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Analysis of Urban Thermal Environment Improved by Blue-Green Spaces on the Landsat Data: A Case Study on Tianjin

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ABSTRACT: China's urbanization is characterized by rapid speed, large scale and high energy consumption, which causes a series of ecological problems. Among these problems, urban thermal environment is particularly prominent, and the most intuitive reflection is the heat island effect. It is of great significance to optimize the urban layout to give full play to the cooling effect of blue-green spaces for improving urban thermal environment. Compared with other methods, it is more extensive and feasible. However, the current research on urban thermal environment mostly focuses on revealing the driving effects of different land use, and lacks of in-depth discussions on blue-green spaces. Tianjin is located in the northeast of the North China Plain, and has a typical warm temperate sub-humid monsoon climate. This paper takes the six districts of Tianjin City as the research area, covering Heping District, Nankai District, Hongqiao District, Hebei District, Hexi District and Hedong District, with a total area of about 181.18 square kilometers. The typical climate and urbanization characteristics of Tianjin can provide reference for cities with the same characteristics. Firstly, this paper had adopted the Landsat changing scenario of the city gained during the periods of 2004, 2011 and 2017 to formulate the land surface temperature by Mono-window Algorithm, and divided the results into seven temperature zones by standard deviation classification method. In regard to blue-green spaces, this paper had identified Landsat satellite data by Maximum Likelihood Classifier, and classified land use into three categories: blue spaces, green spaces, and non-blue and green spaces. And, next, this paper had studied the correlation between the landscape pattern of blue-green spaces and urban thermal environment by Landscape Pattern Analysis, and used Moving-window Analysis to compare the relationship between thermal environment and blue-green spaces at different spatial scales. And so the research results prove that, the high-temperature regions of Tianjin has been expanding along with the expansion and agglomeration of the urban areas and across the river space restrictions, while the low-temperature regions of the city are mainly concentrated in the blue-green spaces, during the periods of 2004, 2011 and 2017. Furthermore, in the landscape pattern level, there is a significant negative correlation between patch perimeter index of blue-green spaces and land surface temperature, and a significant positive correlation between patch perimeter area ratio index of blue-green spaces and land surface temperature. In the multi-scale spatial pattern, the correlation between the Percent of Landscape of blue spaces patches and land surface temperature is the highest in the 1500 meters × 1500 meters sample, and the Percent of Landscape of green spaces patches and land surface temperature is the highest in the 300 meters × 300 meters sample. In addition, the improvement efficiency of thermal environment in blue spaces is higher. In the end, the optimization suggestions of adjusting the layout of blue-green spaces to effectively improve the urban thermal environment problem are proposed. By optimizing the blue-green space landscape patterns at the optimal scale, increasing the blue spaces in the northern high temperature range, widening and transforming the existing waterways, constructing riverside greenways and other strategies to effectively deal with the thermal environmental

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problems, improving the ecology and livability of the city. It is hoped to provide new ideas and references for the construction of ecological and livable city under the background of rapid urbanization. In the research process, due to the limitation of data sources, calculation methods and other factors, the relevant conclusion is still limited at the spatial scale. In the future research, the thermal environment and the pattern of blue-green spatial landscape at the fine scale will be studied.

KEY WORDS: *blue-green spaces; urban thermal environment; land surface temperature; landscape pattern*

Introduction

Cities, the vast carriers intricately intertwined with politics, economy, society, and culture, are human constructs that have gradually become a historical trend in the process of human development. Urbanization in China is characterized by its rapid pace, large scale, and high resource consumption, which has exacerbated a series of ecological problems with thermal environment issues being particularly prominent, manifested most strikingly in the urban heat island effect. The primary causes contributing to thermal environment issues can be attributed to two main factors: urbanization-induced landscape pattern evolution and alterations in the balance between urban surface energy and radiation due to changes in human production and lifestyle [1,2]. Currently, measures that can effectively ameliorate thermal environment issues can be broadly categorized into the following three types: (1) reducing anthropogenic heat sources by limiting motor vehicle travel and decreasing the usage frequency of air-conditioners; (2) enhancing infrastructure materials such as constructing reflective roofs or high-ratio heat capacity roads; (3) optimizing urban layout, for example, increasing the underlying surface of landscape, planning transportation in accordance with the prevailing summer wind direction [3-5]. However, improving infrastructure materials may pose high costs for many developing countries and regions. Hence, apart from minimizing anthropogenic heat sources, a more widely applicable and feasible approach lies in strategic planning that leverages the cooling impacts of green spaces and water bodies [3,6].

Presently, there are three main research methods employed in studying urban thermal environment issues. The first method involves satellite remote sensing image analysis, focusing on a macro scale. It offers advantages such as broad coverage and strong dynamism, albeit susceptible to accuracy issues and computational errors. In 1972, Rao et al. [7] conducted the first study on the urban heat island effect using satellite thermal infrared remote sensing in the mid-western coastal cities of the United States, paving the way for the widespread application of satellite remote sensing images. The second method is on-site observation and measurement, where early research data primarily originated from meteorological stations, similarly centered on a macro scale [8]. With the advancement of infrared thermometers, the "point method" was introduced, directing attention towards local microclimates; however, a significant drawback is the interchange of "point" observations for "area" outcomes. The third method involves computer simulation calculations, leaning towards a meso-micro scale range [9], offering highly visualized results but heavily reliant on external input data. With the enhancement in accuracy of satellite remote sensing image data, scholars have increasingly employed the first method for studying the patterns of urban thermal environment and landscape layout.

In the study of the regularities concerning urban thermal environment and landscape patterns, Singh Prafull et al.[10] creatively incorporated ecological assessments of blue-green spaces into thermal environment evaluations by analyzing surface temperature distribution characteristics in Lucknow of India over the past 12 years using Landsat data. This widened the perspective of thermal environment research and laid theoretical groundwork for the correlation between thermal environment and blue-green spaces. Ding Haiyong et al. [11], based on Landsat data from 2000 to 2015 in Nanjing, researched the evolution patterns of urban heat island effects and landscape layouts, pinpointing significant cooling effects of vegetation and water surfaces. Qin Menglin et al. [12] conducted a study on the spatial evolution of heat islands in urban clusters from 2001 to 2015 using MODIS land surface temperature data, identifying wooded areas as stable cold spots within the city. Shen Zhongjian et al. [1], using Landsat as their data source, analyzed the spatiotemporal patterns of heat islands in Fujian delta urban agglomeration from 1996 to 2017, revealing wooded areas and water bodies as stable cold sources. Deng Yujiao et al. [13], based on remote sensing data from the Guangdong-Hong Kong-Macao Greater Bay Area from 2003 to 2018, analyzed the spatio-temporal distribution characteristics of urban heat islands and highlighted the significant impact of vegetation on heat islands. These studies demonstrate a systematic spatial relationship between urban thermal environment and land use, emphasizing the significant ameliorative effects of blue-green spaces such as green spaces and water bodies.

However, current research on urban thermal environments tends to focus on revealing the driving influences of different land use types, lacking in-depth exploration of blue-green spaces. This paper takes a blue-green spaces perspective, emphasizing the spatiotemporal evolution characteristics of urban thermal environments and blue-green spaces. It investigates the correlation between thermal environments and green spaces as well as water bodies at the landscape pattern level and across different spatial scales. Starting from blue-green spaces, spatial planning recommendations to improve the thermal environment are proposed.

1 Study area and data source

1.1 Study area

Tianjin is located in the northeast of the North China Plain, downstream of the Haihe River basin, and borders the Bohai Sea to the east. It is one of the core cities in the Beijing-Tianjin-Hebei urban agglomeration. The region has a typical warm temperate semi-humid continental monsoon climate, with hot summers and cold winters. As a sample of rapid urbanization in China, Tianjin's urban construction land area expanded from 371.23 square kilometers in 1998 to 950.55 square kilometers in 2018, bringing along serious heat environment issues. Currently, there is limited and insufficient research on the heat environment in the city, with even less related to blue-green spaces [14]. The "Tianjin Municipality's Fourteenth Five-Year Plan for National Economic and Social Development and Vision for 2035" explicitly emphasizes promoting green development and accelerating the construction of a beautiful Tianjin, with blue-green spaces being a key focus. Therefore, this study utilizes Landsat remote sensing image data and selects the core six districts in Tianjin's main urban area as the research focus to explore the relationship between the heat environment and blue-green spaces, including Heping District, Nankai District, Hongqiao District, Hebei District, Hexi District, and Hedong District, covering a total area of approximately 181.18 square kilometers (Figure 1). The typical climate characteristics and urbanization features of Tianjin can serve as reference for cities with similar characteristics.

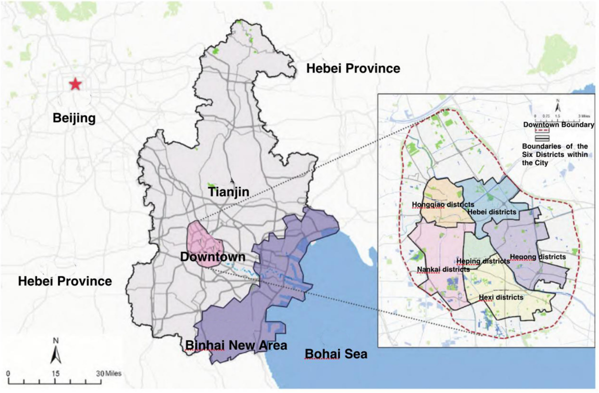

Figure 1 Study area

1.2 Data sources and preprocessing

Geospatial data from the Landsat remote sensing images, published on the Geospatial Data Cloud Platform (http://www.gscloud.cn/), were used as the data source for analyzing the urban heat environment and blue-green space patterns. The imaging dates were July 6, 2004, June 8, 2011, and July 10, 2017. The data source has a large time span which is conducive to studying spatial evolution characteristics, especially during which time the vegetation has a vigorous growth, as shown in detail in Table 1. The data source was processed using ENVI for multispectral radiometric calibration and atmospheric correction, and then was calibrated and clipped to obtain the preprocessed data results.

Table 1 Statistical information of data sources

Imaging time/ year-month-date	Satellite and sensor	Spatial resolution/m×m		Center longitude/ latitude/°	Strip number	Line number	Imaging beijing time	Cloud cover/%
		Thermal infrared band	Other bands					
2004-07-06	Landsat 5 TM	30	30	116.2725E 38.8988N	123	33	10:35:58	0.01
2011-06-08	Landsat 5 TM	30	30	116.242E 38.8995N	123	33	10:43:19	0.03
2017-07-10	Landsat 8 OLI_TIRS	30 (TIRS)	30 (Panchromatic15)	116.2848E 38.9042N	123	33	10:53:43	0.04

2 Research methodology

2.1 Land surface temperature inversion

The Mono-Window Algorithm with minimal errors was selected to invert the urban land surface temperature [15,16]. This algorithm is simpler and more convenient compared to the Radioactive Transfer Equation Method, Single-channel Method, and Image-based Method. Firstly, the average atmospheric action temperature (Ta) for Tianjin was obtained from the China Meteorological Yearbook. The atmospheric transmittance (τ) was calculated using the Atmospheric Correction Parameter Calculator from the official website of the National Aeronautics and Space Administration (http://atmcorr.gsfc.nasa.gov/). Subsequently, using ENVI, the pixel brightness temperature (T) of the thermal infrared band for each year was calculated, and the land surface emissivity (ε) was computed based on the NDVI thresholding method proposed by SobrinoJ et al. [17]. Finally, the land surface temperature in Kelvin (K) for each year was calculated using the Qin Zhihao Mono-Window Algorithm formula:

$$T_{s\_Qin}=\frac{a(1-C-D)+[b(1-C-D)+C+D]T-DT_a}{C} \quad (1)$$

In the equation, a and b are coefficients with values of a = −67.355 35 and b = 0.458 61 when within the range of 0 ℃ to 70 ℃. The calculation formula for C is $C=\tau\times\varepsilon$ and for D is $D=(1-\tau)\times[1+\tau\times(1-\varepsilon)]$.

2.2 Temperature difference zoning

Applying the standard deviation classification method to differentiate surface temperature calculation results [14], and to compare and study the spatiotemporal evolution characteristics of the thermal environment in various years. The final zoning consists of 7 temperature ranges, with extremely low temperature zone, low temperature zone, and relatively low temperature zone representing the urban low-temperature range areas, while extremely high temperature zone, high temperature zone, and relatively high temperature zone representing the urban high-temperature range areas (Table 2).

Table 2 Ground surface temperature zone

	Temperature range/℃	Temperature zones
Low-temperature range area	$LST < T_{mean} - 2T_{std}$	Extremely low temperature zone
	$T_{mean} - 2T_{std} \leqslant LST < T_{mean} - T_{std}$	Low temperature zone
	$T_{mean} - T_{std} \leqslant LST < T_{mean} - 1/2T_{std}$	Relatively low temperature zone
Medium temperature range	$T_{mean} - 1/2T_{std} \leqslant LST < T_{mean} + 1/2T_{std}$	Medium temperature zone
High-temperature range area	$T_{mean} + 1/2T_{std} \leqslant LST < T_{mean} + T_{std}$	Relatively high temperature zone
	$T_{mean} + T_{std} \leqslant LST < T_{mean} + 2T_{std}$	High temperature zone
	$LST \geqslant T_{mean} + 2T_{std}$	Extremely high temperature zone

2.3 Land use classification interpretation

Utilizing the Maximum Likelihood Classifier in Supervised Classification to interpret land use classification from the data source, extracting 3 spatial patterns: blue spaces, green spaces, and non-blue-green spaces, to analyze the relational characteristics among different elements within the landscape system. The blue spaces include natural and artificial water bodies, the green spaces include natural and artificial green areas, and the non-blue-green spaces refer to urban construction land excluding blue-green spaces. Evaluation of the classification results based on the Kappa coefficient showed an overall Kappa coefficient of 0.884, 0.864, and 0.883 for the data classification in the years 2004, 2011, and 2017, respectively, meeting research standards and accuracy requirements. The classification results effectively reflect the land use landscape pattern of the study area.

2.4 Landscape pattern analysis

Based on the feature level, the landscape pattern can be divided into three analytical levels: (1) patch level, representing the spatial characteristics of individual patches; (2) type level, reflecting the spatial characteristics of landscape patches of the same type; (3) landscape level, reflecting the spatial characteristics of the entire landscape mosaic. Landscape pattern indices are considered as the primary tools for quantitatively assessing landscape patterns, measuring the heterogeneity of different landscape elements in space or time, and characterizing their composition and distribution features [18]. Landscape pattern indices were calculated using Fragstats: three indices were selected at the patch level to study the correlation between the area, edge, and shape of the blue-green space patches and the internal temperature of the patches; one index was chosen at the type level to study the correlation between landscape components and unit land surface temperature, to analyze the thermal environment improvement effects based on the blue-green space landscape patterns level.

Considering that spatial patterns at different scales will gradually lose or alter landscape information characteristics[19], leading to differences in landscape analysis results for the same landscape, it is crucial to select an appropriate spatial scale. To mitigate the impact of landscape unit size on landscape patterns and thermal environment analysis differences, a Moving-Window Analysis is employed to investigate the relationship between thermal environment and blue-green spaces at multiple scales. By using GIS grid tools to partition surface temperatures within windows and resampling the average surface temperature within each window to characterize the thermal environment of the samples. Given that the remote sensing image pixel size used in this study is 30 meters × 30 meters, using smaller landscape units as the moving-window would result in a large computational burden and lead to overly homogenized landscape classifications, and the landscape classification below the window would tend to become more homogenized [20-22], reducing the significance of the research findings. Additionally, to ensure that each temperature pixel is independently contained within the moving-window and to minimize unnecessary calculations between overlapping pixels, it is preferable to choose a moving-window size that is a multiple of the pixel size. To summary, taking into account the unit scales used in landscape pattern analyses by Xu Shuang[23], Zou Jing [24], Shen Zhongjian[1,25], and others, the final selection includes five sizes for the moving-window: 300 meters × 300 meters, 600 meters × 600 meters, 900 meters × 900 meters, 1200 meters × 1200 meters, and 1500 meters × 1500 meters.

3 Results and analysis

3.1 Comparison of temporal and spatial evolution between thermal environment and blue-green spaces

At the overall urban pattern level, by comparing the data related to land surface temperature from 2004 to 2017 (Table 3) with the changes in the area of various land use patches (Figure 2), it was observed that there is a negative correlation between the area of green space patches and the average land surface temperature. During the period from 2004 to 2011, a significant amount of non-blue-green spaces were transformed into green spaces, which is associated with the implementation of Tianjin's Overall Urban Planning released in 2006. With the increase in artificially constructed green spaces, the green spaces system in the central urban area gradually improved, leading to a noticeable growth in the area of green space patches, especially in the southern parts of Hedong and Hexi districts. Simultaneously, the high-temperature range areas in these two districts decreased. Overall, the urban land surface average temperature in 2011 slightly decreased compared to that in

2004. However, from 2011 to 2017, the areas of blue-green space patches in the six districts of Tianjin decreased, resulting in a significant rise in the urban land surface average temperature.

Table 3 Data statistics of surface temperature

Date/year-month-day	Minimum temperature T_{min}/℃	Maximum temperature T_{max}/℃	Average temperature T_{mean}/℃	Standard deviation T_{std}
2004-07-06	26.77	51.93	39.43	3.90
2011-06-08	21.68	47.23	35.30	3.86
2017-07-10	29.12	52.91	41.13	3.93

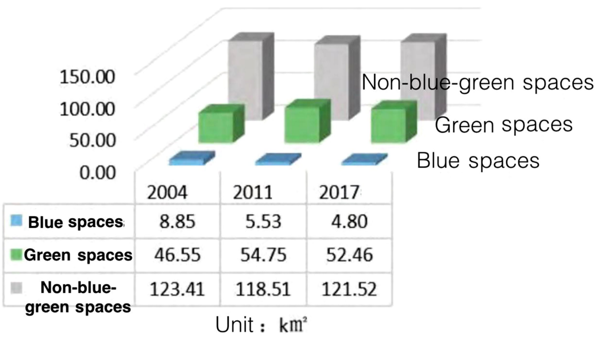

Figure 2 Comparison of land use patch areas by type from 2004 to 2017

Based on the interpretation of temperature difference zones and land use classifications, a comparative analysis of the temporal and spatial evolution of thermal environment and blue-green spaces in the six districts of Tianjin was conducted yearly. Additionally, a thermal environment profile analysis was carried out respectively in the north-south and east-west direction at the urban transport hub Tianjin West Station and Tianjin Station. This profile analysis traverses from the high-temperature range areas in the north to the low-temperature range areas in the south, passing through densely populated areas in the city core, which holds significant research value. In 2004 (Figure 3), the high-temperature range areas were primarily concentrated at the junction of Hebei and Hongqiao districts, followed by the northern parts of Nankai district, the banks of the Haihe River where Hebei, Hedong, and Hexi districts meet (Jinwan Square, Tianjin Station), and the eastern part of Hexi district. The low-temperature range areas were mainly concentrated around blue spaces such as rivers (Haihe River, North Canal, etc.), lakes (Tianta Lake, etc.), and large parks (Water Park, Beining Park, etc.) that include blue-green spaces, with the southwestern urban area forming the extremely low-temperature region. Additionally, low-temperature range areas were found in highly vegetated areas such as universities, like the Balitai area in Nankai district. From the analysis of the thermal environment profile, it was evident that different types of land use are significant contributors to the interleaving of peaks and valleys, with blue spaces serving as distinct low-temperature valley areas (Figures 4, Figures 5). In conclusion, it was found that the majority of urban low-temperature range areas are concentrated within blue-green spaces.

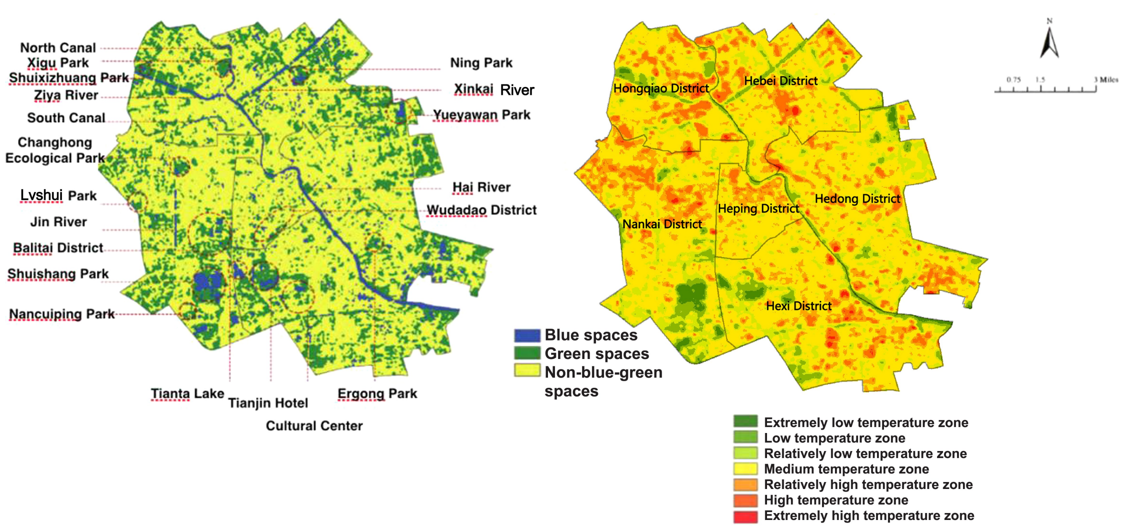

Figure 3 Contrasting analysis of blue-green spaces and thermal environment patterns in the six districts of Tianjin in 2004

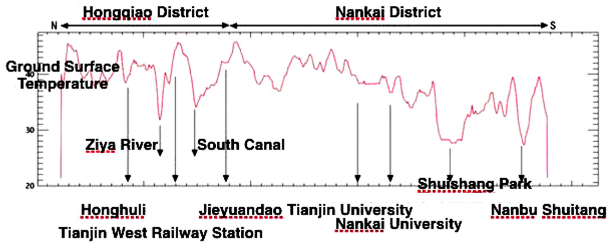

Figure 4 Variation of thermal environment in the north-south section in 2004

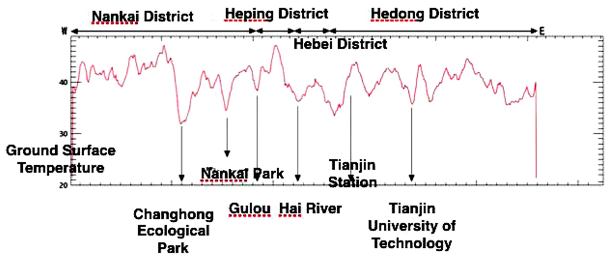

Figure 5 Variation of thermal environment in the east-west section in 2004

In 2011 (Figure 6), the high-temperature range areas began to expand outward, beyond the constraints of the river flows of Ziya River, South Canal, and Haihe River. Simultaneously, significant rise in ground surface temperatures can be observed across the entire Hedong District from the change diagram of the hot environment east-west section, with the emergence of multiple high-temperature peaks and a gradual increase in temperature differences at local levels. The low-temperature range areas still concentrate around blue-green spaces, but compared to the year 2004, there has been an overall reduction in the spatial layout, particularly noticeable in the southern part of Nankai District where the development of the Olympic Park has fragmented the area into disjointed hot environment patches. Additionally, a more intuitive change is the gradual decrease in north-south temperature difference depicted on the hot environment section analysis diagram, along with the addition of high-temperature peak areas in the south (Figures 7, Figures 8), further revealing the positive correlation between urban development land use and the hot environment, as well as the ameliorating impact of blue spaces on the hot environment.

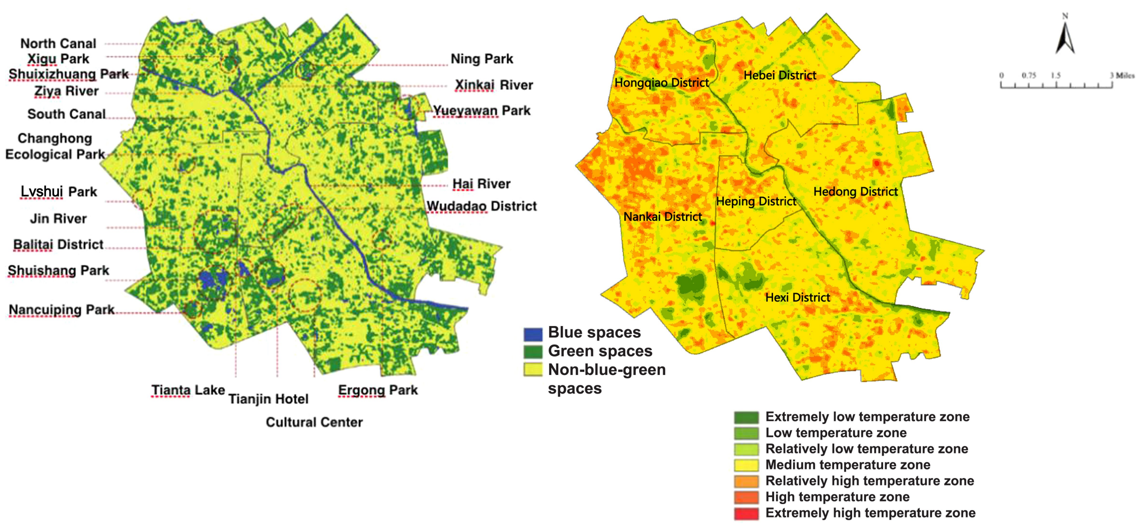

Figure 6 Contrasting analysis of blue-green spaces and thermal environment patterns in the six districts of Tianjin in 2011

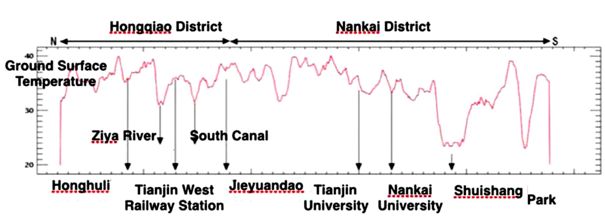

Figure 7 Variation of thermal environment in the north-south section in 2011

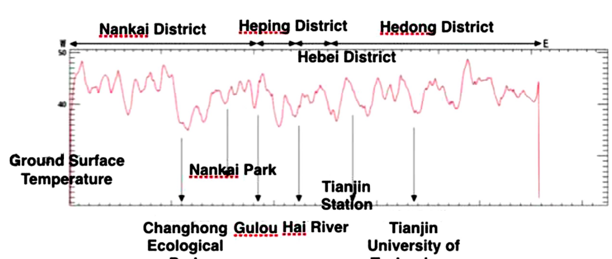

Figure 8 Variation of thermal environment in the east-west section in 2011

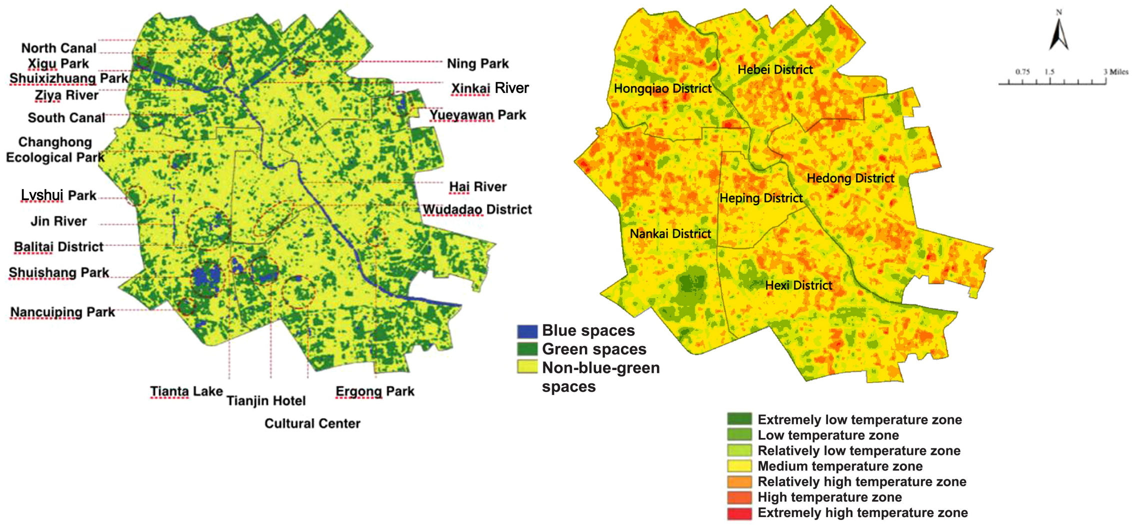

Figure 9 Contrasting analysis of blue-green spaces and thermal environment patterns in the six districts of Tianjin in 2017

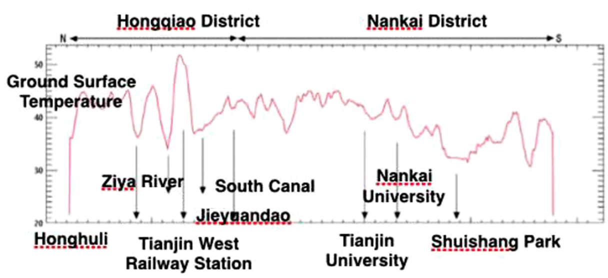

Figure 10 Variation of thermal environment in the north-south section in 2017

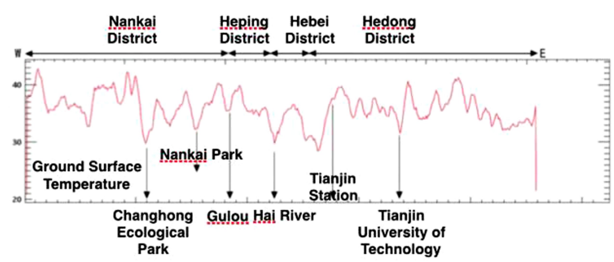

Figure 11 Variation of thermal environment in the east-west section in 2017

In 2017 (Figure 9), the high-temperature range areas expanded extensively from west to east across the Haihe River, notably displaying a more prominent clustering effect of hot environment patches in the Hedong and Hebei Districts compared to previous years. The ground surface temperatures in the north-south profiles show an overall rising trend, with the low-temperature valley in the southern part of Nankai District significantly higher than in 2004 and 2011 (Figures 10, Figures 11). Furthermore, the low-temperature range areas have seen the addition of numerous linear areas within the existing spatial layout, such as the northern rail line in the north of Hebei District and along the city moat in Hexi District, revealing the significant cooling effects of linear green spaces like strip protections and waterfront green spaces.

Examining the spatiotemporal evolution characteristics of the thermal environment and blue-green spaces in the six districts of Tianjin from 2004 to 2017, it is evident that the high-temperature range areas have been influenced by the urbanization process. With the continuous expansion of urban development directions, the early hot environment patches were relatively scattered, but later on, they expanded across river constraints and aggregated on a large scale. The development of urban construction land has a strengthening impact on the thermal environment. On the other hand, the low-temperature range areas continue to be prominently concentrated within blue-green spaces. This reveals the spatial connection between urban thermal environment and blue-green spaces, highlighting the significant improvement role of blue-green spaces in the thermal environment. Particularly, the cool islands formed by blue spaces play a crucial role in promoting heat exchange both within and outside the city.

3.2 Correlation between thermal environment and blue-green space landscape patterns

Taking the data from 2017 as an example, an in-depth analysis was conducted on the relationship between blue-green space patches and the thermal environment. In 2017, the average ground surface temperature of the six districts in Tianjin was 41.13℃, with the blue space patches at 38.7℃ (standard deviation of 2.63) and green space patches at 40.9℃ (standard deviation of 2.19), both below the overall average temperature. By analyzing the temperature distribution of blue-green space patches (Table 4), it was found that in the blue space patches, the proportion of low-temperature range patches exceeded half; while in the green space patches, the proportion of moderate-temperature range patches exceeded half, further revealing the more prominent cool island effect in blue spaces.

Table 4 Blue-green space patches temperature difference zoning statistics

	Blue spaces		Green spaces	
Temperature zone	Patches/piece	Percentage occupied by patches/ %	Patches/piece	Percentage occupied by patches/ %
Extremely low temperature zone	3	0.92	1	0.07
Low temperature zone	97	29.75	68	5.38
Relatively low temperature zone	98	30.06	197	15.58
Medium temperature zone	110	33.74	798	63.13
Relatively high temperature zone	15	4.60	180	14.24
High temperature zone	3	0.92	20	1.58
Extremely high temperature zone	0	0	0	0

The area, perimeter, perimeter-to-area ratio of blue-green space patches were selected, and their correlation with the internal minimum temperature was analyzed, with results shown in Table 5. The correlation analysis indicated a significant positive correlation between the internal minimum temperature of blue-green space patches and their perimeter-to-area ratio, a significant negative correlation with the perimeter, and a relatively lower correlation with the area. The correlation with the perimeter-to-area ratio was slightly higher than that with the perimeter. This suggests that the internal minimum temperature of blue-green space patches is more sensitive to changes in the perimeter-to-area ratio and perimeter, with a more complex shape and irregular edge of blue-green space patches providing stronger cooling effects compared to simpler and regular-edged patches. Optimizing the perimeter and perimeter-to-area ratio of blue-green space patches can significantly enhance their ability to improve the thermal environment.

Table 5 Correlation between temperatures of blue-green space patches and landscape pattern indices

	Landscape pattern index	Correlation coefficient with the minimum temperature within patches
Blue spaces	Patch perimeter	-0.461^{**}
	Patch area	-0.375^{**}
	Patch perimeter-to-area ratio	0.549^{**}
Green spaces	Patch perimeter	-0.415^{**}
	Patch area	-0.396^{**}
	Patch perimeter-to-area ratio	0.442^{**}

Note: ** indicates $P < 0.01$

3.3 Multi-scale connections between thermal environment and blue-green spaces

Using the moving-window method to divide the temperature difference zones obtained in 2017 into windows, the sample sizes were 1844, 421, 177, 90, and 54 respectively. The overlay of spatial patterns of thermal environment and blue-green spaces is depicted in Figure 12, indicating the relationship between thermal environment and blue-green space at different scales. The index of blue-green space patches area percentage in the samples was selected and correlated with the temperature from resampled samples, revealing a significant negative correlation between ground surface temperature and blue-green spaces at the landscape component level (Table 6). With increasing spatial scale, the correlation between the percentage of blue space patches area in the landscape and surface temperature gradually strengthens, reaching the highest in the 1500 meters × 1500 meters sample; while the correlation between the percentage of green spaces patch area in the landscape and surface temperature gradually weakens, peaking in the 300 meters × 300 meters sample. Regression analyses were conducted using the most strongly correlated blue-green spaces data, with both regression models passing significance level tests. The regression coefficient for the 1500 meters × 1500 meters sample and blue spaces were −0.211, and for the 300 meters × 300 meters sample and green spaces were −0.051. By comparing the regression coefficients, it is evident that blue spaces are more efficient in improving the thermal environment compared to green spaces, and adjusting the proportion of blue spaces in the 1500 meters × 1500 meters scale is more effective in addressing thermal environment challenges.

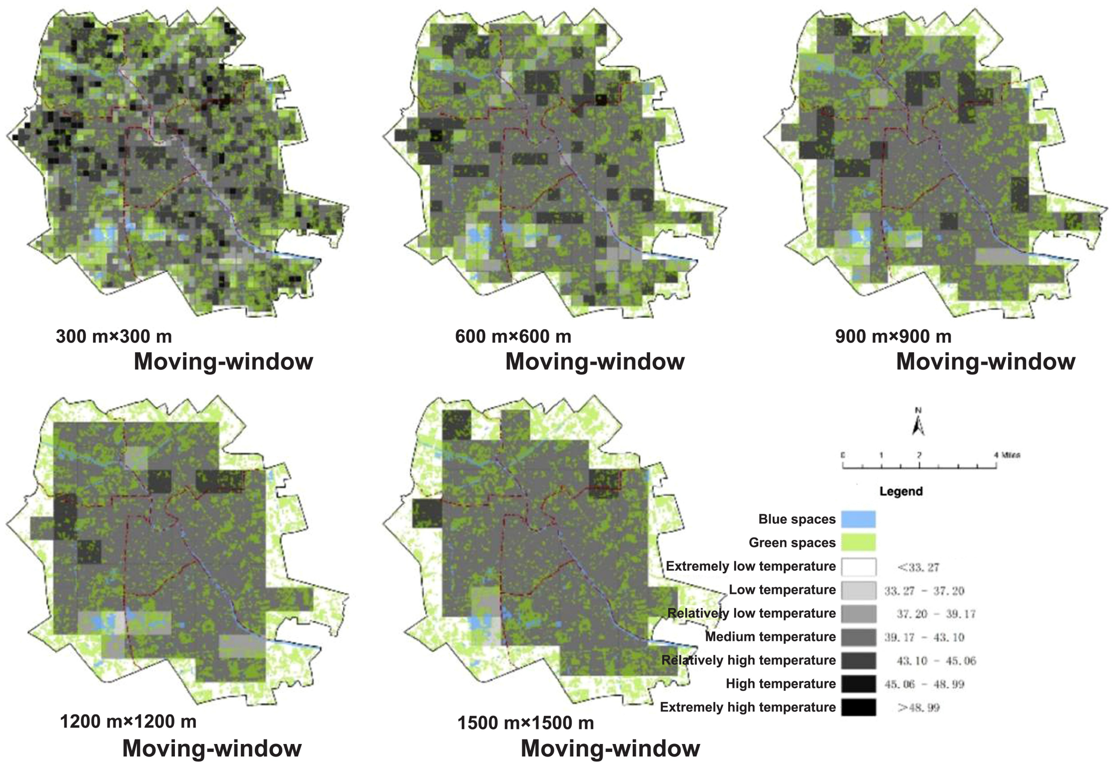

Figure 12 Comparison of the overlay of multi-scale sample thermal environment pattern and blue-green space patterns

Table 6 Correlation between sample temperature and landscape pattern index

Sample window scale	Correlation coefficient between sample temperature and percentage of landscape area occupied by patches	
	Blue spaces	Green spaces
300 meters × 300 meters	−0.604**	−0.513**
600 meters × 600 meters	−0.598**	−0.492**
900 meters × 900 meters	−0.630**	−0.456**
1200 meters × 1200 meters	−0.622**	−0.452**
1500 meters × 1500 meters	−0.724**	−0.431**

Note: ** indicates $P < 0.01$

4 Recommendations for improving thermal environment

Based on the relevant principles of enhancing urban thermal environment through blue-green spaces and considering the current status of thermal environment and blue-green spaces in the six districts of Tianjin, recommendations are proposed to optimize the blue-green space patterns and enhance the effectiveness of improving the thermal environment from the following three aspects.

4.1 Optimize the landscape pattern of blue-green spaces at the optimal scale

Research on the relationship between urban thermal environment and blue-green space landscape patterns reveals that increasing the percentage of blue spaces in the 1500 meters × 1500 meters spatial scale has the most significant cooling effect, while green spaces show significant effects at 300 meters × 300 meters scale. Blue spaces are more effective in improving the thermal environment compared to green spaces. Increasing the perimeter of blue-green space patches and reducing the perimeter-area ratio index can effectively enhance the thermal environment. It is recommended to optimize the landscape pattern indices targeting the optimal spatial scales of blue-green spaces and prioritize adjustments to the blue space landscape components to achieve optimal efficiency in improving the thermal environment. Specific implementation strategies may include adding pocket parks, active water parks, street green spaces, etc., and optimizing the edge shapes of blue-green space patches at the urban design level.

4.2 Focus on increasing blue spaces within the high-temperature zones in the northern region

Through comparative studies on temporal and spatial evolution, it is observed that blue spaces have a more significant impact on improving the thermal environment compared to green spaces. Currently, the distribution of blue spaces within the six districts of Tianjin is uneven, with most water areas concentrated in the southern part of Nankai District, leading to a scarcity of water areas in other regions. It is recommended to focus on increasing blue space patches within the high-temperature zones in the northern region, especially in Hebei District and Hedong District. Strategies such as expanding the water surface area in Yueyawan Park and Er Gong Park in Hedong District, increasing water areas in Zhongshanmen Park, and adding blue spaces in the high-temperature zones at the border of Hedong District and Hebei District are suggested to alleviate the more prominent thermal environment issues in Hebei District and Hedong District.

4.3 Expanding the renovation of existing waterways and promoting greenways construction

The North Canal and Ziya River flowing through Hongqiao District, the Xinkai River in Hebei District, and the Hai River converging at the junction of the six districts collectively form the crucial river framework for improving the thermal environment in Tianjin, playing a significant role in cooling. However, the average width of the South Canal, Jin River, Weijin River, the city moat, and Yueya River is only about 25 meters, with some even narrower than 20 meters, much smaller than the Hai River, leading to a significantly reduced cooling effect. This paper proposes to locally widen and link the South Canal, Jin River, Weijin River, the city moat, and Yueya River while constructing riverside greenways on the basis of paying much importance to protect all of the rivers, aiming to enhance and maximize the cooling advantages of linear blue-green spaces.

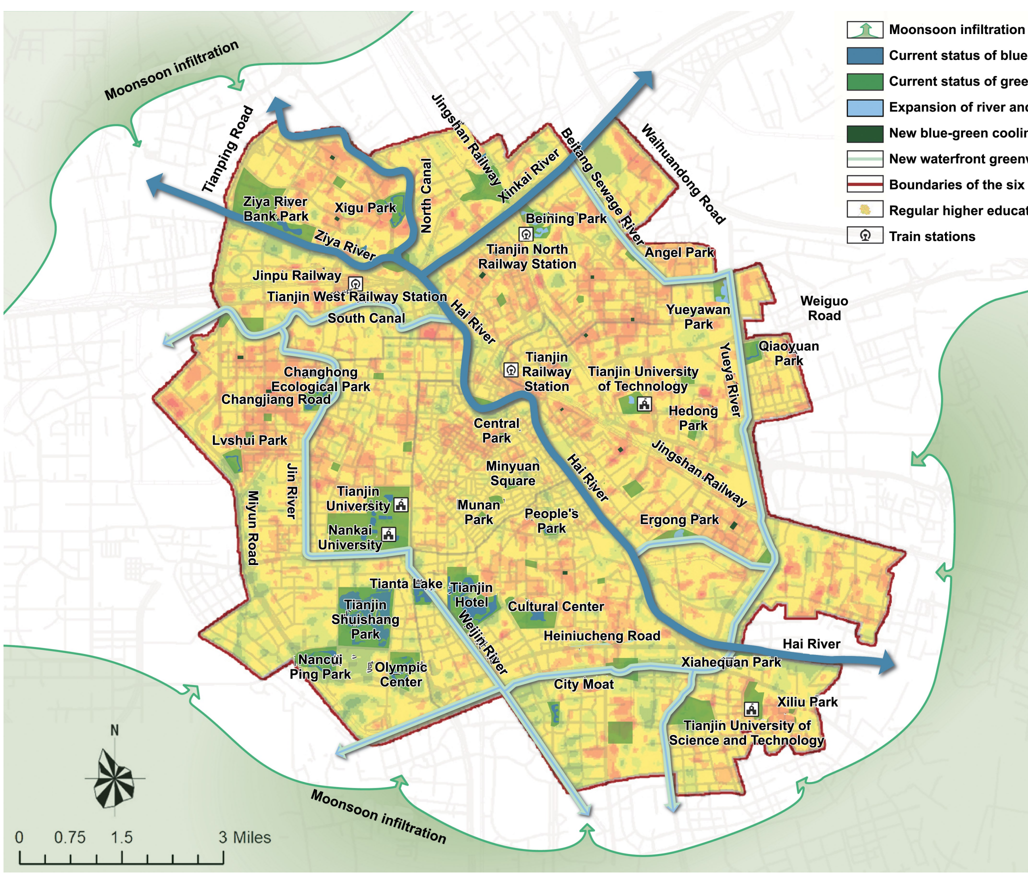

Figure 13 Suggested planning for blue-green spaces in the six districts of Tianjin city

By integrating the optimization measures mentioned above, the paper presents the blue-green spaces planning recommendations for the six districts of Tianjin as shown in Figure 13. Through optimizing the landscape pattern of blue-green spaces, increasing blue spaces within the high-temperature zones in the northern region, expanding and renovating waterways, and establishing riverside greenways, these strategies effectively address thermal environment issues, enhancing the city's ecology and livability.

Conclusion and outlook

Through the comparative analysis of the spatiotemporal evolution characteristics of the thermal environment and blue-green spaces in the six districts of Tianjin in 2004, 2011, and 2017, the following conclusions are drawn: (1) blue-green spaces play a significant role in improving the urban thermal environment. At the level of landscape pattern, ground surface temperature is significantly negatively correlated with the perimeter-area ratio of blue-green space patches and significantly positively correlated with the perimeter-area ratio index. (2) In the multiscale spatial pattern analysis, it is found that the ground surface temperature is most closely related to the ratio of blue space patches to landscape area in the 1500 meters × 1500 meters samples and most closely related to green space patches in the 300 meters × 300 meters samples, with blue spaces showing better thermal environment improvement efficiency. (3) Recommendations for thermal environment improvement based on optimized blue-green space landscape patterns are proposed.

Utilizing the cooling effect of blue-green spaces to improve the urban thermal environment has been a hot topic in recent years. This paper analyzed the relationship characteristics between the thermal environment and blue-green spaces at the level of landscape pattern, providing suggestions for addressing climate challenges and promoting ecological civilization construction. The conclusions drawn so far still have limitations in terms of spatial scale, and future research will continue to explore the patterns of the thermal environment and blue-green space landscapes at a finer scale to effectively harness the ecological cooling effects of blue-green spaces with precision and efficiency.

Figure and table sources

All figures and tables in this paper are drawn by the author.

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