration and atmospheric correction on the remote images to obtain environmental information on surface construction in Tongzhou.

In this study, the heat island intensity (HII) was used to characterize the intensity of the UHI effect, and the data was processed according to

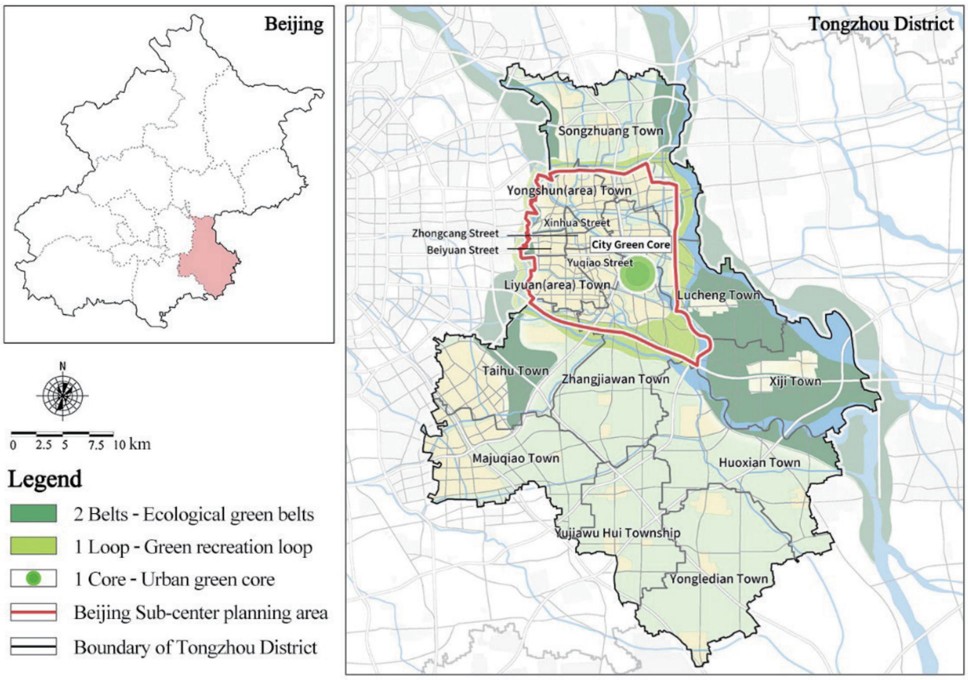

Fig. 1. (Color online) Study location and green space system structure in the Tongzhou District [revised according to the Beijing Urban Master Plan (2016–2035)].

$$HII = \frac{T_L - T_{min}}{T_{max} - T_{min}}, \quad (1)$$

where HII represents the HII index, T_L is the surface temperature of each pixel obtained by remote sensing inversion, and T_{max} and T_{min} represent the highest temperature and the lowest temperature, respectively. The mixed pixel decomposition method was used to calculate the vegetation coverage (F_V), that is, the land types of the whole image were roughly divided into water, vegetation, and construction land.

The specific calculation is shown in

$$F_V = (NDVI - NDVI_S)/(NDVI_V - NDVI_S), \quad (2)$$

where *NDVI* is the normalized differential vegetation index, $NDVI_s$ is the NDVI value of bare soil or unvegetated area, and $NDVI_v$ represents the *NDVI* value of pixels completely covered by vegetation.

NDBI is the normalized differential building index, which represents the percentage of the vertical projected area of the building on the ground in the statistical area.

$$NDBI = (NIR - SWIR)/(NIR + SWIR), \quad (3)$$

Here, *NIR* is the near-infrared light, and short-wave infrared (*SWIR*) is the longest wavelength.[23]

2.3 Zoning statistics for changes in building environment

To explore environmental changes due to the different construction types in different areas of the Tongzhou District, data were processed through land use supervised classification, land transfer matrix, and Arc graphic information system (ArcGIS) zoning statistics.

According to "Classification of Land Use Status (GB/T 21010-2017)",[24] "Urban Green Space Planning Standard (GB/T51346-2019)",[25] and "Urban Green Space Classification Standard (CJJ/T 85-2017)",[26] the land use types were divided into green space (grassland, forest land, cultivated land, water areas) and non-green space (industrial, mining, and residential land in urban and rural areas), and the maximum likelihood method was used to classify land use types on Landsat 8 remote sensing images of the Tongzhou District in 2013 and 2019. Finally, ArcGIS calculated the land transfer matrix data by zoning to obtain the changes in the built environment of different subdistricts in the Tongzhou District.

2.4 Calculation of cooling performance and landscape characteristic index

The typical parks in the Tongzhou District were selected to calculate the cooling performance of the parks and the landscape characteristic values, after which a correlation analysis was carried out. The cooling performance of the parks was comprehensively judged by the effective cooling distance, the cooling extent of the surrounding urban built environment, and the internal average temperature.

In terms of park cooling performance, the cooling extent can be calculated according to

$$PCI = T_{max} - T_{park}, \tag{4}$$

where PCI is the maximum cooling extent of the park; the larger its value, the stronger the cooling performance of the city. The term T_{park} is the average temperature in the park, and T_{max} is the temperature at the park boundary (L_{max}). The term L_{max} is the maximum distance affected by park cooling.

The second step was to calculate the effective cooling distance of the park's cold island. Taking 80 m as the gradient, a multi-ring buffer zone was constructed within 0–800 m around the park, and the difference between the average temperature in each buffer zone and the average temperature in its adjacent buffer zone was calculated to obtain the temperature changes in the park buffer zone. A multiple-function fitting curve of the temperature difference and effective cooling distance was created using MATLAB. The effective cooling distance was obtained according to the intersection point between the curve and the x–axis.

Finally, the characteristics of the parks were selected. The morphological characteristics included the area of the urban park, the perimeter of the park, and the shape index.[15] The area and proportion of the construction land, vegetation, and water area of the park were selected as the constituent characteristic index.[27] The shape index (D) measured the complexity or shape of the boundary of the green patch, as shown in

$$D = \frac{S}{2\sqrt{\pi A}}. \quad (5)$$

3. Correlation between Surface Built Environment and Heat Island Intensity at Macroscopic Scale

The relocation of the focus of green space construction and the expansion of urban development in the Tongzhou District have resulted in a green space structure of "one center, one ring, two belts, and two districts" for the sub-center.(28)

3.1 Spatial and temporal evolutionary characteristics

The results of the heat island intensity analysis show that the overall temperature of the Tongzhou district is on the rise and the extent of the heat island is gradually expanding (Fig. 2). The red area is a region of high heat island intensity with a value of 0.6–1, which is slightly higher than the reported urban heat island intensity of about 0.5 in Beijing.(29) From 2013 to 2015, the surface temperature of the western core construction area increased rapidly, and the heat island effect spread from west to southeast; from 2015 to 2017, the heat island intensity decreased in the southeast direction, and two major concentrated high-temperature areas appeared in the west and northwest; from 2017 to 2019, the overall temperature in the west and north increased, and the temperature in the southeast increased slightly, showing decreasing temperature characteristics in the northwest-southeast direction. The distribution is roughly the same as that of the Beijing urban sub-center, the Taima group, and the centralized construction area of new towns.

From the perspective of vegetation coverage, the construction of green areas in the Tongzhou District is favorable. The vegetation coverage in the core construction area continues to decline, while the peripheral villages have tended to be built centrally in recent years, and the vegetation coverage on both sides of the river has changed less. The vegetation in the rural areas has gradually recovered from the fragmentation of green space caused by the expansion of villages to the vegetation coverage level in 2013.

In terms of construction intensity, the high-intensity areas are concentrated in the center of each group, indicating that the urban construction in the Tongzhou District is basically consistent with the planning structure. From the analytical results, the construction intensity of the concentrated construction area in the Tongzhou district has increased year by year, and the increase is more significant in the area of the Beijing City Vice Center and the south side of Universal Studios and its surrounding. The construction of the entire Tongzhou district tends to be concentrated, being high in the northwest and low in the southeast.

3.2 Correlation between surface temperature changes and vegetation cover

To visually compare the correspondence between vegetation cover and heat island intensity in spatial and temporal changes, a profile line analysis of surface temperature and vegetation

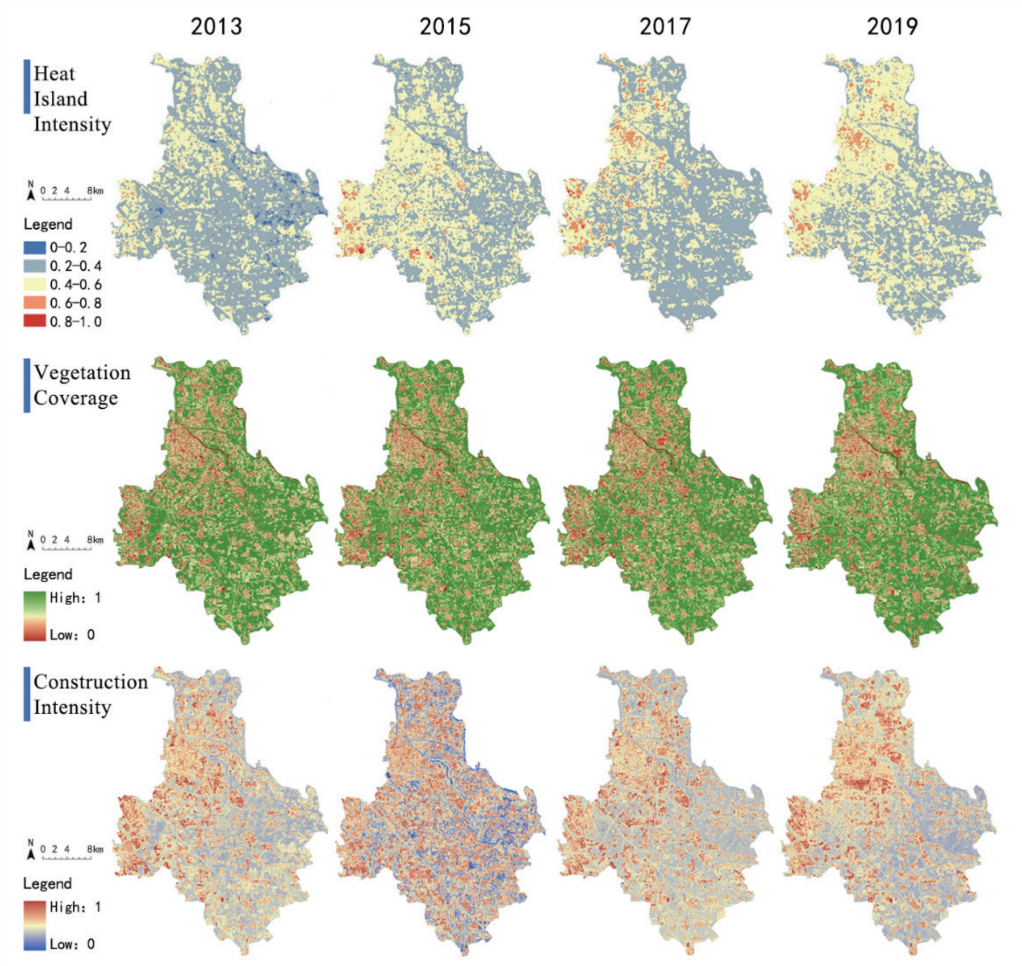

Fig. 2. (Color online) Spatial and temporal changes in heat island intensity, vegetation cover, and construction degree in the Tongzhou District, 2013–2019.

cover data was conducted using ArcGIS. The north-south and east-west profile lines through the Beijing sub-center (Fig. 3) were selected to compare the fluctuation trends in vegetation cover and surface temperature (Fig. 4). It was found that surface temperature and vegetation cover were negatively correlated overall; when vegetation cover decreased significantly, the surface temperature in most areas showed a negative correlation with elastic upward changes, and there was a small decrease in temperature after the increase in a small part of the area, which might be related to vegetation growth or to other factors affecting temperature. The few areas with positive correlations between vegetation cover and surface temperature are located in the river water and its surrounding areas, where the water temperature is low and there is little vegetation, so the surface temperature is affected by vegetation to a lesser extent. Taking the 1-1 profile in August 2019 as an example, the vegetation cover values range from 0 to 1 and the temperature values range from 28.1 to 42.2°C; when the vegetation cover is 1, the temperature is 28.4°C, and when the vegetation cover is 0, the temperature is 40.5°C; the areas with large fluctuations in vegetation cover are mostly located in the sub-center of Beijing and the surrounding areas.

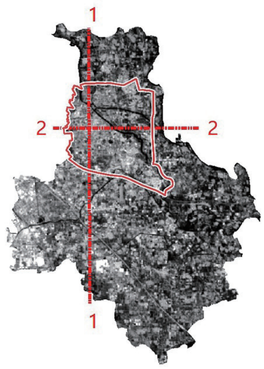

Fig. 3. (Color online) Schematic diagram of the profile line.

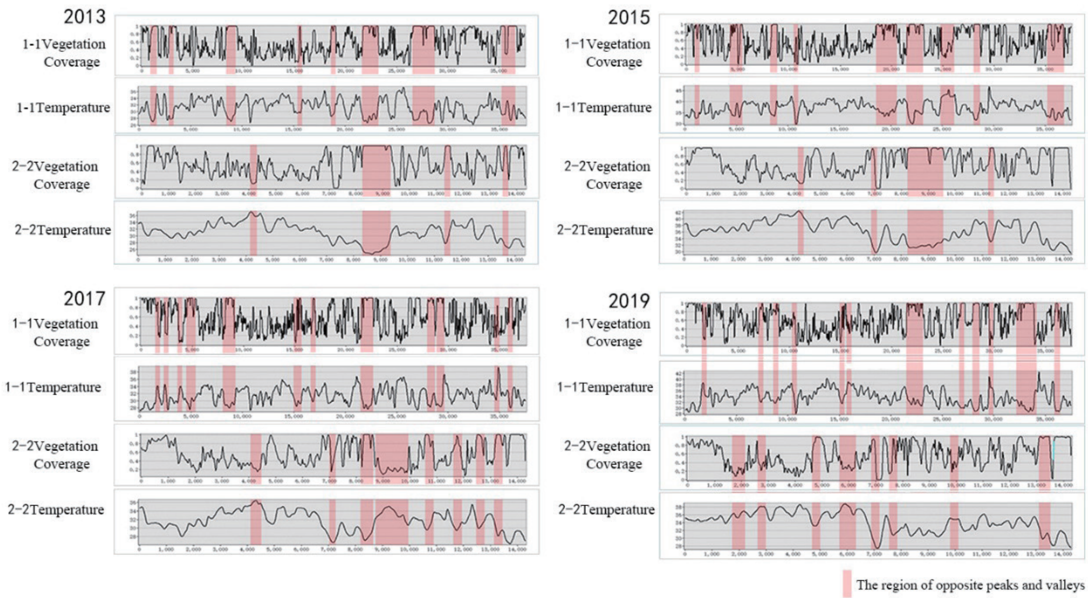

Fig. 4. (Color online) Analysis of the profile line.

To study the heat island effect changes in the whole Tongzhou area, ArcGIS was used to divide the shape file of Tongzhou area into 1750 "900 × 900 m^2" grids; each grid contained 900 grids of raw information on surface temperature and vegetation cover. The grids were turned into points to represent the average surface temperature and vegetation cover of each grid (Fig. 5), and regression analysis was applied to study the correlation between vegetation cover and surface temperature (Fig. 6).

Overall, according to the slope of the regression line, for every 10% increase in vegetation cover, the temperature decreased by 0.58–0.68 ℃ (all linear regressions are significant at the 0.005 level), and the comparison shows that the effect of vegetation cover on surface cooling gradually weakened from 2013 to 2017 and then was enhanced again in 2019, indicating that the green space construction in Beijing's urban sub-center has improved the effect of green space in the Tongzhou District to mitigate the heat island effect. A separate analysis of points with large

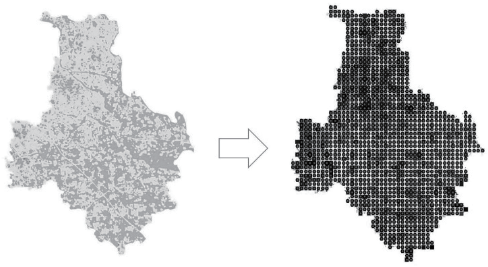

Fig. 5. Schematic diagram of the grid analysis.

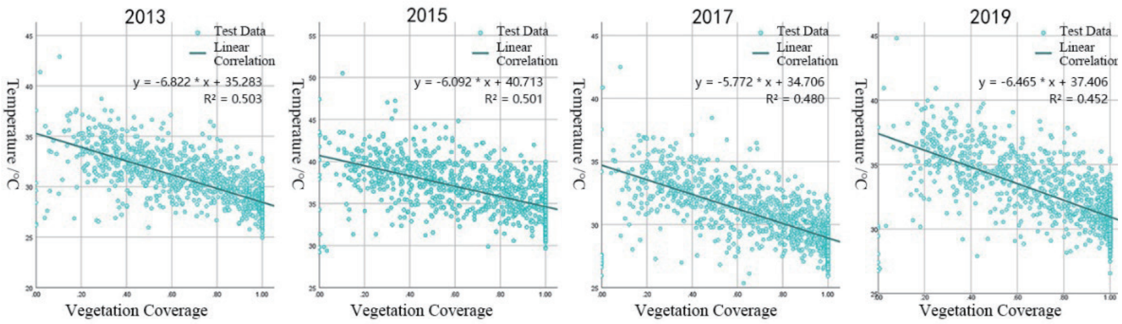

Fig. 6. (Color online) Correlation analysis between surface temperature and vegetation cover in the Tongzhou District, 2013–2019.

deviations from the linear relationship reveals that, for points with higher surface temperature and vegetation cover, the development intensity of the surrounding urban built environment is also higher, while points with lower surface temperature and vegetation cover are often close to water areas or large wetlands.

4. Green Space Change and UHI at Subdistrict Scale

Both an increase in urban land use and changes in the nature of the urban underlying surface affect the urban climate.(30) The construction of Beijing's urban sub-center makes the land use situation in different districts of the Tongzhou District significantly different, so the degree of green space construction in different districts to mitigate the UHIs is also different. As the subdistrict is the smallest administrative and statistic unit in China, the subdistrict scale was chosen to represent the meso scale.

4.1 Spatial and temporal changes in green space distribution and UHIs

ArcGIS was used to calculate and record the annual surface temperature of the Tongzhou District and the boundaries of towns and townships in the District. The average surface temperature and vegetation coverage of each subdistrict are obtained to represent the change in the UHIs and green space distribution of each subdistrict (Fig. 7).

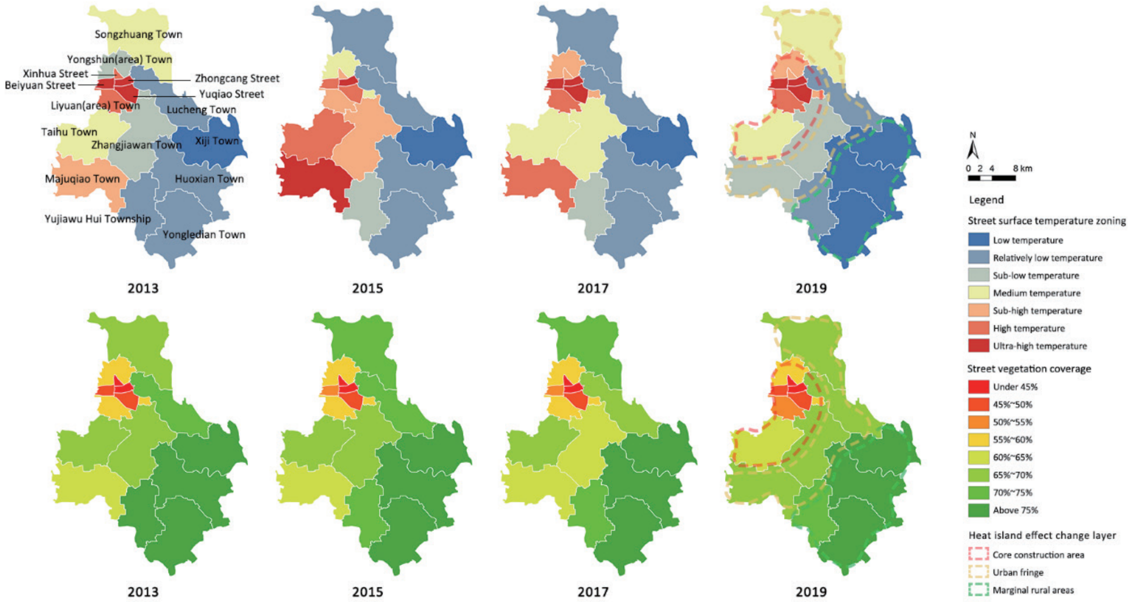

Fig. 7. (Color online) Distribution map of surface temperature zoning and greenbelt ratio of each subdistrict in the Tongzhou District from 2013 to 2019.

The profile of the change in UHIs in the Tongzhou District has a circlular structure, and the green space, HII, and urban spatial structure tend to match. By comparing the spatial changes in the surface temperature and the vegetation coverage from 2013 to 2019, Tongzhou can be divided into three regions: (1) the core construction area, (2) the urban-rural transition zone, and (3) marginal rural areas. Most of the core construction areas have been urbanized due to construction by the government. During 2013–2019, some villages in the urban and rural transition area were demolished and merged, gradually being transformed into a new type of town with an intensive layout, and the overall green space coverage increased. The marginal rural areas have always maintained a high green coverage.

On the whole, the NDVI of the Tongzhou District is declining from the northwest core construction area to the southeast. The NDVI of the towns of Zhongcang, Xinhua, Yuqiao, and Beiyuan in the core construction area has always been at a low level, with low green space coverage. Under the influence of the construction of the Tongzhou sub-center, the NDVI of Yongshun and Liyuan continues to decline; the NDVI in the urban and rural transition zone has been changing continuously, the green land restoration effect in Majuqiao Town and Zhangjiawan Town is obvious, and the NDVI in marginal rural areas has been at a high level.

4.2 Dynamic changes in green space in each subdistrict and UHIs

To reflect the dynamic change in green space in the Tongzhou District, the land use types in 2013 and 2019 were analyzed by superposition, and the land use change and land transfer matrix in the Tongzhou District from 2013 to 2019 were obtained (Fig. 8 and Table 1).

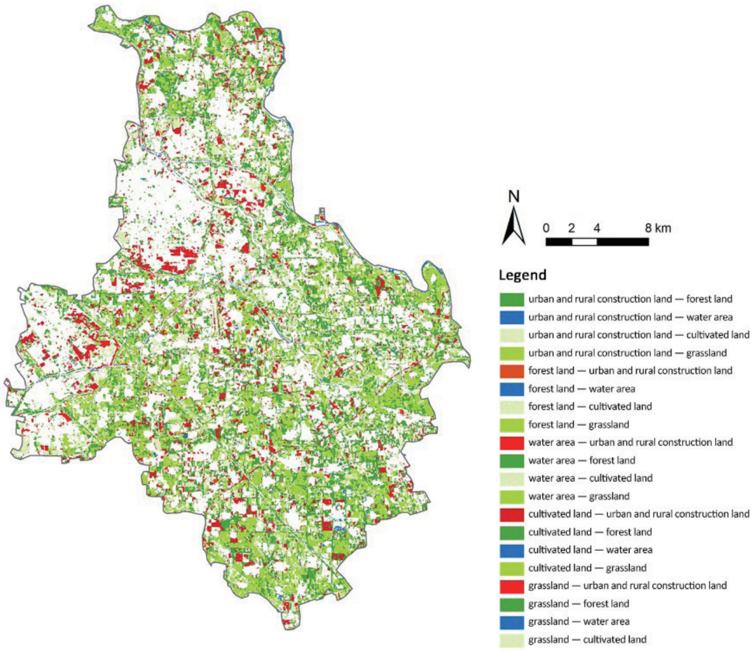

Fig. 8. (Color online) Map of change in land use in the Tongzhou District from 2013 to 2019.

Table 1
Land use transfer matrix for the Tongzhou District from 2013 to 2019 (area unit: km^2).

Year		2013							
Year	Land-use Type	Urban and Rural Construction Land	Grassland	Arable land	Woodland	Water	Total	Increment	Rate of Change (%)
2019	Urban and Rural Construction Land	317.80	9.89	47.35	4.05	2.76	381.85	−114.52	−0.23
	Grassland	64.20	33.41	79.51	14.31	1.30	192.73	110.71	1.35
	Arable land	38.18	16.36	70.26	5.00	1.09	130.88	−123.69	−0.49
	Woodland	72.07	22.10	56.30	23.51	1.76	175.74	128.55	2.72
	Water	4.11	0.26	1.16	0.32	15.16	21.01	−1.05	−0.05
	Total	496.37	82.02	254.57	47.19	22.07	902.22	—	—

It can be seen from the land use transfer matrix of the Tongzhou District that the total amount of urban green space increased by 114.52 km^2 in 2013–2019, and those of forest land and grassland increased by 128.55 and 110.71 km^2, respectively. That of cultivated land decreased by 123.69 km^2, most being transformed into grassland and forest land. The area of water was reduced by 1.05 km^2, but that number is small. That of non-green space (urban and rural industrial residential land) has decreased significantly, mainly by being converted to forest land and cultivated land.

The change in the green space in the Tongzhou District was divided into towns using ArcGIS. Owing to the small sample size of 15, ten random points are taken from each town to generate ten Tyson polygons. Finally, the incremental percentages of green space and the scatter map of temperature increments of 150 samples were obtained.

By analyzing the green space change and temperature change of each ring town (Fig. 9), we found that the green space increment was negatively related to the temperature increment. The core construction area was greatly affected by high-intensity development and construction, with high-temperature increments and low green space increments. In addition, green space in many areas was significantly reduced, and the increase in green space had less of an effect on the mitigation of UHIs. In the urban and rural transition zones, urban greening and urban construction were carried out at the same time. The span of temperature increments and green space increments was large, showing a negative correlation overall. The increase in green space has an obvious effect on controlling the temperature increments. The temperature increments in the marginal rural areas were low, and the green space increments were high, which is a negative correlation, but the correlation is relatively low in the transition areas.

In general, the percentage of urban green space increments has a significantly negative relation to the urban temperature increments. The degree of mitigation of UHIs by green space construction in different circles is different, but the role of green space construction in urban and rural transition areas in mitigating UHIs is obvious.

5. Cooling Island Effect of Parks at the Micro Scale

City parks are the basic components of urban green space systems, and parks have an important impact on improving the urban microclimate and the mitigation of heat island effects.[31]

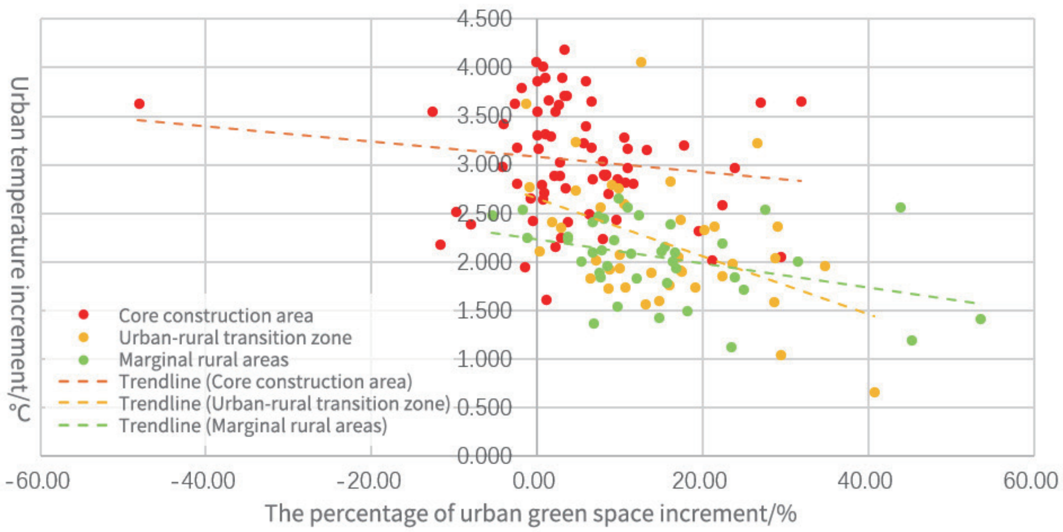

Fig. 9. (Color online) Scatter plot and correlation of green space changes and temperature changes in each ring town in the Tongzhou District.

To improve accuracy, samples with a high percentage of other green areas in the surrounding area and close to other parks were removed, and 15 samples of parks with different areas were selected; these parks are basically distributed within the area of the Beijing sub-center (Fig. 10). In the correlation analysis, owing to the large gap in other data units that may lead to abnormal trends of change in the fitted functions, the urban green center park and Tongzhou Canal Park, both with areas larger than 1000 ha, were removed to reduce bias in the results.

5.1 Effect on the surrounding environment

The data on the effective cooling distance and cooling extent along with each characteristic index and constitutive characteristic index was imported into Statistical Package for the Social Sciences (SPSS), and the factors with higher fitting coefficients were selected for analysis to obtain each fitting function, and a comprehensive comparison of the coefficient of determination (R^2) of different fits revealed that the linear function fit was the best (Fig. 11).

From this analysis, we made the following conclusions:

(1) The cooling effect of the surrounding environment is significantly strengthened by increasing the green area, perimeter, vegetation area, and water area of the parks, with all regressions significant at the 0.006 level.

(2) Neither the construction area nor the shape ratio of the parks has a significant effect on reducing the temperature of the surrounding environment.

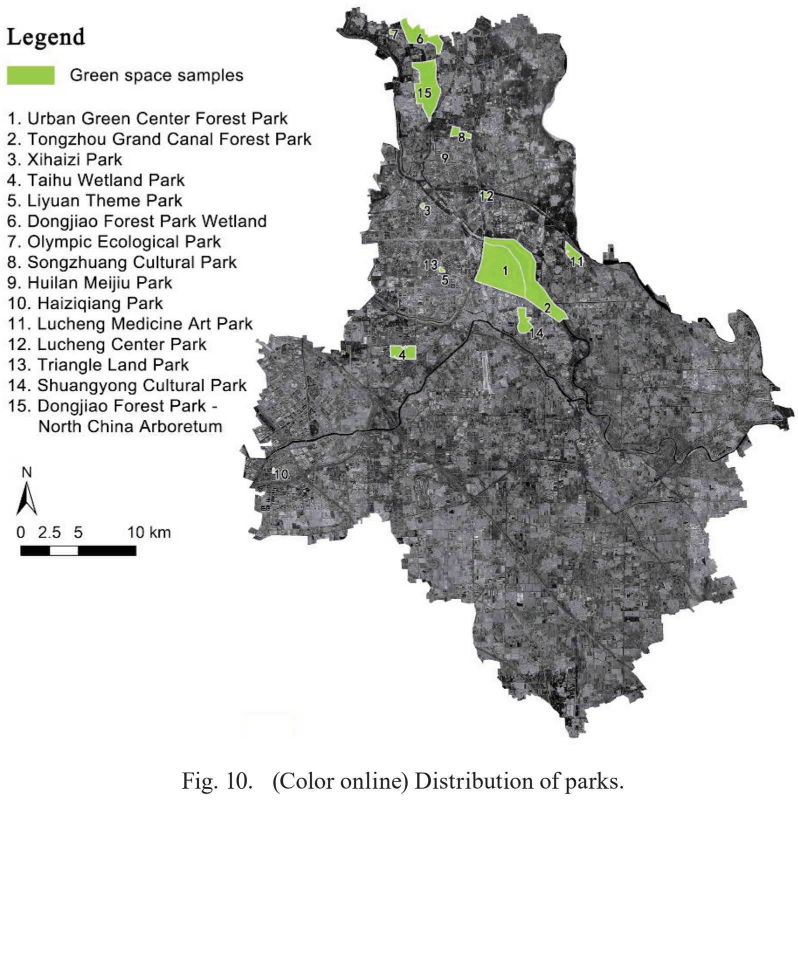

Fig. 10. (Color online) Distribution of parks.

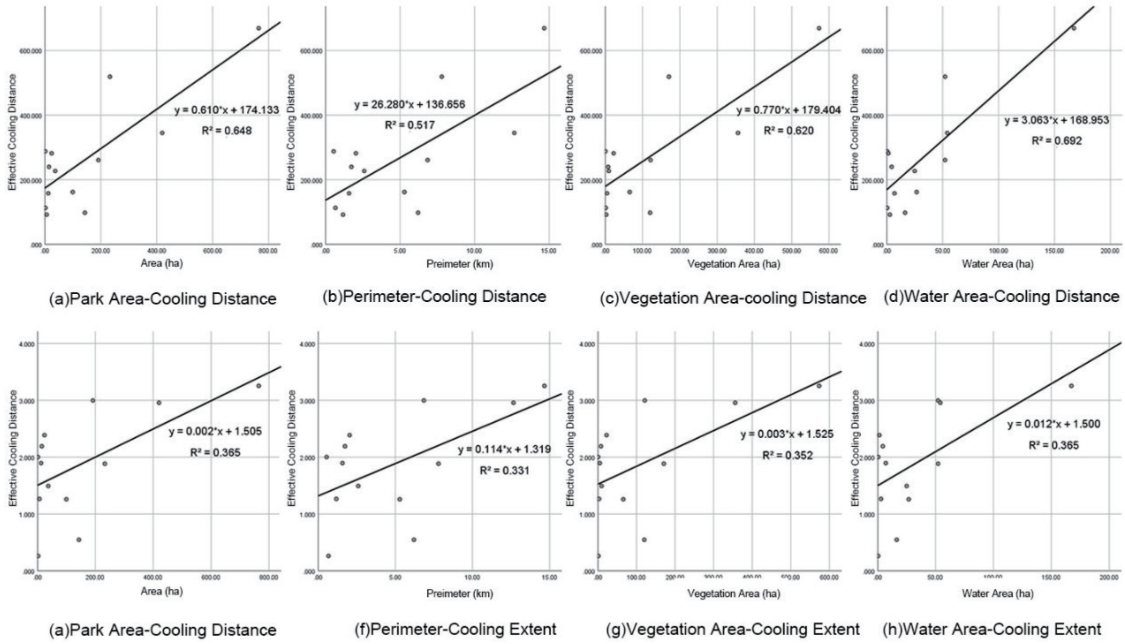

Fig. 11. Correlation curves of characteristic indicators for cooling distance and cooling extent.

(3) The cooling extent is affected by the surrounding urban environment and is not strongly correlated with a single factor.

5.2 Effect on internal temperature

The correlations between a park's internal temperature and each characteristic index were analyzed by SPSS curve fitting, and the results of each regression correlated significantly at the 0.001 level.

Figure 12(a) shows that the average park temperature decreased with increasing park area. When the park area increased from 1 ha to 105 ha, the park temperature decreased by about 4 °C; however, when the area increased from 105 to 200 ha, the park temperature decreased by only about 0.5 °C. Therefore, the cooling benefit of the park is higher when its area is 105 ha or less. This reference value is higher than the lower area requirement for comprehensive parks in the Urban Green Space Planning Standard (GB/T51346-2019)(25) and Urban Green Space Classification Standard (CJJ/T 85-2017),(26) which is 50 ha and 10 ha, respectively, and higher than the threshold value of 55 ha found by Hua (27) and others for the cold island enhancement effect in Xiamen coastal urban parks.

Areas of water and vegetation have a large effect on the internal temperature of the park, and, when the water and vegetation areas increase, the park temperature decreases significantly [Figs. 12(b) and 12(c)]. Park vegetation covering absorbs heat and releases water into the surrounding environment, thus reducing the surrounding air temperature.(32) It is advisable to build parks to increase the areas of vegetation and water to enhance the cooling effect.

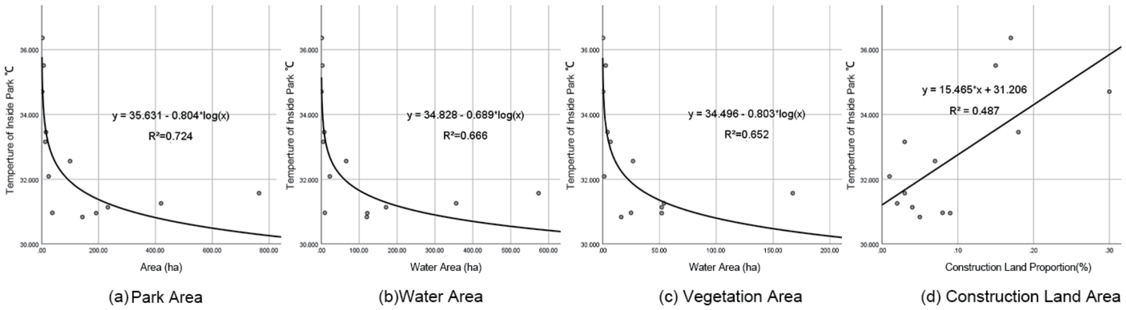

Fig. 12. Schematic diagram of the results of the regression analysis of park landscape features and internal temperature.

The ratio of park construction land area to park surface temperature correlates positively, and an increase in the area of construction land leads to an increase in park surface temperature [Fig. 12(d)]. The park construction land includes impervious hardened pavement areas and building areas in the park, and heat is exchanged more in the form of sensed heat, which leads to a rapid increase in surface temperature.(33) It is advisable to minimize the area of construction land to reduce the average temperature of a park during planning and design.

6. Discussion and Prospect

Researchers on the UHI effect and green space construction generally take either the overall macro administrative district or the micro individual park as the research object, interpret remote-sensing image data, analyze the relationship between regional heat island changes and green space construction, or explore what kind of green space can produce a more ideal cold island effect. At the meso level, studies and analyses focus on the degree of aggregation, landscape fragmentation, landscape evenness, and other characteristics of green space pattern(34) to explore a more reasonable green space layout structure. The Ministry of Housing and Urban Rural Development also provides guidance on planning structure, classification, and reference indexes for the green space system in relevant standards and design specifications.(25,26)

However, the construction of urban green space is often closely related to urban planning policies, and under the "double carbon" target, the construction of new urban towns, new districts, and even individual parks may have an unexpected impact on the urban thermal environment. Urban planning for the Beijing urban sub-center is ecologically oriented, which represents the trend of future ecocity construction to some extent. On the basis of our research, we summarize herein the temperature-based multi-scale decision process in the planning of urban green space (Fig. 13).

Because the positioning of the Tongzhou District as Beijing's urban sub-center has been clarified, the local ecological structure has been reasonably protected during construction. In 2018, Beijing started a new round of afforestation and greening(35) and controlled the boundary and intensity of development according to relevant planning,(28) as a consequence of which the ecological base was partially restored after 2019. The distribution circle of LST and green land

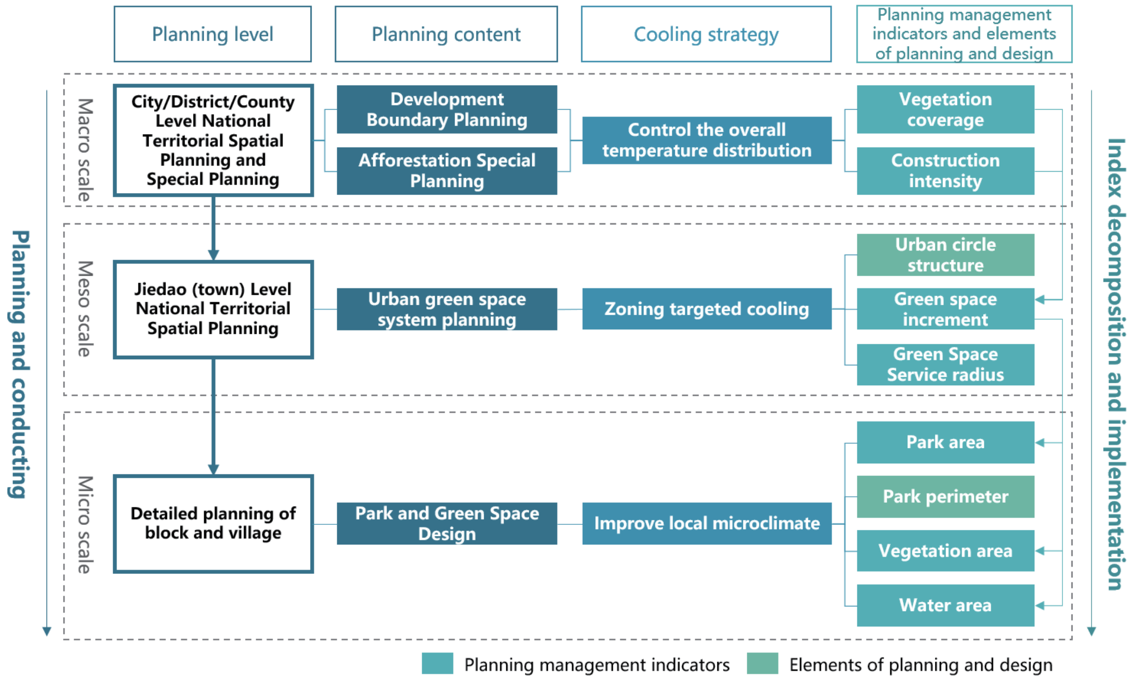

Fig. 13. (Color online) Guidance for the temperature-based multi-scale decision process for the planning of urban green space.

rate at the town level was also gradually formed. The urban–rural transition zone, under green space construction, such as an urban green center and a green corridor on the east side of the sub-center, can better control the increase in LST, which shows that the protective construction of green space in the Beijing green belts is crucial to alleviate the urban heat island. By 2019, a large number of urban parks had been built in the core construction area of Tongzhou, and this had improved the local microclimate.

Under the "double carbon" goal, China has put great effort into promoting the low–carbon transition of urban–rural construction and management patterns. New requirements for green and low-carbon considerations have been proposed, which impact the implementation in each link of urban–rural planning, construction, and management. How to make better use of the carbon sink and emission reduction capacity of urban green space and mitigate the heat island effect are the key problems that the current planning for urban green space systems need to solve.

In general, from the macro to the meso, the green space structure in the Tongzhou District has alleviated the heat island effect, but the structure has not resulted in overall planning and coordination with individual park construction. In the future, the planning for the regional green space system of a city should refer to the regional heat island intensity distribution and scientifically determine the indicators of ecological structure and green space construction.

In the central urban area (especially the area of high heat island intensity between 0.6 and 1), the effective cooling distance index should be used to optimize the green space layout and improve cooling efficiency. In the urban–rural transition zone, the HII is between 0.2 and 0.6, so ecological corridors should be constructed to improve vegetation coverage. In the marginal rural areas, the HII is mostly lower than 0.4, so it is advisable to control the area of construction land and protect the ecological base. Relevant green space planning standards also need to refine green space area, vegetation coverage, and other indicators according to different urban areas to better guide the overall spatial layout and internal spatial structure of urban green space to alleviate the heat island effect and promote the realization of the "double carbon" goal. As the Tongzhou District is the urban sub-center of Beijing, its planning and construction have certain particularities. In the future, we must expand the sample capacity to further verify the universality and scientific basis of the conclusions.

7. Conclusions

Taking the Tongzhou District as an example, we conducted a multi-scale study at macro, meso, and micro levels, which enables us to more clearly explain the relationship between top-down green space planning and the spatial-temporal evolution of UHIs. Meanwhile, the direction of urban spatial cooling and carbon control at different levels can be clarified. It is also of great significance for the layout of a macro policy, normative standard formulation, all-level planning, and individual park design. Our main conclusions are as follows:

At the macro level, the changes in HII and the construction environment on the land surface in the Tongzhou District correspond to the planned structure in the main. With the construction of the urban sub-center in Beijing, the areas with high HII, high construction intensity, and low vegetation coverage gradually concentrated in the sub-center area and in the constructed areas of other villages and towns. In 2019, an increase in the vegetation coverage of 10% caused a decrease in temperature, indicating that the heat island effect had been improved by adding green space.

At the meso level, a circular structure was observed in the distribution of green space and heat island intensity of each town in the Tongzhou District, and the total amount of urban green space in most areas increased. The effect of green space construction on the mitigation of the heat island effect was different in different circles. The effect was clear in the urban-rural transition zone, whereas it was relatively small in the core built area and the marginal rural area.

At the micro level, urban parks reduce local surface temperature, which plays a key role in the mitigation of heat islands in the surrounding built environment. Increasing a park's area, perimeter, vegetation area, and water area can significantly promote a cooling effect in the surrounding environment. The inner cooling effect correlated positively with the park area, vegetation area, and water area. Parks with less than 105 ha of area had a higher cooling effect, and forest and wetland parks had a better cooling ability.

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