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Remote Sensing-Based Analysis of the Mitigating Effect of Urban Green Space on Heat Island Effect: A Case Study of Changsha City

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Abstract:
Under the dual background of urbanisation and global warming, Urban Heat Island(UHI) effect is becoming more and more significant, and has become a key issue restricting the sustainable development of cities. It is of great practical significance to explore the regulating effect of urban green space on the surface thermal environment to optimise the spatial layout of urban green space and alleviate the heat island effect. In this study, taking the main urban area of Changsha City as an example, the surface temperature (LST) was inverted and the normalised vegetation index (NDVI) was extracted based on Landsat 8 images in 2013, 2016 and 2019. The spatial regulation of the thermal environment by green space was systematically explored through Pearson's correlation coefficient, global Moran's index and cold hotspot analysis. The results showed that the LST showed a gradient distribution of 'high in the centre and low in the periphery', with a significant positive spatial correlation; the NDVI always had a stable negative correlation with the LST, and the temperature was significantly lower in the area covered by high green space; the cold hotspot analysis further revealed that the hot zone was concentrated in the high-density built-up area, while the cold zone corresponded to the area where the green space was concentrated. This study can provide data support and methodological reference for the optimisation of green space allocation to mitigate UHI.

Keywords: LST; NDVI; urban heat island effect; spatial correlation; Changsha city

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1. Introduction

As global warming and urbanisation continue to accelerate, hot weather is becoming more and more frequent in cities, and the problem of extreme thermal environments continues to intensify. Among them, Urban Heat Island (UHI), as one of the most significant manifestations, is posing serious challenges to the health of residents, energy consumption, and the resilience of urban operations, and is gradually evolving into a key factor constraining the ecological safety and quality of life in cities. Among the many strategies to deal with urban heat problems, urban green space is widely regarded as an important ecological infrastructure for mitigating the heat island effect due to its good vegetation cover, evapotranspiration capacity and shading effect.

Numerous studies have confirmed that the presence of urban green spaces can effectively reduce the surface temperature of the surrounding area and mitigate the UHI effect[1-4]. Therefore, dynamic monitoring of green space distribution and changes is crucial for understanding and regulating the heat island effect. However, traditional analysis methods are inefficient and limited in coverage, making it difficult to meet the demand for rapid and comprehensive research[5].

The development of satellite remote sensing technology provides strong support for this. Its image accuracy has been continuously improved and data acquisition has become more convenient and efficient, and it has been widely used in natural resources monitoring, ecological environmental protection and other fields[6]. The use of remote sensing technology can not only quickly and effectively obtain urban surface coverage information, but also detect the surface radiation temperature through sensors to achieve effective monitoring of urban green space. At present, the main surface temperature inversion methods include surface specific radiance inversion, single window algorithm, split window algorithm and atmospheric correction method[7-9]. In this study, the surface specific radiance inversion method is used to monitor and analyse the green space in Changsha.

In addition, significant progress has been made in using remote sensing to study the relationship between green space (NDVI) and surface temperature (LST). For example, Jia Zhanhai et al. found that NDVI and LST were negatively correlated in summer and positively correlated in winter based on 2014 and 2019 remote sensing data in Beijing[10], and Yang Liping et al. combined Landsat-8 data with measured surface temperatures to reveal significant differences in LST between different surface types in Xi'an City, and the overall negative correlation between NDVI and LST was linear.

Based on this, this study takes Changsha City as the study area and selects Landsat 8 remote sensing image data in the summer of 2013, 2016 and 2019. Firstly, the images were pre-processed with radiometric calibration and atmospheric correction to ensure data consistency and comparability. Secondly, ENVI and ArcGIS were used to identify the urban green spaces and extract the normalised vegetation index and surface temperature statistics at the scale of the main urban area, so as to quantitatively assess the thermal environment mitigation capacity of the green spaces in different periods. Finally, by comparing and analysing the data of the three periods, the spatial and temporal evolution characteristics and spatial heterogeneity of the thermal mitigation effect of green space are systematically revealed. This study aims to reveal the relationship between green space and thermal effect and its evolution pattern, and provide scientific basis for the optimisation of urban green space system, climate adaptation planning and thermal environment improvement.

2. Data and Methods

2.1 Overview of the Study Area

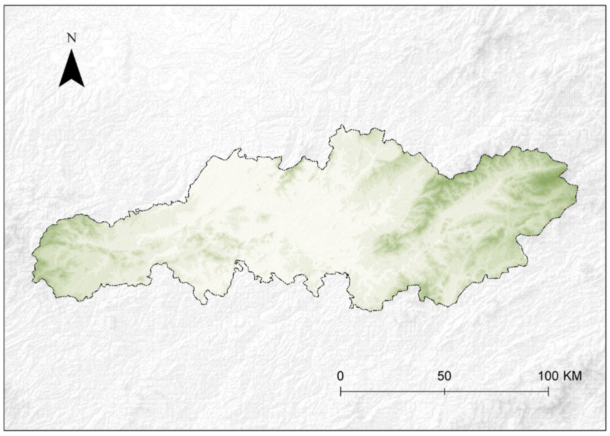

Fig. 1 Location Map of Changsha

In this study, Changsha City in Hunan Province is selected as the study area, which is located in the middle reaches of the Xiangjiang River in the south-central part of China and the northeastern part of Hunan Province, with geographic coordinates ranging from about 111°53′ to 114°15′ east longitude and 27°51′ to 28°41′ north latitude (Fig.1). The terrain is dominated by plains and hills, and the altitude is generally low, which is conducive to the acquisition and interpretation of remote sensing data.

Changsha has a subtropical monsoon climate with four distinct seasons, high temperatures and rainy summers, and a significant UHI effect. In recent years, with the acceleration of urbanisation, the urban area of Changsha is expanding rapidly, with a resident population of more than 10 million, and the contradiction between urban construction land and green space resources is becoming more and more prominent.

This study focuses on the main urban areas of Changsha, including the districts of Tianxin, Furong, Yuelu, Kaifu, and Yuhua, which concentrate a large number of residential, commercial, and transport facilities, as well as the areas with the most significant changes in the thermal environment.

2.2 Data Sources

In this study, Landsat 8 OLI/TIRS TOA reflectance imagery (spatial resolution of 30 m/100 m, temporal resolution of 16 days) was used to construct high-precision NDVI with red band (B4) and near-infrared band (B5), which can significantly improve the ability of vegetation identification with the synergy of the two bands. Meanwhile, based on the thermal infrared band (B10) for the inversion of LST, Landsat 8 has added dual thermal infrared channels and 12-bit radiometric resolution, which can provide a more reliable database for temperature inversion (Table 1).

The satellite image data used in this study mainly come from the Geospatial Data Cloud Platform (https: //www.gscloud.cn/), and the Landsat 8 satellite images in July of summer 2013, 2016 and 2019 with less cloud cover were selected as the main data source, covering the urban area of Changsha City. The ENVI was used to process to obtain: the LST, which was used to portray the distribution of the urban thermal environment; and the NDVI, which was used to characterise the vegetation cover. In addition, the vector boundary data of the study area were obtained from the 2024 version of the National Geographic Information Public Service Platform (https://cloudcenter.tianditu.gov.cn/administrativeDivision).

The urban green space vector data used in this study comes from the literature raster dataset [11], which covers the main urban area of Changsha City. In order to comprehensively reflect the mitigation effect of green space on the urban thermal environment, this paper does not limit the specific green space type, but takes the overall urban green space as the research object, and combines the LST and NDVI data to analyse the relationship between the spatial pattern of the thermal environment and the distribution of green space in Changsha City in the summers of 2013, 2016 and 2019. The green space data were preprocessed by coordinate unification and boundary cropping before analysis to ensure the accuracy of the spatial overlay and cropping analysis.

Table 1. Description of Remote Sensing Data Sources

Image or Data Type	Band	Band Name	Description
Landsat 8 OLI/TIRS TOA Reflectance Imagery	B4	Red band	Calculation of NDVI for subsequent estimation of surface specific emissivity.
	B5	Near-infrared band	Also used to calculate NDVI
	B10	Thermal infrared band	Thermal infrared band Used to calculate brightness temperature, a key input to the LST calculation
Data from calculations	NDVI	Normalised Vegetation Index	Calculated based on B4 and B5 and used to estimate PV
	PV	Proportional Vegetation Cover	Calculated from NDVI to estimate surface specific radiance
	Specific Surface Emissivity	-	Calculated from the PV, it is an important parameter for calculating the LST
	Brightness Temperature	-	Calculated based on B10-band data, it is an intermediate step in the calculation of the LST
	LST	Surface temperature	Final result, calculated from brightness temperature and surface specific emissivity

2.3 Data Pre-processing

In order to analyse the thermal mitigation capacity of urban green spaces in Changsha City, this paper selected Landsat8 satellite remote sensing image data from 2013, 2016 and July 2019, and inverted the LST and extracted the NDVI based on the ENVI software. At the same time, the vector data of the green spaces in Changsha City with

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complete coverage were collected as the spatial boundaries for the extraction of the analysed objects.

In the data preprocessing stage, the LST and NDVI data were firstly radiometrically calibrated, atmospherically corrected and banded to generate LST and NDVI raster data for each phase. Subsequently, in order to ensure that the analysis object focuses on the urban green areas, the 'Extract by Mask' tool in Arc GIS is used to crop the LST and NDVI raster data of the three phases using the green areas vector layer, so as to extract the temperature and vegetation indices of the urban green areas.

The cropping operation not only eliminates the interference of the non-greenfield part of the city, but also lays the foundation for the subsequent image element extraction and correlation analysis. The cropped data are saved in TIFF raster format and are ready for statistical and analytical processing at the pixel level.

2.4 Research Methodology

(1)Surface Specific Emissivity Inversion Method

Surface temperature is a central parameter for monitoring the energy exchange between the surface and the atmosphere [12]. Existing inversion methods mainly include four categories: atmospheric correction method, single-window algorithm, split-window algorithm, and multi-channel multi-angle algorithm [13], which are suitable for different sensor configurations and observation conditions, respectively. In this study, the surface specific radiance method in the atmospheric correction method is used to invert the surface temperature by using the Landsat8 TIRS band (Band 10) with the following equations:

$$LST = \frac{T_b}{1 + \left(\frac{\lambda \bullet T_b}{\rho} \right) \bullet ln(\epsilon)} \quad (1)$$

Where LST is the surface temperature, T_b is the bright temperature, obtained by inversion in the thermal infrared band (Band 8), λ is the effective wavelength, ρ is a constant term, and ϵ is the surface-specific emissivity, which is assigned according to the land cover type lookup table.

In practice, the study first calculates the bright temperature based on the Landsat 8 thermal infrared band. This is then combined with the specific emissivity correction formula to estimate the true surface temperature to more accurately reflect the thermal characteristics of the surface.

(2)Correlation analysis

In order to investigate the relationship between NDVI and LST within the urban green space, this study used Pearson Correlation Coefficient (PCC) to analyse the correlation between the two. The Pearson Correlation Coefficient measures the degree of linear correlation between two variables, and its calculation formula is as follows:

$$r = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 \sum_{i=1}^{n} (Y_i - \bar{Y})^2}} \quad (2)$$

Where X_i and Y_i represent the LST and NDVI values at the ith sample point, and $\bar{X}$ and $\bar{Y}$ are their mean values, respectively.

In the specific operation, the LST and NDVI raster data were firstly cropped using the urban green space vector data to ensure that the analysis scope was limited to the urban green space. The cropped raster data were then converted into point data, and the LST and NDVI data were matched to the same spatial point by using the 'Spatial Connection' tool in Arc GIS10.8 software. Finally, the scatter plot and Pearson's correlation coefficient of the point data were calculated in Excel to evaluate the strength and direction of the linear correlation between the two data, and the negative correlation between LST and NDVI usually characterise the mitigating effect of vegetation on the UHI effect, i.e., the higher the NDVI, the lower the LST tends to be.

(3)Spatial Autocorrelation Analysis

In order to further analyse the spatial distribution characteristics of LST within urban green spaces, this study adopted the global Moran's I index for spatial autocorrelation analysis of surface temperatures. Moran's I can reflect the spatial agglomeration or disagglomeration of a variable, and its calculation formula is as follows:

$$I = \frac{n}{W} \times \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} (x_i - x)^2} \quad (3)$$

where n is the number of sample points, x_i and x_j are the LST values of the ith and jth points, $\bar{x}$ is the average LST value, w_{ij} is the spatial weight with respect to the points,. $W = \sum_i \sum_j w_{ij}$.

The Global Moran's I (GMI) method was used to assess the spatial aggregation of the overall surface temperature in the city. This index can reveal the overall spatial distribution pattern of LST values, i.e. whether there is a systematic 'heat island' or 'cold island' phenomenon in the city.

Further, in order to identify the local aggregation characteristics of LST, this paper introduces the Anselin Local Moran's I index, and carries out cold hotspot analysis with the help of the tool 'Clustering and Outlier Analysis' in ArcGIS. This method can identify the spatial aggregation types such as 'high temperature-high temperature' (HH), 'low temperature-low temperature' (LL), and 'high temperature-low temperature' (HL), as well as 'high temperature-low temperature' (HH). -low temperature' (HL) and 'low temperature-high temperature" (LH) outliers, so as to analyse the spatial distribution of specific hotspots and cold spots in the city. The processed LST raster data are converted into point data for spatial analysis, and the output hot and cold spot maps can provide spatial decision support for the regulation of the urban thermal environment and the optimisation of green space layout.

This study combines the analytical perspective of time series to compare the distribution pattern of spatial hot and cold spots in different years, which helps to reveal the evolutionary trend of the urban thermal environment under the regulation of green space distribution.

3. Results and Discussion

3.1 LST and NDVI spatial distribution characteristics

By comparing the images, it can be found that the NDVI values of Changsha City showed a trend of increasing high value areas between 2013 and 2016, indicating that the green space coverage in the urban area has increased; while the low value areas showed a slight increase between 2016 and 2019, suggesting that the city may be experiencing a certain expansion trend.

Meanwhile, the spatial distribution of LST also changes with years. Fig. 2 shows that the range of the high-temperature zone (red) shows a contraction, while the low-temperature zone (blue) expands, reflecting that the UHI effect has been effectively controlled to some extent in recent years.

The spatial distribution maps of LST and NDVI in July 2013, 2016 and 2019 show that (Fig. 2 and Fig. 3): LST shows a spatial distribution pattern of 'high in the centre of the city and low in the periphery', especially in the main urban areas, industrial agglomerations, and other areas with a high degree of hardening of the ground surface and sparse vegetation, the LST value is significantly high. The high value of NDVI is mostly concentrated in urban green areas, such as Yuelu Mountain, Liuyang River and other ecological corridors, showing the reverse distribution trend of 'high at the edge and low at the centre'; vertical comparison of the three years of data reveals that, with the passage of the year, the green coverage of urban areas as a whole shows a trend of increase, and at the same time, the range of high temperature areas shrinks to a certain extent. This phenomenon reveals the relationship between urban expansion and the development of the city. This phenomenon reveals the potential impact of urban expansion and changes in green space layout on the thermal environment.

In addition, the areas of Changsha city with good vegetation cover in urban green areas are mainly concentrated in Ningxiang city and Liuyang city, whose regional surface temperatures are relatively low, showing a certain cold island effect. On the contrary, the temperature is significantly higher in the areas with lower NDVI, indicating a more prominent UHI problem.

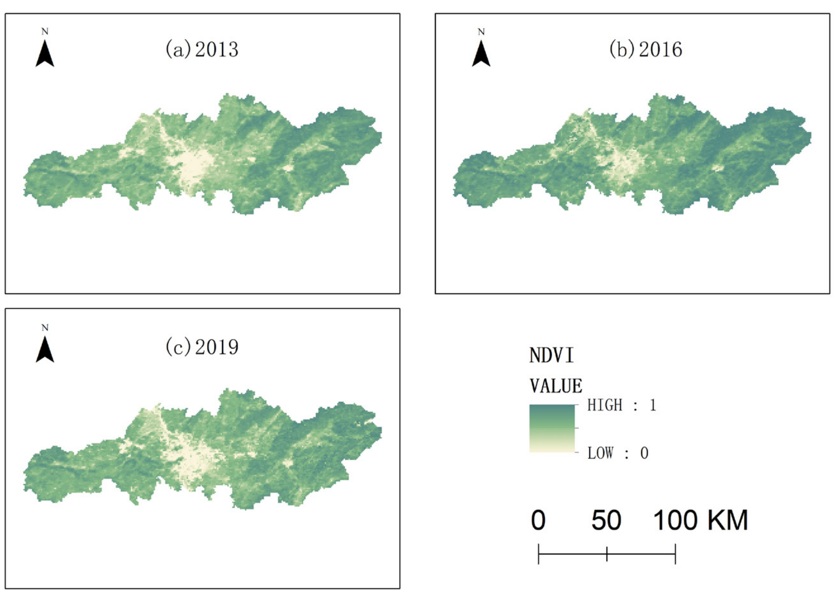

Fig. 2 Spatial distribution of NDVI in Changsha in three time phases

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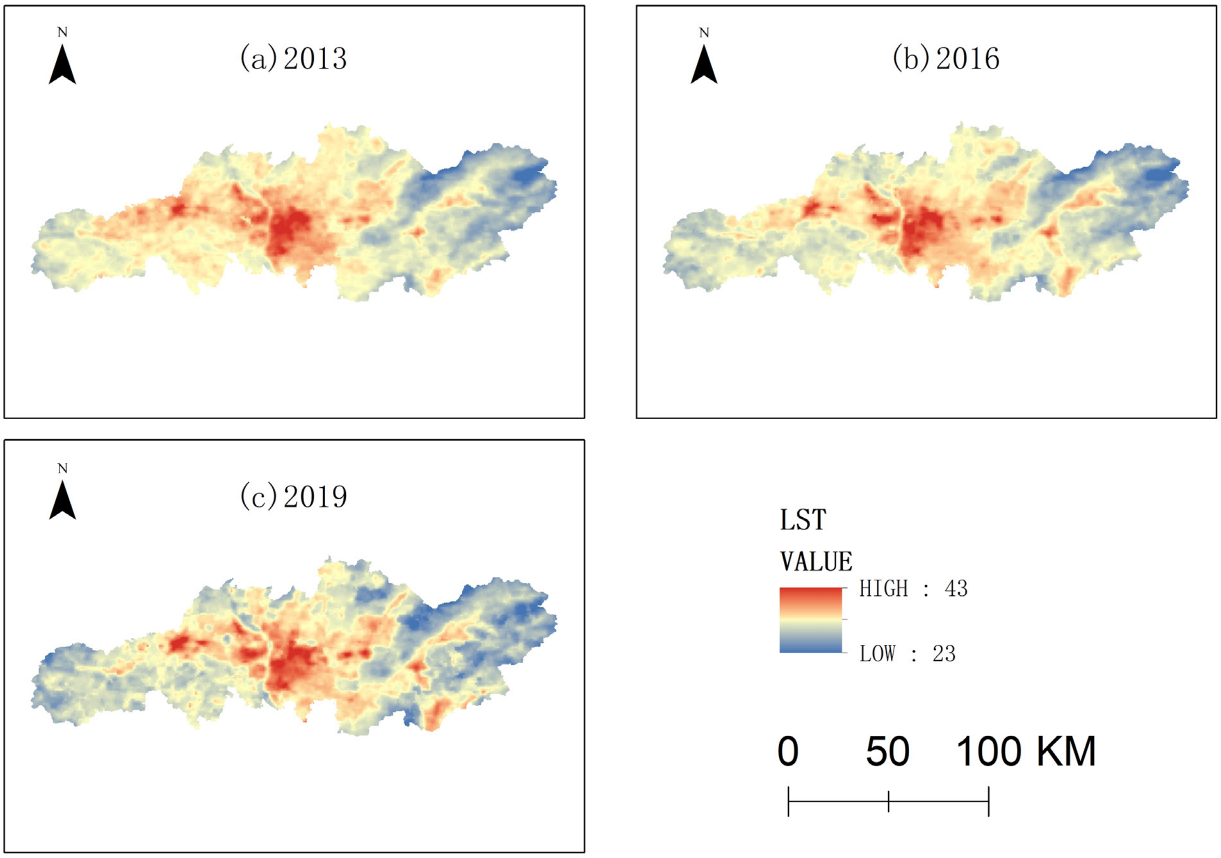

Fig. 3 Spatial distribution of LST in Changsha in three time phases

3.2 Results of the correlation analysis

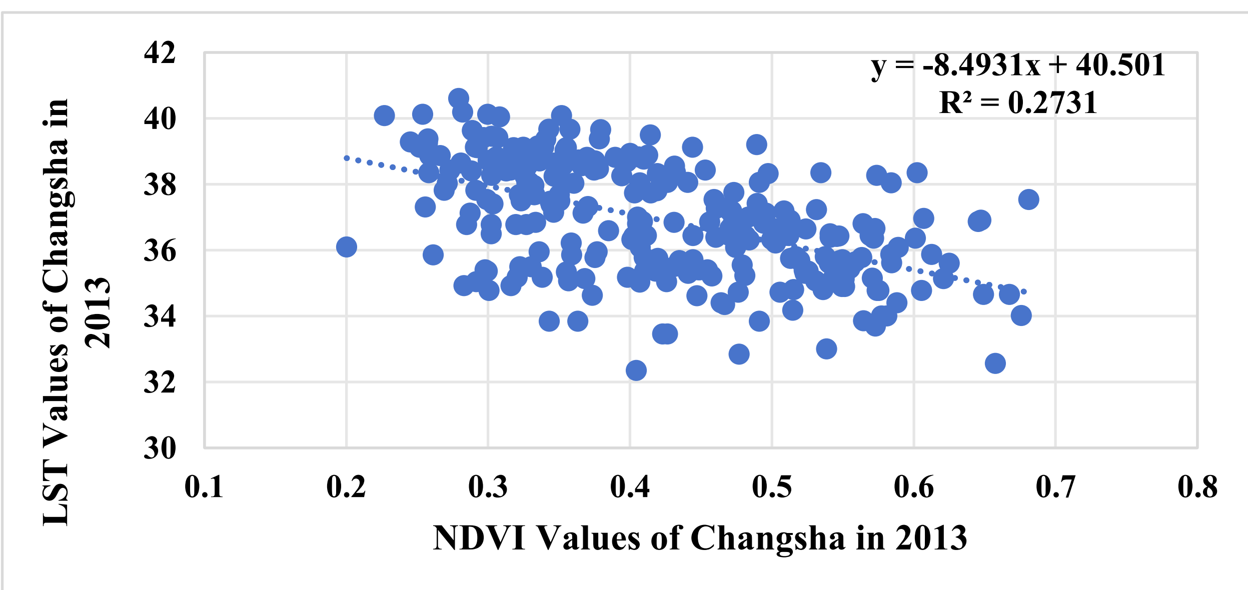

Fig. 4 Correlation results between LST and NDVI in Changsha in 2013

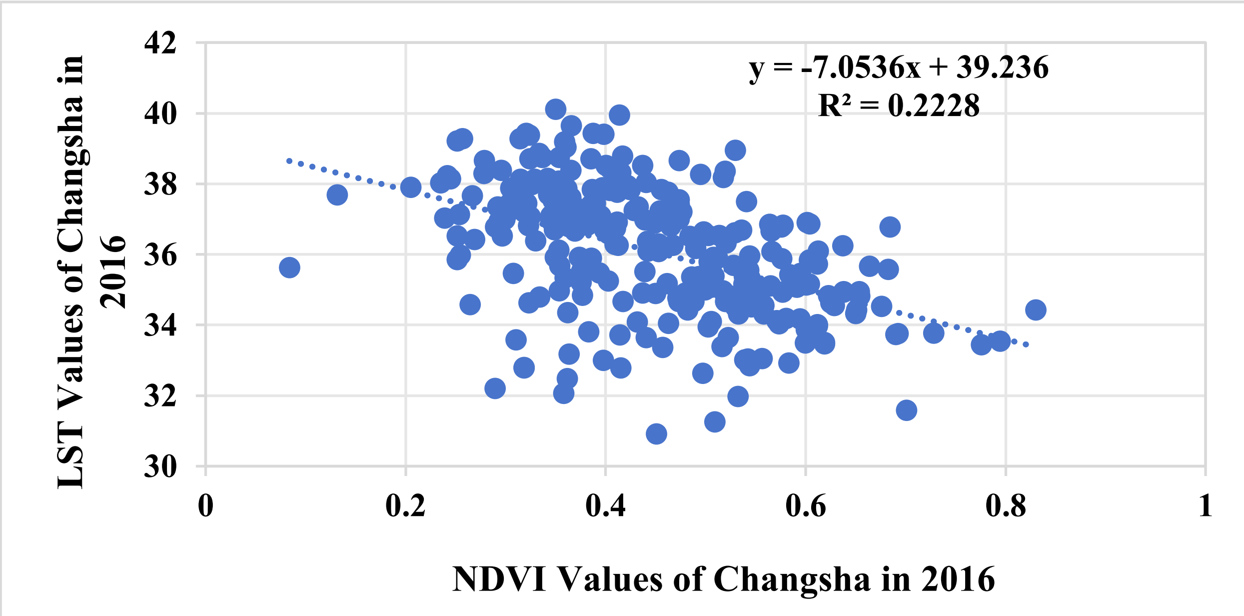

Fig. 5 Correlation results between LST and NDVI in Changsha in 2016

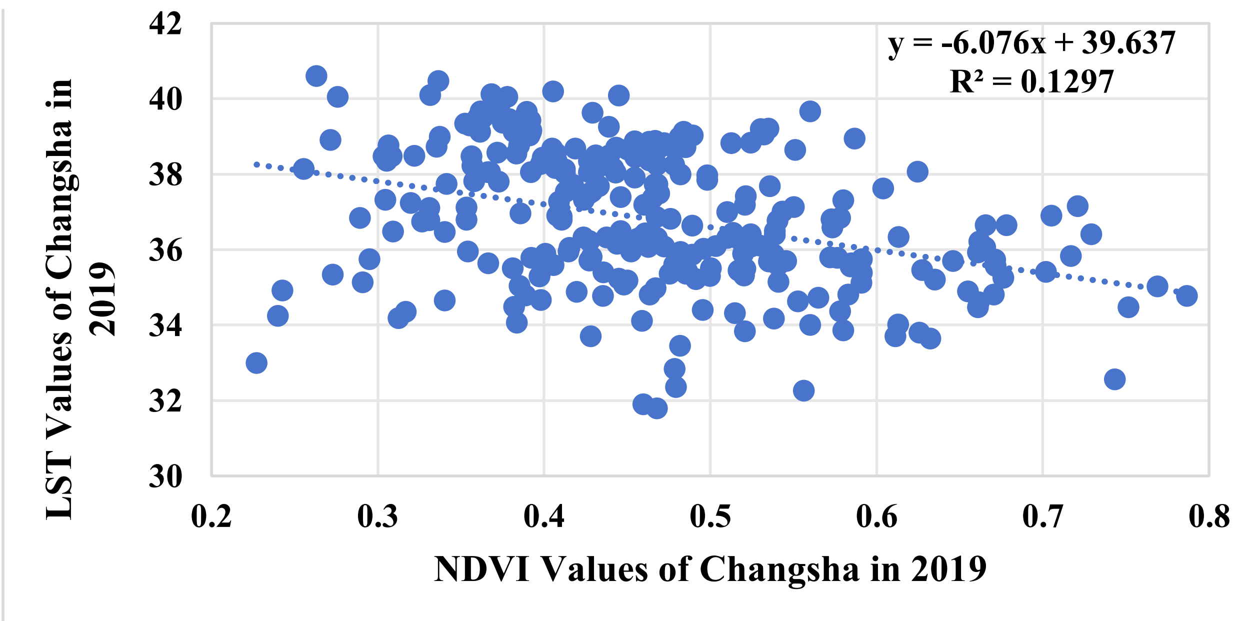

Fig. 6 Correlation results between LST and NDVI in Changsha in 2019

By constructing the spatial correspondence between LST and NDVI, this paper carries out the correlation analysis of the thermal environment mitigation effect of the three phases of green space, which is shown in Fig. 4, Fig. 5 and Fig. 6. After calculating the Pearson's correlation coefficient, the results show that there is a significant negative correlation between LST and NDVI, with the correlation coefficient between NDVI and LST of r = -0.52 in 2013, which is a moderately negative correlation; in 2016, the correlation is r = - 0.47 in 2016, with a slightly stronger correlation, and r = -0.36 in 2019, with the most significant negative correlation. In addition, R^2 was 0.2731 in 2013, 0.2228 in 2016, and 0.1297 in 2019, with the degree of correlation weakening, indicating that the mitigating effect of green space on the hot environment has gradually degraded in recent years. According to the correlation scatter plot, most of the points show the trend of 'the higher the NDVI, the lower the LST', which further confirms the mitigating effect of urban green space on surface temperature.

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It can be seen that the negative correlation between NDVI and LST in Changsha during the three periods shows a significant time decay. This trend is consistent with the general pattern of the city cluster in the middle reaches of the Yangtze River, and also with the expansion of the built-up area of the city (with an average annual growth rate of 4.7%), such as the highly synchronous development of the industrial land in the 'Eastern New City' (the proportion of which has increased from 12% to 27%), which reflects the more intense conflict of urban expansion in Changsha as a pilot area of the 'two-type society'. This reflects the fact that Changsha as a pilot area of 'two-type society' is facing a more intense contradiction in the expansion of production and urbanisation. Meanwhile, the LST in the NDVI-negative zone along the Xiangjiang River remains low, while the LST in the emerging industrial zones (e.g., Changsha Economic and Technological Development Zone) climbs to 42.3°C during the same period, even though the NDVI is close to zero. This spatial variation suggests that relying solely on the NDVI indicator may underestimate the complexity of the urban thermal environment, and it is necessary to optimise the heat island mitigation strategy by combining the thermal attributes of the surface materials and the local circulation characteristics in the future.

3.3 Analysis of cold and hot spots in space

3.3.1 Spatial Autocorrelation Analysis

Table 2. Spatial autocorrelation statement

Year	Moran I index	z-score
2013	0.907	43.967
2016	0.884	42.868
2019	0.856	41.489

By analysing the global Moran index of surface temperature data for the three periods of 2013, 2016 & 2019, this paper assesses the spatial aggregation characteristics of urban surface temperature (Table 2). The results show that the Moran indices of the three periods are all greater than 0, and the p-values are all 0 with a high significance level, indicating that the LST shows obvious positive autocorrelation in space, i.e., the high or low temperature regions have a tendency to be aggregated rather than randomly distributed.

Specifically, during the study period, the Moran index was 0.907 in 2013, with a z-value of 43.967; the Moran index decreased slightly to 0.884 in 2016, indicating a weakening of aggregation; and the Moran index went on to decrease to 0.856 in 2019, suggesting that spatial aggregation of LST has significantly weakened.

The trend shows that the spatial aggregation of the heat island effect is weakening with the process of urban regeneration, especially in the areas of emerging urban clusters and green space distribution, where the distribution of high temperatures tends to be dispersed. Possible reasons for this include the networking of green space systems and the development of multi-centre clusters, etc. It is necessary to continue the eco-priority strategy in urban regeneration and to strengthen local heat risk control.

3.3.2 Cold and Hot Spots Analysis

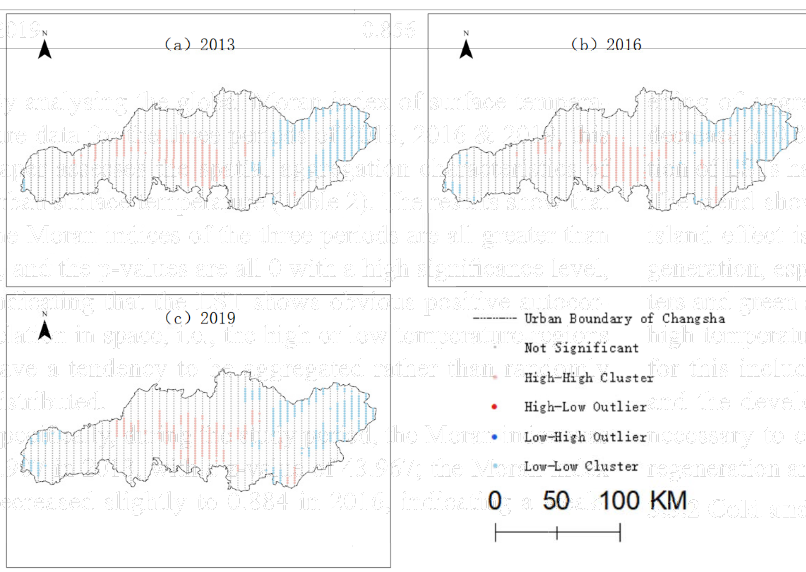

Fig. 7 Cold hotspot analysis of Changsha City in three time phases

In order to further identify the local aggregation characteristics of surface temperature in the city, this paper adopts the Getis-Ord Gi index to analyse the cold and hot spots of the three-phase LST data. In the resultant figure, the significant hotspot areas (red) are mainly concentrated in high-density construction areas, such as the urban core area and the periphery of the main roads, while the cold-spot areas (blue) are mostly distributed in the suburban areas or the areas of green space concentration (Fig.7).

Comparison of different years reveals that: in 2013, the distribution of hotspot areas was relatively sporadic and the number of cold spots was high; in 2016, the area of hotspot areas was expanded and extended to the edge of the city; and in 2019, hotspots were more densely distributed to form a contiguous area, and the number of cold spots increased significantly.

The result shows that with the acceleration of urbanisation, the thermal anomaly problem is more serious near the city centre and the development axis, while the cold spot area with mitigating thermal effect has increased. It can be seen that the heat island effect in Changsha city has decreased at present, and the green space is effective in controlling the temperature, and in the future, we can continue to strengthen the protection and rational layout of the green space, which is of great significance in alleviating the thermal environment problems in the city.

3.4 Discussion

The study of heat island effect in Changsha reveals that the cooling effectiveness of vegetation was degraded during 2013-2019, and the negative correlation between LST and NDVI was gradually significant, which is in line with the evolutionary pattern of rapidly urbanising regions. Accordingly, this study puts forward three suggestions for optimising green space planning in Changsha: firstly, it is necessary to prioritise the protection and restoration of large tree green spaces, such as the Yuelu Mountain area, instead of blindly increasing the area of inefficient lawns; secondly, it is possible to use the cold sources of Xiangjiang River, Liuyang River and other bodies of water to construct a waterfront vegetation corridor to enhance the spatial continuity of the cold island. Finally, it is suggested to quantify the impact of 3D greening indicators on LST by integrating high-resolution remote sensing (e.g., Sentinel-2) and urban microclimate models.

In addition, this study still has some deficiencies. Firstly, this study only analyses the summer satellite images of Changsha City, which lacks the time-series dimension and seasonal differences are not fully considered; secondly, the green space types are not subdivided, and the degree of influence of different green space types on the thermal environment has not yet been distinguished; lastly, the spatial resolution may affect the accuracy of the analyses, which can be improved by the combination of higher-resolution or multi-source data in the subsequent studies.

4. Conclusion

This study analyses the spatial distribution characteristics, correlation and spatial aggregation properties of surface temperature and vegetation cover in the main urban area of Changsha based on the remote sensing data of three time sections in 2013, 2016 and 2019, aiming at revealing the spatial mechanism of urban green space in mitigating the heat island effect. The study reached the following main conclusions:

1) The spatial distribution of LST and NDVI is inverse: the UHI effect is concentrated in the high-density built-up area, while the high NDVI area mostly corresponds to the low-value area of LST, and the green space has an obvious regulating effect on the urban thermal environment.

2) The overall negative correlation between LST and NDVI and the fluctuation between different years indicate that the intensity of regulation of the thermal environment by urban green space coverage is influenced by factors such as urban expansion and green space layout.

3) Surface temperature has significant spatial autocorrelation, with a tendency to decrease in aggregation with yearly changes, showing an overall pattern of ‘high-temperature aggregation - low-temperature dispersion’, and the distribution of heat islands has a certain spatial structure.

4) The cold hotspot analysis further reveals the spatial mismatch between the high temperature hotspots and the distribution of green space, and the high temperature areas are mainly distributed in the districts where the green space is missing or the urban heat source is dense, so it can be known that the optimisation of the spatial distribution of green space is of great significance to alleviate the urban thermal environment.

Overall, the study verified the spatial effect of urban green space in mitigating the surface thermal environment and also revealed the contradictory relationship between the current green space distribution and heat island pattern. In the future, Changsha city can start from both the quantity and spatial structure of green space to improve the cooling service capacity of green space system and provide scientific support for building a healthy and livable urban space.

References

[1] GUO Yi, LU Ziyu, ZHAO Zhiming, et al. A study on the impact of green space landscape pattern on thermal environment--taking the plain area of Beijing as an example[J]. Urban Architecture,2024,21(20):206-213.

[2] MENG Siyu, LIN Geng, WANG Ying. Study on the influence mechanism of urban built environment factors on thermal environment--Taking the central city of Tianjin as an example[J]. Journal of Tianjin Urban Construction University,2024,30(06):434-442.

[3] Huang Qunfang. Progress of research on the multi-scale influence of urban spatial morphology on urban heat island effect[J]. Geoscience,2021,41(10):1832-1842.

[4] QI Qianlong, MENG Qinglin, DONG Lili, et al. Discussion on the combination of urban planning and urban thermal environment research[J]. Journal of Western Habitat Environment,2021,36(03):46-56.

[5] Pan Weiwei. Application of remote sensing image processing technology in the study of urban heat island effect[J]. Longitude and Latitude World, 2021(5):50-54.

[6] Ziming Zhu, Yuanzhen Song, Menglin Qin. Study on the spatial relationship between urban heat island effect and construction intensity[J]. Geospatial Information,2022,20(4):37-43..

[7] Liu S, Yu Q, Cai G. A practical atmospheric correction method and its application to TM imagery[J]. Journal Series of Sun Yat-sen University, 2004(3):297-300

[8] QIN Zhihao, LI Wenjuan, XU Bin et al. Estimation of surface

ISSN 2959-6157

specific radiance in the range of Landsat TM6 band[J]. Remote Sensing of Land Resources, 2004(3):28-32+36-41+74

[9] ZHAO Yang, QI Jinlei, LI Hui. Comparison of multiple single-channel inversion algorithms based on Landsat8 and MODIS Terra satellite data[J]. Journal of Cebu Academy, 2021,36(9):6-12+17

[10] Jia Zhanhai. Research on the change of spatio-temporal pattern of impervious surface and its thermal environment effect in Beijing [D]. Chengdu:Chengdu University of Technology,2020.

[11] Shi, Q., Liu, M., Marinoni, A., and Liu, X.: UGS-1m: fine-grained urban green space mapping of 31 major cities in China based on the deep learning framework, Earth Syst. Sci. Data, 15, 555–577, https://doi.org/10.5194/essd-15-555-2023, 2023.

[12] Yang Dongfang, Wang Fengyou. Application of mathematical models in ecology and research 33 [M]. Beijing: Ocean Press. 2015.

[13] Wei Wenshou. Satellite remote sensing applications [M]. Beijing: meteorological press.2013.