ECOLOGICAL COOLING DEMAND IN CHANGCHUN CITY OF CHINA: SPATIAL RESPONSE TO DIFFERENCES IN URBAN THERMAL ENVIRONMENT INTENSITY

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Abstract. Rapid urbanization promotes social and economic development, but it also causes severe urban thermal environmental problems. Identifying the cooling priority zones, which is dependent on the intensity and spatial differentiation of an urban heat island (UHI), has become the key to alleviating the urban thermal environment problem. Using Changchun City of China as an example, this study used the split window algorithm (SWA) to extract the land surface temperature (LST) information from Landsat 8 OLI/TIRS image data and then discussed the ecological cooling priority zones of green landscapes by analyzing the multi-level structure of administrative division, quadrant, and loop differences in the thermal environment. The results revealed that there was an average LST difference of up to 5 °C between the inner and outer urban areas. The average temperature of the administrative region with the highest cooling demand was 2.57 °C higher than that of the region with the lowest demand. From a quadrant perspective, the regions with the lowest and highest ecological cooling demands were located in the northeast and southwest, respectively. Additionally, based on the loop, the ecological cooling demands of the central urban area in Changchun City increased from the perimeter to the center, with the center being 4.05 °C warmer than the perimeter. This study determined, from a multi-structure perspective, the priority order of cooling demand in the central urban area of Changchun City. The results pointed in the right direction for effectively mitigating the urban heat island effect and optimizing the landscape structure and layout of urban green space.
Keywords: *urban heat island, ecological cooling demand, priority, differentiation, Changchun City*

Introduction

Urbanization is accelerating in response to rapid economic development. Urban diseases are a growing concern around the globe because of a lack of environmental awareness and planning guidance, as well as excessive resource consumption and widespread environmental degradation (Liu et al., 2019; Streule et al., 2020). The urban heat island (UHI) has become a global urban challenge, which poses a threat to the livelihood and health of people by causing a variety of diseases (Nie et al., 2021), and indirectly leading to increases in crime rates, frequent hazy weather conditions, and

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excessive energy consumption (Martilli et al., 2020; Ulpiani, 2021). Reducing the UHI effect is an urgent problem that needs to be solved. An accurate assessment of the spatial priority of urban ecological cooling demand is essential for mitigating the UHI effect (Shi et al., 2019; Feng et al., 2022). Land surface temperature (LST) provides an important parameter of climate change for defining surface energy changes in recent years, as it provides a trajectory to alleviate the urban thermal environment through quantifying the UHI intensity (Qiao et al., 2020; Chen et al., 2020). The split window algorithm (SWA) is the most commonly used method for extracting LST information from Landsat 8 thermal infrared (TIR) data (Ho et al., 2022; Ye et al., 2022), as it is less dependent on atmospheric conditions and simple to implement (Yu et al., 2014a; Cavalli, 2018; Wang et al., 2019).

The urban thermal environment is becoming more regionalized and different because of various factors such as climatic conditions (Nguyen et al., 2022), spatial morphology (Li et al., 2022), substratum types (Wu et al., 2021), and human activity intensities (Qiao et al., 2022). From the city center to the outer suburbs and from residential areas to green parks, research on the spatial patterns of the thermal environment deepens the dynamic interaction between the UHI effect and urban built-up areas (Yang et al., 2020, 2022) which guides the development of ecologically desirable living environments in urban construction and planning (Peng et al., 2021). However, it is still necessary to investigate the variability of the thermal environment resulting from urban spatial zoning that is geared towards urban planning and development strategies (Yang et al., 2019; Yi et al., 2019). In recent years, research has shown that landscape metrics within a specific range of values have significant interaction effects on LST (Zhou et al., 2022), and a growing number of studies have shown that urban green spaces have an excellent ecological cooling effect (Naeem et al., 2018), which can effectively reduce temperatures and mitigate the UHI effect through shading and transpiration (Grilo et al., 2020; Zhao et al., 2020). As the relationship between urban green spaces and the UHI effect has been extensively studied in landscape ecology (Zhao et al., 2020; Xie et al., 2021), research on the relationship between urban green spaces and the UHI effect has developed rapidly. However, further research is required to identify the urban hot spots where the UHI effect is most prominent, and its mitigation is a top priority via characterization of the spatial changes of the urban thermal environment using LST. There is still a lot of work to be done in terms of scientifically quantifying urban ecological cooling demand and adjusting the structure and spatial layout of urban green spaces from the perspective of spatial prioritization (Martilli et al., 2020; Shorabeh et al., 2020).

In this study, Changchun City, the capital city of Jilin Province in China, served as a case study. From Landsat 8 remote sensing images, we extracted LST data to analyze the spatial distribution pattern of the thermal environment. We also used the multi-level structure of administrative divisions, quadrants, and loops to quantify how much ecological cooling was required for the mitigation of the UHI effect. The two main aspects of this study were as follows:

(1) To alleviate the UHI effect, we classified the urban thermal environment, derived from the SWA, as a parameter to characterize the ecological cooling demand of the city.

(2) We analyzed the ecological cooling demand of green spaces in the central district of Changchun City using a multi-level structure of administrative divisions, quadrants, and loops, which provides a research basis for rational urban planning and layout based on the difference of urban land surface temperatures.

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The remainder of this research paper is structured as follows. Section 2 describes the study area and data sources. Section 3 introduces the methodology and procedure for analyzing the spatial distribution patterns of the thermal environment and UHI intensity using brightness temperature inversion, the SWA, and the normalized difference impervious surface index (NDISI). Section 4 discusses the experiments and results. Section 5 addresses the ecological cooling demand of green spaces in the central district of Changchun City using the multi-level structure of administrative divisions, quadrants, and loops. Finally, section 6 draws some conclusions.

Materials and Methods

Study area and datasets

Study area

Changchun City is located in Northeast China, with longitude and latitude ranging from 124°18′ to 127°05′ E and 43°05′ to 45°15′ N, respectively (*Fig. 1*). The climate type is a temperate continental humid climate, which exhibits typical continental climate characteristics such as cold winters and hot summers, a monsoon climate, and precipitation in the hot season (Zheng et al., 2018). As one of the oldest industrial bases in Northeast China, the central urban area of the city expanded swiftly via rapid urbanization. A large number of anthropogenic sources of industrial emissions and heat, expansion of sclerotic area, along with the effects of global warming, have caused a mean annual temperature difference of approximately 0.5 ℃ between urban and surrounding areas (Li et al., 2020; Chen et al., 2022). Rising urban temperatures have hurt ecological city construction and the productivity and livelihoods of residents. One of the most important factors affecting the quality of urban life is the urban thermal environment (Yang et al., 2022). As a result of outstanding achievements in urban greening development and management, studying the spatial variations in LST and the ecological cooling potential of Changchun City can not only control the thermal environment of Changchun City in detail but also reduce the UHI effect and improve the urban environment.

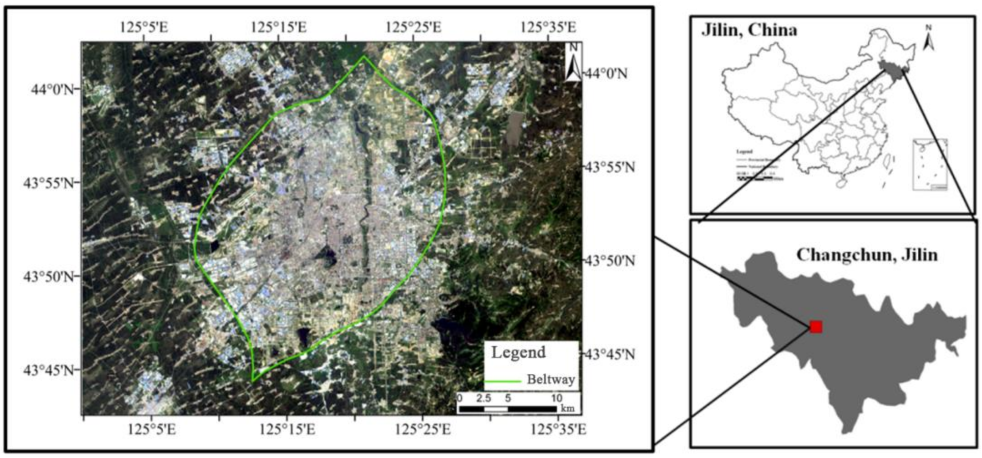

Figure 1. *Location map of Changchun City. (Image source: GF-2 remote sensing image taken in 19 May 2016)*

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Datasets

Since its launch on 11 February 2013, the Landsat 8 satellite has transmitted a vast amount of observational data to the ground at a rate of 550 images per day. It has a 16-day return period and, when combined with Landsat 7 ETM +, it forms an 8-day interval Landsat repeated observational period (Rozenstein et al., 2014). The Landsat 8 satellite is equipped with two main sensors: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). The OLI has nine bands, and the TIRS has two independent thermal infrared bands (Jiang et al., 2013).

The data used in this study were acquired from the United States Geological Survey (USGS) (https://www.usgs.gov/) on 4 July 2016 in the form of Landsat 8 images of the Changchun City area. The summer images were selected for the urban heat island study in view of the fact, that the results by Yang et al. (2020) revealed the most significant heat island effect in Changchun city in summer. The images were Level 1T terrain correction images that had been geometrically corrected using terrain data and the UTM-WGS84 projection coordinate system. As a result, no geometric correction was required while processing Landsat 8 images.

The administrative divisions and loop zoning in this study are based on the Changchun City Master Plan provided by the Changchun City Planning and Natural Resources Bureau (http://gzj.changchun.gov.cn/). Changchun City started the fifth loop planning in 2017, and the construction of the fifth loop has not been completed yet. Therefore, the study was chosen to be conducted in 2016 when the ring road status was stable.

Additionally, the hourly temperature data were obtained from the Changchun meteorological station, which was recorded by 23 encryption stations located in and around the central urban area of Changchun City on 4 July 2016 (*Figure 2*).

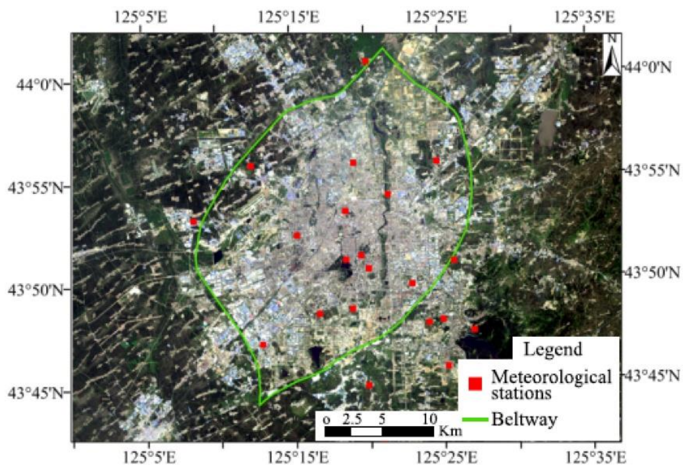

Figure 2. *Distribution of meteorological stations in Changchun City*

Methods

Brightness temperature inversion

For Landsat 8 TIRS data, Band 10 and Band 11 were calibrated as brightness temperature to obtain the LST data of the remote sensing image. In accordance with the USGS announcement, the digital numbers (DN) values of the Landsat 8 TIRS data were

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transformed into spectral radiance by *formula (1)*, and the spectral radiance was transformed into brightness temperature by the Planck radiation function *formula (2)*, as follows:

$$R_i = M_i Q_i + A_i \text{-} O_i \quad \text{(Eq.1)}$$

$$T_{i=} \frac{K_2}{\ln\left(1+K_1 / R_i\right)} \quad \text{(Eq.2)}$$

where R_i was the spectral radiance (W·m-2·sr-1·μm-1); Q_i was the DN value of band I; T_i was the brightness temperature of slope i. M_I, A_i, O_i, K_2, and K_1 were constant parameters. It should be noted that Oi can be ignored after February 3, 2014.

Split Window Algorithm (SWA)

The SWA is the primary method for calculating land surface temperatures from thermal infrared data. McMillin (1975) initially presented an algorithm for observing ocean surface temperature using Advanced Very High Resolution Radiometer (AVHRR) thermal infrared data. Based on this, Rozenstein et al. (2014) enhanced the SWA for Landsat 8 images and simplified the calculation formula for surface temperature inversion. The calculation formula for the SWA was as follows:

$$T_s = A_0 + A_1 T_{10} - A_2 T_{11} \quad \text{(Eq.3)}$$

where T_s was the land surface temperature; T_{10} and T_{11} were the brightness temperature bands 10 and 11, respectively; A_0, A_1, and A_2 were the parameters calculated using the following formulas:

$$A_0 = E_1 a_{10} + E_2 a_{11} \quad \text{(Eq.4)}$$

$$A_1 = 1 + A + E_1 b_{10} \quad \text{(Eq.5)}$$

$$A_2 = A + E_2 b_{11} \quad \text{(Eq.6)}$$

$$C_i = \varepsilon_i \tau_i \quad \text{(Eq.7)}$$

$$D_i = (1-\tau_i)\left[1+\left(1-\varepsilon_i\right)\tau_i\right] \quad \text{(Eq.8)}$$

$$A = D_{10} / E_{10} \quad \text{(Eq.9)}$$

$$E_1 = D_{11}\left(1-C_{10}-D_{10}\right) / E_0 \quad \text{(Eq.10)}$$

$$E_2 = D_{10}\left(1-C_{11}-D_{11}\right) / E_0 \quad \text{(Eq.11)}$$

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$$E_0 = D_{11}C_{11} - D_{10}C_{11} \quad \text{(Eq.12)}$$

There were four constants (a_{10}, b_{10}, a_{11}, and b_{11}) and two basic parameters (ε_i and τ_i). ε_i was the surface emissivity corresponding to band i; τ_i was the atmospheric transmittance corresponding to band i.

Normalized Difference Impervious Surface Index (NDISI)

The standard building index method tends to classify bare land and sandy soils as impervious surfaces. This study calculated impervious surfaces using the NDISI developed by Xu (2008). The calculation formula of NDISI was as follows:

$$NDISI = \frac{R_{TIR} - (MNDW + R_{NIR} + R_{MIR})/3}{R_{TIR} + (MNDWI + R_{NIR} + R_{MIR})/3} \quad \text{(Eq.13)}$$

$$MNDWI = \frac{R_G - R_{MIR}}{R_G + R_{MIR}} \quad \text{(Eq.14)}$$

In the formula, $NDISI$ was the Normalized Difference Impervious Surface Index; $MNDWI$ was the modified Normalized Difference Water Index; R_{TIR}, R_{NIR}, and R_{MIR} were thermal infrared (5th Landsat 8 OLI), near infrared (6th Landsat 8 OLI), and medium infrared (10th Landsat 8 OLI) bands, respectively.

Urban heat island intensity

UHI intensity refers to the temperature difference between urban and rural areas caused by the UHI effect and other factors. In accordance with prior research, this study used the UHI intensity index to quantitatively analyze the spatial distribution law of UHI intensity in the central urban area of Changchun City. The UHI intensity was calculated using the following formula:

$$T_R = \frac{T_i - T_a}{T_a} \quad \text{(Eq.15)}$$

where T_R was the UHI intensity, *i* in the surface temperature calculation was a pronoun referring to a location or area in the study area, T_i was the LST at i, and T_a was the average LST in the study area.

The inversion calculation and visualization analysis of surface temperature in the study were mainly performed by ArcGIS 10.8 and ENVI 5.6.

Ecological cooling demand

The study area was narrowed down to the area within the Changchun City bypass highway to discern the UHI disparities within the central city for further investigation of the ecological cooling demand of green spaces. The UHI intensity was calculated to characterize the ecological cooling demand, which was divided into six classes (*Table 1*). The ecological cooling demand of the central urban area was finally

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determined, allowing us a greater understanding of the spatial distribution patterns of UHI intensity in the central part of Changchun City. Furthermore, we analyzed the distribution of ecological cooling demand in the central urban area of Changchun City from the perspectives of administrative divisions, quadrants, and loops. This laid the foundation for improving the cooling efficiency of urban green spaces and promoted sensible urban planning.

Table 1. *Characterization of UHI intensity and classification of ecological cooling demand*

T_R Range	Grade	Ecological cooling demand
-1 - 0.2	1	No demand
-0.2 - 0	2	No demand
0 - 0.1	3	weak demand
0.1 – 0.2	4	Medium demand
0.2 – 0.4	5	Strong demand
0.4 - 1	6	Extremely strong demand

Results

Analysis of spatial distribution pattern of thermal environment in Changchun City

The validation of surface temperature inversion results

The measured temperature data were used to verify the accuracy of the LST inversion results. This study validated the reliability and accuracy of the LST inversion results by comparing them to the observed temperature data. As it was known that the vegetation canopy temperature was approximately equal to the air temperature at meteorological stations with high vegetation coverage (Yang et al., 2016), the air temperature recorded at these stations was selected to validate the retrieved surface temperature. Since the transit time of the Landsat 8 satellite was 10 a.m., surface temperature verification was conducted using the temperature data recorded at 10 a.m. of the same day. *Figure 2* depicts the distribution location of meteorological stations in Changchun City. Verification was conducted on 10 of the 23 meteorological stations located in densely vegetated areas. The air temperature during satellite transit as recorded by meteorological stations and the surface temperature as calculated by SWA were used for verification (*Table 2*). *Table 1* shows that the average temperature difference of the SWA results was 1.08 ℃, and the root mean square error was 0.94. The retrieved surface temperatures were slightly higher than the air temperatures recorded by the meteorological stations. The results were reasonable and consistent with the research of Yang et al. (2017).

Preliminary assessment of the intensity of the UHI effect in central Changchun City

Figure 3 depicts the results of retrieving the Changchun City LST using the SWA, indicating that the LST in the urban area was significantly higher than that in the suburbs. To gain a preliminary understanding of the intensity of the UHI effect in Changchun City, the average LST within the central urban area was compared to the average LST outside. The NDISI was used to extract the impervious surfaces to obtain the NDISI of Changchun City (*Figure 4*). Based on the criterion that an NDISI value greater than 0.28 indicated an impermeable surface, the image was divided into permeable and impermeable surfaces. The water bodies and permeable surfaces within

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the city were eliminated to obtain the central urban boundary of Changchun City. Based on the statistics, the average LST inside the central urban area was 38.1 ℃, and the average LST outside the central urban area was 32.5 ℃, signifying a difference of 5.6 ℃, The results of the investigation indicated that the UHI effect in Changchun City was severe.

Table 2. *Comparison between land surface temperatures retrieved by split window algorithm and recorded temperatures at meteorological stations*

Number	Local meteorological	Split Window Algorithm	
	Temperature (℃)	Temperature (℃)	△
1	31.60	33.63	2.03
2	30.70	32.79	2.09
3	31.60	33.78	2.18
4	31.65	32.83	1.18
5	28.65	27.76	-0.89
6	28.35	29.47	1.12
7	31.15	32.45	1.30
8	30.50	31.66	1.16
9	28.70	29.58	0.88
10	30.9	30.66	-0.24
Average difference			1.08
RMSE			0.94

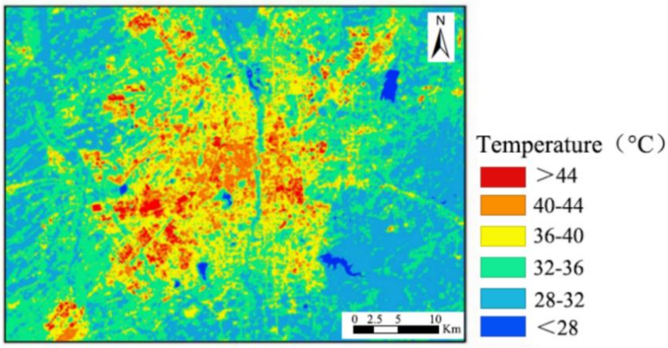

Figure 3. *Inversion results in land surface temperature in Changchun City*

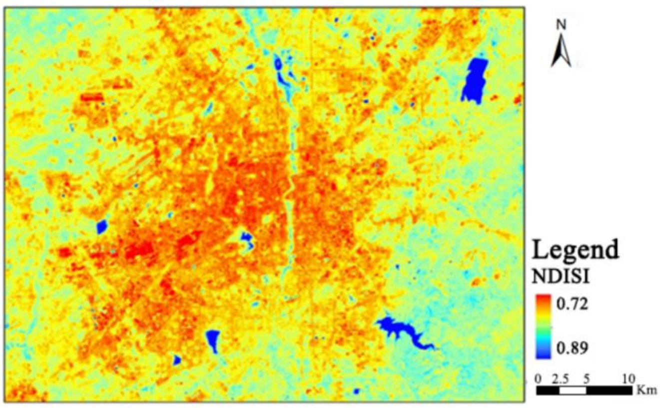

Figure 4. *Distribution of the Normalized Difference Impervious Surface Index (NDISI) in Changchun City*

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Analysis of the ecological cooling demand of green spaces in the central urban area of Changchun City

Analysis of ecological cooling demand in Changchun City by administrative division

To understand the distribution characteristics of ecological cooling demand in the central urban area of Changchun City, the average LST, the area of ecological cooling demand, and the proportion of ecological cooling demand were analyzed from the perspective of administrative division. The ecological cooling demand area was defined as the area with medium or higher demand. The area covered by the case study comprised Kuancheng, Erdao, Nanguan, Chaoyang, and Lvyuan Districts (*Figure 5*). Average LST, ecological cooling demand area, and the proportion of ecological cooling demand area as a percentage of the total were recorded separately (*Table 3*).

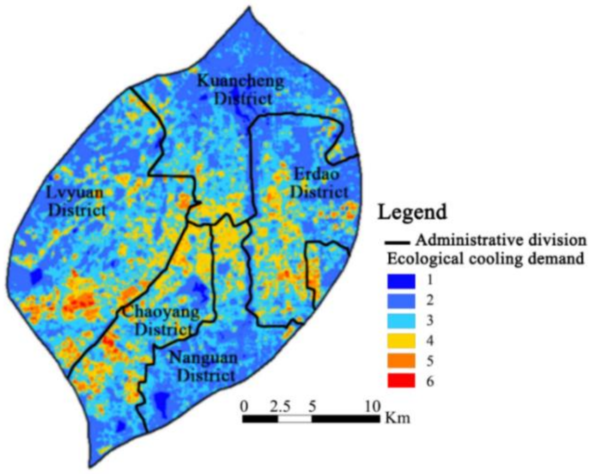

Figure 5. *Administrative division map of ecological cooling demand*

Table 3. *Distribution of ecological cooling demand among different administrative regions*

	Erdao District	Chaoyang District	Kuancheng District	Nanguan District	Lvyuan District
Average land surface temperature (°C)	37.93	38.92	36.35	37.13	38.19
Total demand area (ha)	2126.88	2439.72	1153.26	1161.36	3937.86
Percentage of total demand (%)	22.53%	32.55%	10.07%	15.03%	24.43%
Extremely strong demand area (ha)	9.45	35.64	0	3.6	64.44
Percentage of extremely strong demand (%)	0.10%	0.48%	0.00%	0.05%	0.40%
Strong demand area (ha)	309.6	407.97	70.65	127.44	800.28
Proportion of strong demand (%)	3.28%	5.44%	0.62%	1.65%	4.96%
Medium demand area (ha)	1807.83	1996.11	1082.61	1030.32	3073.14
Proportion of medium demand (ha)	19.15%	26.63%	9.46%	13.33%	19.07%

To facilitate the comparison of ecological cooling demand differences between administrative regions, we statistically plotted the total demand area proportions and average surface temperature data for each administrative region in *Figure 6*. The figure illustrates that the higher the average surface temperature was, the greater the percentage of demand area within each administrative region. Chaoyang District had the

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highest demand for ecological cooling, with an average LST of 38.92 ℃ and a total demand area of 2126.88 ha, which accounts for 32.55% of the whole administrative region (within the study area); the ecological cooling needs of Lvyuan District and Erdao District were similar and ranked second and third, respectively. The average LST in the Lvyuan District was 38.19 ℃, and the total demand area was 3937.86 ha, which accounted for 24.43% of the whole administrative region. The average LST of Erdao District was 37.93 ℃, and the total demand area was 2126.88 ha, which accounted for 22.53% of the whole region. Nanguan District had the fourth highest demand for ecological cooling, with an average LST of 37.13 ℃ and a total demand area of 1161.36 ha accounting for 15.03% of the total. Based on the average LST of each administrative region, the ecological cooling needs of each administrative region were vastly distinct. The average temperature difference between the highest and the lowest administrative regions was as high as 2.57 ℃.

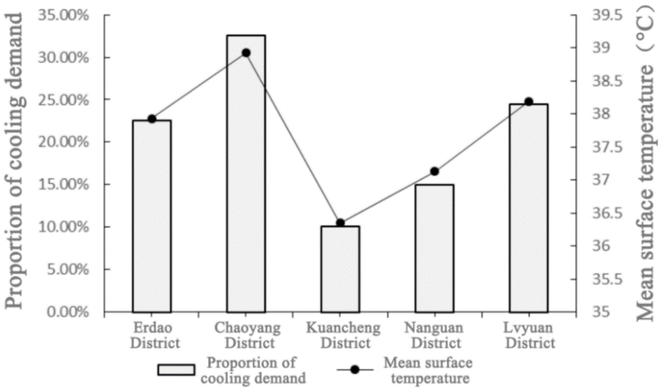

Figure 6. *Proportion of average land surface temperature and ecological cooling demand areas in each administrative region*

The areas of extremely strong demand were as follows (descending order of strength): Lvyuan District > Chaoyang District > Erdao District > Nanguan District > Kuancheng District. The proportions of extremely strong demand were Chaoyang District > Lvyuan District > Erdao District > Nanguan District > Kuancheng District. The area and proportion of strong and medium demand were similar to those of extremely strong demand. It can be seen that regions with greater ecological cooling demand were more likely to have a cooling effect with higher demand. Therefore, it is possible to prevent an area with strong cooling demand by breaking up a large area of ecological cooling demand area with green spaces or water bodies.

Analysis of ecological cooling demand in Changchun City by quadrant

The study was divided into four quadrants using the center of gravity of the study area as the origin to create the coordinate axis, as shown in *Figure 7*. The average LST, the proportion of ecological cooling demand areas, and the proportion of ecological cooling demand in the entire area were measured. According to the analysis presented above, the spatial distribution laws of extremely strong, strong, and medium demand were consistent. It indicates that only the total demand area and a proportion of the demand area in each quadrant were considered when calculating the spatial distribution of ecological cooling demand areas. *Table 4* was obtained.

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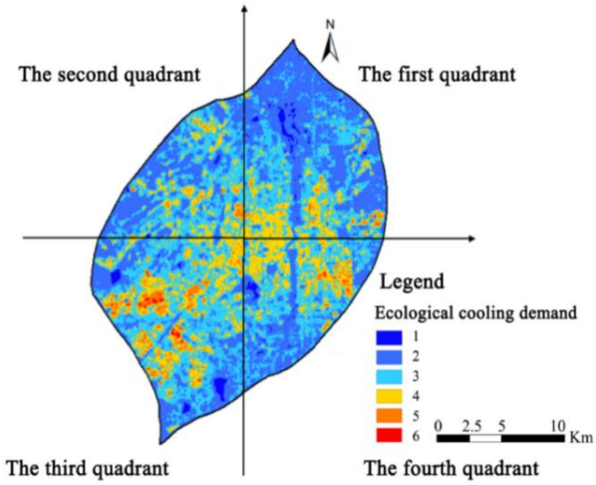

Figure 7. *Distribution of ecological cooling demand in quadrants*

Table 4. *Proportion of average land surface temperature and ecological cooling demand area in different quadrants*

	The first quadrant	The second quadrant	The third quadrant	The fourth quadrant
Average LST	36.67	37.40	38.62	38.08
Total demand area	2227.05	1622.97	4551.12	2417.85
Proportion of total demand	11.73%	16.17%	28.25%	23.90%

Using the table as a guide, a statistical chart depicting the proportion of average LST and ecological cooling demand areas in each quadrant was created (*Figure 8*). As seen in the chart, the relationship between the proportion of demand area and the average LST was as follows: third quadrant > fourth quadrant > second quadrant > first quadrant. This indicated that the southwest had the highest demand for ecological cooling within the study area. The average LST was 38.62 °C, and the proportion of ecological cooling demand areas was 28.25%. The southeast has the second highest demand for ecological cooling, with an average LST of 38.08 °C and an ecological cooling demand area accounting for 23.90% of the total area. Apart from that, the demand for ecological cooling in the northwest was weak, the average LST was 37.40 °C, and the proportion of ecological cooling demand areas was 16.17%. The Northeast had the weakest demand for ecological cooling, with an average LST of 36.67 °C and a proportion of ecological cooling demand areas of 11.73%. Therefore, according to partitioning by quadrant, the relationship between the proportion of ecological cooling demand areas and the average LST in the main urban area of Changchun City was as follows: third quadrant > fourth quadrant > second quadrant > first quadrant. The results indicate that it was imperative to focus on the ecological cooling demand of green spaces in the southwest and southeast sections of the study area to reduce temperatures and moderate the UHI effect.

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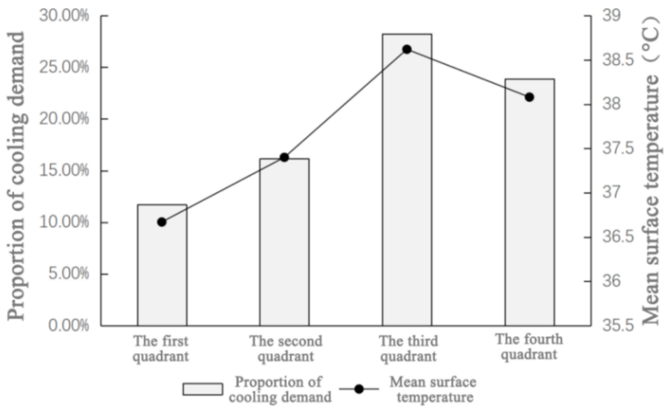

Figure 8. *Proportion of average land surface temperature and ecological cooling demand areas by quadrant*

Analysis of ecological cooling demand in Changchun City by loop

As illustrated in *Figure 9*, the loop in Changchun City divided the study area into 1-4 loops and areas outside the four loops. In each loop, the average LST, total area requirement, and proportional area were determined. The statistical data are shown in *Table 5*. According to *Figure 10*, derived from the data in this table, the average LST of the first loop was the highest at 40.63 °C, whereas those of the second, third, and fourth loop areas were lower. However, there was little distinction between the second, third, and fourth loop areas. The average LST of the second, third, and fourth loop areas were 38.78 °C, 38.80 °C, and 38.74 °C, respectively. The LST outside the fourth loop was the lowest at 36.58 °C. The proportion of ecological cooling demand areas was as follows; the first loop (64.71%) > the second loop (33.60%) > the fourth loop (26.83%) > the third loop (25.52%) > outside the fourth loop (11.96%). The figure demonstrates that the proportion of average LST and ecological cooling demand areas decreases from the inside to the outside, and there is little difference between the average LST and demand area from the second loop to the fourth loop, with an average temperature difference as high as 4.05 °C between the urban center and the urban edge.

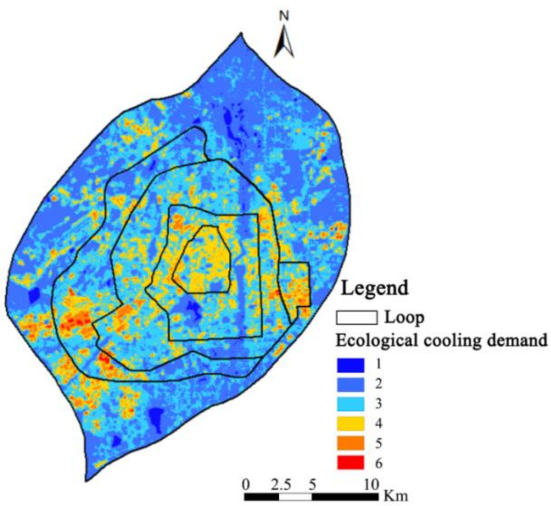

Figure 9. *Distribution of ecological cooling demand by loop*

Table 5. *Proportion of average land surface temperature and ecological cooling demand area in each loop*

	The first loop	The second loop	The third loop	The fourth loop	Outside of the fourth loop
Average land surface temperature	40.63	38.78	38.8	38.74	36.58
Total demand area	1066.5	1818.63	2511.45	2161.17	3264.42
Proportion of total demand	64.71%	33.60%	25.52%	26.83%	11.96%

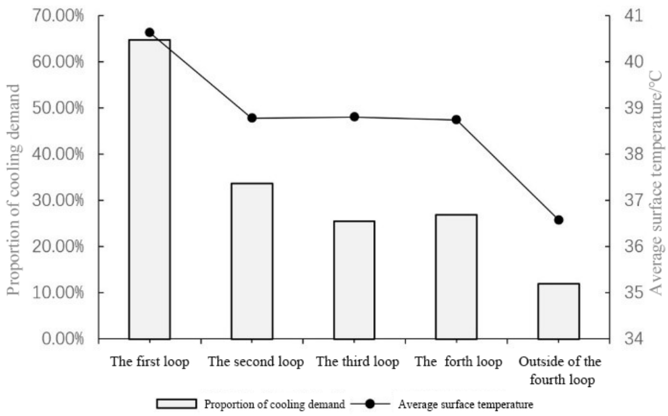

Figure 10. *Proportion of average land surface temperatures and ecological cooling demand areas in different loop areas*

Discussion

Relevant UHI research has been focused on other tropical, subtropical, and temperate cities, while snow-climate city like Changchun should receive more attention. In this study, we used Changchun City as a case study and extracted the LST values from Landsat 8 remote sensing images to analyze the spatial distribution patterns of the thermal environment and UHI effect intensities. Firstly, the split window algorithm is selected to retrieve the LST of Changchun City. It has been applied in a large number of urban thermal pattern studies, and has been proved to have high inversion accuracy. The SWA was utilized to invert the LST as the basis for the analysis of the UHI effect. To ensure the accuracy of the research, we validated the data by selecting 10 meteorological stations in areas with dense vegetation coverage and comparing the air temperatures recorded at the meteorological stations during satellite transit to the surface temperatures inferred by the SWA (*Table 1*). As shown in *Table 1,* the average LST difference among the results of the SWA was 1.08 °C and the root mean square error was 0.94, reflecting the same trend as that recorded at the meteorological station. It ensured that the LST obtained by the application of the SWA was a more accurate reflection of the spatial variability of the thermal environment in Changchun City. It also implied that the SWA required only two parameters, ε and τ, to invert LST with high accuracy, making it less dependent on atmospheric parameters than the SWA (Yu et al., 2014b; Wang et al., 2019). Consequently, this overcame the limitations of traditional surface temperature inversions that rely on external data from MODIS water vapour products (Jiang et al., 2021).

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The accuracy of the inversion results was verified by comparing the inverse LST with the LST measured in the field. The method verified by measured temperature is faster and more accurate than based on radiation intensity and the cross-comparison method with MODIS land surface temperature products (Song et al., 2015). On the one hand, the simulation process based on radiation intensity using atmospheric simulation software such as MODTRAN is complex. On the other hand, there is a temperature difference between MODIS temperature products and Landsat 8 surface temperature inversion results, with a satellite transit time difference of about half an hour between the two and a scale effect due to the large difference in spatial resolution (Zhang et al., 2019). Therefore, in view of the time lag between the acquisition of the measured temperature and the transit of the Landsat 8 satellite, and the time and effort required to acquire the measured data representing 30m pixels, air temperature records from weather stations with good temporal continuity and balanced distribution were chosen as validation data.

We also evaluated the state of the UHI effect to quantify the ecological cooling needs from the multi-level structure of administrative divisions, quadrants, and loops. In contrast to previous research on the analysis of urban ecological cooling potential, this paper combines a breakthrough from the past analysis of ecological patches with an analysis of urban heat island and ecological cooling demand patterns in terms of administrative districts and loops that reflect the overall spatial planning and infrastructural framework of the city, and in conjunction with regional quadrants (Li et al., 2015). Based on obtaining the surface temperature of the central urban area of Changchun City, this study analyzed the ecological cooling demand of urban green spaces in depth and confirmed that the ecological cooling demand was the highest within the first loop of the central urban area of Changchun City, Chaoyang District, and the southwest. It indicated that the ecological cooling needs were more pronounced in the urban center than in the urban outskirts areas, which was consistent with the spatial variability of cooling demand in urban thermal environments demonstrated by Liu et al. (2022). Meanwhile, compared to Beijing City, which is located in the temperate zone, we found Changchun City has a more concentrated area of ecological cooling needs and significant differences between the ecological cooling needs of the administrative districts (Shi et al., 2019). This may be due to differences in regional size, population density, and development between administrative regions.

The administrative divisions, quadrants, and loops that represent the urban structure and layout have always been the fundamental support units of local governance (Yifei and Kaiyong, 2019; Kaiyong et al., 2020). It has a limited impact on the factors that mitigate the UHI effect, such as land use transfer, population flow, and landscape change (Ye, 2016; Hu et al., 2018). Based on mastering the spatial distribution information on the UHI in Changchun City, we identified the areas with the highest ecological cooling demand that required prioritized mitigation, laid the foundation for research on the planning scheme of ecological cooling demand priority areas, selected green space sites and layout, optimized the structure of green spaces in Changchun City, and indicated the direction for alleviating the UHI effect.

In a subsequent investigation, we should continue investigating the urban green spaces of Changchun City, and analyze their phenological period, spatial distribution, and quantity (Hu et al., 2020; Gomez-Martinez et al., 2021). Based on the inversion of surface temperatures and the extraction of urban green spaces, the influence of the attributes of urban green spaces on their cooling effect has been researched in-depth

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(Way et al., 2021; Wang et al., 2021). Then, from the perspective of maximizing the cooling effect, we should clarify the urban green space planning scheme and establish the optimized configuration for green landscapes. This will promote the following: establishing the highest ecological cooling efficiency of urban green landscapes; guiding the spatial layout optimization of urban green space to alleviate the UHI effect, protect the health of people, and reduce energy consumption; improving the urban microclimate.

Conclusions

Using Landsat 8 satellite image data of Changchun City, we applied the SWA to obtain the LST of the central urban area of Changchun City. We also used the inversion results of the LST as the basic parameters for further research and analyzed the spatial distribution law of the thermal environment and the ecological cooling demand of the central urban area of Changchun City. To alleviate the UHI effect, the UHI intensity was graded, which was then used to quantify the urban ecological cooling demand. The distribution analysis of the ecological cooling demand of the green landscape in the central urban area of Changchun City was conducted using a multi-level structure of administrative divisions, quadrants, and loops. The research showed that the ecological cooling demands within the first loop of the central urban area, Chaoyang District, and the southwest section were the highest, and hence should be prioritized. The specific conclusions were as follows:

1) Based on the temperature difference between the interior and exterior of the central urban area, the average LST difference between the interior and exterior of the central urban area of Changchun City was as high as 5.6 ℃, indicating that the UHI effect in Changchun City was extremely severe and needs to be addressed urgently.

2) In accordance with various zoning regulations, the spatial distribution of ecological cooling demand in the central urban area of Changchun City was analyzed. It was found that the temperature distribution in the central urban area of Changchun City was also uneven. The average temperature in the administrative region with the highest ecological cooling demand was 2.57 ℃ higher than that in the administrative region with the lowest ecological cooling demand. Among the administrative districts, Chaoyang District had the highest demand for ecological cooling, whereas the Kuancheng District had the lowest demand for ecological cooling. Therefore, priority should be given to improving the layout and structure of green spaces in the Chaoyang District.

3) Based on the difference in ecological cooling demand in four quadrants, the relationship between the proportion of ecological cooling demand areas and the average LST was as follows: third quadrant > the fourth quadrant > the second quadrant > the first quadrant. This indicated that the ecological cooling demand in the northeast was the lowest and that the ecological cooling demand in the southwest was the highest. Overall, the southern UHI effect of Changchun City was more significant, thus ecological cooling demand in the southwest and southeast should be given priority.

4) The zoning of the loop revealed that the ecological cooling demand of Changchun showed an obvious increasing trend from the exterior to the interior. Among them, the ecological cooling demand from the second to fourth loops was relatively uniform, and the temperature difference between the urban center and the urban edge was as high as 4.05 ℃. In general, the proportion of ecological cooling demand areas was

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synchronized with the distribution of average LST. The average LST in areas with a high proportion of ecological cooling demand area was also high. Therefore, priority should be given to the ecological cooling demand in the first loop.

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