Sustainable Cities and Society 97 (2023) 104736

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Potential grading refrigeration system? Based on urban agglomeration thermal environment analysis perspective

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ARTICLE INFO

Keywords:
Graded refrigeration system
Urban agglomeration
Thermal environment intensity
Landscape pattern index
Complex networks

ABSTRACT

Urban heat stress is a critical issue impacting the sustainable development of urban agglomerations. Ecological land is an important factor in alleviating the heat environment stress of urban agglomerations. However, few scholars have taken a macro, interconnected perspective to consider the cooling effects of different ecological land. This study reveals that urban agglomerations have a potential hierarchical natural cooling system. Based on the heat environment assessment of the Beijing-Tianjin-Hebei (BTH) urban agglomeration and the Minimal cumulative resistance (MCR) model, we extracted the graded cooling patches and cooling corridors from 2005 to 2020. The research findings indicate that the heat environment intensity of the BTH urban agglomeration presents a spatial pattern of high intensity in the southeast and low intensity in the northwest, and the heat environment intensity of the urban agglomeration remains at a relatively high level. The number of graded patches and corridors shows a trend of first decreasing and then increasing, and the central and southern regions have relatively few corridors and patches, which require targeted optimization and improvement. Additionally, the overall length of corridors in the BTH urban agglomeration has increased, while the cooling effect of patches has decreased. The robustness and connectivity of the cooling system have both increased over 15 years, but further optimization and improvement are still needed to alleviate the heat environment intensity of urban agglomerations. This study quantifies the trends in urban agglomeration heat environment stress and the functional and topological properties of patches, corridors, and systems, providing valuable information for natural-based urban planning and management, as well as new solutions and research perspectives for alleviating heat environment stress in urban agglomerations.

1. Introduction

Extreme high temperature climates have a significant impact on human life and social development (Gao et al., 2015; Zhang et al., 2021a). Urban thermal environments are often caused by impervious surfaces with low solar reflectance replacing ecological land (forests, shrubs, grasslands, water), which absorb and retain greater solar radiation (Byrne & Jinjun, 2009; Oke et al., 2017; Yu et al., 2020). In addition, the urban geometry, dominated by buildings and street canyons, reduces overall ventilation, which makes it difficult to dissipate heat from the city (Grimmond & Oke, 1999; Marciotto et al., 2010). Heat release from human activities also contributes to heat accumulation. However, to meet the increasing demands of residents for housing and infrastructure, the impervious surfaces of urban areas are gradually increasing and expanding outward, exacerbating the urban heat environment (Argüeso et al., 2014; Cao et al., 2018; Li et al., 2020). Therefore, it is very important to understand the changes of urban thermal environment and formulate solutions and strategies for urban planning, design and sustainable development.

There has been a considerable amount of research on urban heat environment. Studies have shown that various factors, including urban geometry, climate conditions, and building materials and structures, can influence the urban heat environment (Zhou et al., 2020; Zhou et al., 2021a). The expansion of cities has significantly altered the surface energy balance and hydrological cycle, leading to changes in temperature, humidity, and precipitation (Cao et al., 2016; Georgescu et al.,

Abbreviations: BTH, Beijing-Tianjin-Hebei; MCR model, Minimal cumulative resistance model; LST, Land surface temperature; GDP, Gross Domestic Product; FVC, Fractional vegetation cover; NDWI, Normalized difference water index; NDVI, Normalized Difference Vegetation Index; SHDI, Shannon's diversity index; LSI, Landscape shape index; ED, Edge density; Division, Landscape Division index; Contag, Contagion index.

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https://doi.org/10.1016/j.scs.2023.104736
Received 19 March 2023; Received in revised form 22 May 2023; Accepted 15 June 2023
Available online 23 June 2023

2013). However, by implementing rational urban planning and design, adjusting building layouts, and employing other strategies, it is possible to effectively alleviate the pressure of urban heat environment. Furthermore, the use of advanced building materials and technologies, such as green roofs, insulation materials, and energy-efficient equipment, can reduce the absorption and conduction of heat by buildings (Susca et al., 2011). In addition to urban form and building materials, studies have shown that green and blue spaces in cities can effectively mitigate urban heat environment pressure (Targino et al., 2019). These studies classify green and blue spaces into different types based on their spatial scales and propose different parameters to assess their impact on the urban heat environment at various research scales. Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) are commonly used in large-scale studies (Neinavaz et al., 2020), while metrics such as Vegetation Coverage (FVC) are applied in medium-scale research, such as streets and neighborhoods (Klemm et al., 2015). Leaf density is often used in small-scale studies, such as courtyards (Darvish et al., 2021). The reduction of these indicators is associated with an increase in urban heat environment pressure. While these findings provide theoretical support for mitigating the urban heat environment, there is a lack of research that specifically proposes concrete strategies and engineering measures based on green and blue spaces to alleviate urban heat environment pressure.

Developing solutions for urban heat environment issues is particularly urgent in urban agglomerations where the problem is prominent (Chapman et al., 2017). With the increase in urban building density and population, urban residents are more exposed to extreme high-temperature environments, severely impacting their health and increasing the risk of heat-related illnesses and deaths (Heaviside et al., 2017; Tan et al., 2010). As an important economic region in northern China, the BTH urban agglomeration has been experiencing expanding urban areas, deteriorating ecological environments, and high energy consumption, leading to increasingly prominent urban heat environment issues (Chen et al., 2020). Especially in summer, the combination of seasonal high-temperature climate and urban heat island effect subjects urban residents to more severe heat stress (Luo & Lau, 2018). Some studies indicate that over one-third of the counties in the BTH urban agglomeration show a significant increase in the intensity of the summer heat environment (Hou et al., 2021). Moreover, the central and southern regions of the urban agglomeration exhibit high-temperature conditions (Shen et al., 2022), with a gradient attenuation trend of the heat environment between the city center and surrounding non-urban areas (Fu et al., 2022). Although there have been numerous quantitative studies analyzing the heat environment in the BTH urban agglomeration, strategies to alleviate heat environment pressures, particularly through natural means, are scarce. Mitigating and reducing the impacts of extreme heat extremes in cities has become an urgent issue for improving the overall urban ecological environment in the BTH region, as emphasized in the integrated development plan. Additionally, government authorities have explicitly stated in the framework for urban climate action and overall urban planning the need to improve urban wind circulation and alleviate urban heat environment pressures (C40 Cities, 2018; Watts et al., 2017). Therefore, the assessment of the heat environment in the BTH urban agglomeration and the proposal of improvement strategies are pressing needs for government authorities.

Quantitative analysis of urban thermal environment is the first step in mitigating cumulative urban heat and can help us understand the risk patterns of the entire urban cluster. Currently, the main quantitative approaches for urban thermal environment include field measurements, simulation modeling, and remote sensing inversion (Lin & Lin, 2016; Ng et al., 2012). Yan et al. conducted on-site measurements using temperature sensors in large green parks in Beijing, quantitatively analyzing the regional thermal environmental intensity. The study found that as the distance from the park boundary increased, the thermal environmental intensity of the urban area gradually increased (Yan et al., 2018). Huang et al. developed a numerical simulation program for urban thermal environment, which analyzed the spatial distribution of wind speed, air temperature, and humidity within the measurement area to quantitatively simulate the thermal environmental intensity of the city (Huang et al., 2005). Yang et al. measured the two-dimensional and three-dimensional thermal environmental intensity of the city using drones and multi-source remote sensing data, and found that building and vegetation coverage were the most significant factors influencing the increase and decrease of thermal environmental intensity in the city (Yang et al., 2021). In existing research, remote sensing inversion is one of the most widely used methods for assessing urban thermal environment intensity. Through land surface temperature (LST) parameters, urban thermal environment intensity can be monitored on a large scale and in real-time. Some scholars have already used density segmentation methods to evaluate urban thermal environment, effectively identifying high-temperature and low-temperature areas within urban clusters (Yuan et al., 2017; Zhao et al., 2016). This provides an analytical approach and means for quantifying urban thermal environment and serves as a foundation for addressing urban thermal environment issues.

On the basis of quantitative analysis, proposing feasible and effective mitigation strategies is the second step. Currently, a large number of scholars have pointed out that increasing the ventilation performance of cities and absorbing a certain amount of heat can alleviate the urban heat environment by changing the building density, building form, and building facade material (Peng et al., 2012). However, the reduction of building density, changes in building form, and alterations to building facades often involve demolition and construction of buildings, which are often constrained by policymakers and overall urban planning. Additionally, this method incurs high economic and time costs, and corresponding research is more suitable for future urban planning and design. For large urban agglomerations that have already been developed, more effective approaches need to be adopted. Ecological land in urban agglomerations is considered the most effective element for alleviating the urban heat environment (Peng et al., 2016; Yao et al., 2020). Through evapotranspiration, shading, and heat absorption, urban ecological land forms a "cool island effect" in urban agglomerations. Previous research has shown that ecological land types include forests, shrubs, grasslands, wetlands, and lakes, and they can effectively regulate the local thermal environment of surrounding areas (Gunawardena et al., 2017). The area, shape, and distribution of various ecological land also determine the effectiveness of alleviating the urban heat environment (Estoque et al., 2017; Feyisa et al., 2014). However, we found that most ecological land exists in an isolated point-like distribution, lacking effective connections with each other. This limits the cooling effect of ecological land to the surrounding areas and insufficiently affects the cooling of other areas. Additionally, most ecological land is often located in the marginal areas or suburbs of cities, and many ecological lands have a small cooling effect on urban areas. Furthermore, existing studies primarily focus on exploring the relationship between the topological characteristics of ecological land and heat stress, but they lack specific engineering measures to mitigate heat stress. In this context, we have identified a potential natural refrigeration system within urban agglomerations. By connecting different ecological land patches through a patch-corridor-network configuration, and implementing graded refrigeration systems through human construction and preservation, isolated ecological land can be interconnected to achieve better cooling effects, alleviate overall heat stress in urban clusters, and improve the living environment for urban residents.

As a rapidly developing urban agglomeration, the BTH region has long been facing ecological problems related to urban heat islands, which affect the sustainable development and livable environment of cities. With urban development, ecological land has become increasingly fragmented, exacerbating urban heat island effects, especially in the summer. Previous studies have shown that the urban heat island phenomenon is most significant in the BTH region during the summer months of June to August (Cui et al., 2021; Fu et al., 2022). Therefore, we have chosen the BTH region during the summer seasons (June to August) from 2005 to 2020 as the study area to investigate the question of "how to leverage natural ecological cooling systems to alleviate heat environment pressures in urban agglomerations." The objectives of this study are as follows: (1) to evaluate the spatiotemporal variation of the urban heat island effect in the BTH urban agglomeration during the summers from 2005 to 2020; (2) to propose a hierarchical natural cooling system, consisting of source areas, corridors, and networks, based on the source-sink theory, and to suggest mitigation strategies using graded protection and construction; (3) to explore the relationship between the spatial distribution and geometric complexity of source areas and the spatiotemporal variation of the urban heat island effect using landscape pattern indices; and (4) to evaluate the stability of the cooling system in the BTH region during the study period using five network attack types and to propose optimization strategies.

2. Methods

2.1. Study area and data sources

The BTH urban agglomeration is located in the northern part of the North China Plain, covering a total area of 218,000 km^2, and is one of the three largest urban agglomerations in China (Fig. 1). In recent years, due to rapid development, the level of urbanization in the BTH urban agglomeration has been continuously increasing, with a surge in population and GDP, making it one of the largest economic centers in China. According to data from the National Statistical Yearbook, the population of the BTH region has reached 110 million, and its GDP accounts for 8.5% of the national total (Zhou et al., 2021). However, due to the intensified urbanization, urban construction land has replaced original ecological land, and the urban heat stress has become an important factor restricting urban development.

In this study, administrative boundary data of the BTH was sourced from the Resource and Environment Science and Data Center (https://www.resdc.cn/). DEM and slope data from 2005 to 2020 were obtained from the Geographical Information Monitoring Cloud Platform (http://www.dsac.cn/).Both datasets have a spatial resolution of 1 km $\times$ 1 km. Evapotranspiration data from 2005 to 2020 were obtained from the 1 km monthly potential evapotranspiration dataset in China (1990–2020) from the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (Peng et al., 2017). NDWI data from 2005 to 2020 were processed using the MCD43A4.061 MODIS data product through the Google Earth Engine platform, and after cloud removal and normalization, the NDWI data were obtained; Land use and NDVI data from 2005 to 2020 were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/). Precipitation data from 2005 to 2020 were obtained from the dataset 1 km monthly precipitation dataset for China (1901–2021) from the National Tibetan Plateau Scientific Data Center (http://data.tpdc.ac.cn/zh-hans/) (Shouzhang, 2020). LST data were obtained from the Daily 1 km all-weather land surface temperature dataset for the Chinese landmass and its surrounding areas from the National Tibetan Plateau Science Data Center (https://www.tpdc.ac.cn/) (Zhang et al., 2021b). Population density dataset from 2005 to 2020 were obtained from WorldPop, with a spatial resolution of 1 km $\times$ 1 km (https://www.worldpop.org/). All raster data were clipped to the study area using ArcGIS 10.4 and resampled to 1 km x 1 km. The construction of the graded refrigeration system is described as follows (Fig. 2).

Due to the influence of natural and artificial factors, the range of LST values varies between different years, and the heat environment intensity reflected by the same LST value can also differ across different years. Therefore, comparing the numerical values of land surface temperature alone cannot adequately reflect the relative heat environment intensity between different years. By employing the mean-standard deviation method, different levels of urban heat island heat environment intensity can be delineated, allowing for a horizontal comparison of heat environment intensity across different years and effectively representing the spatial distribution of the urban heat environment in the Beijing-Tianjin-Hebei region. Compared to the equal interval method, the mean-standard deviation can better reflect the deviation degree of temperature relative to the average temperature, as well as the variation of temperature in different regions (Yu et al., 2022; Yuan et al., 2023). Based on this, we divided the urban thermal environment intensity into 5 levels (Table 1). At the same time, by constructing the transition matrix of urban thermal environment intensity, we quantitatively revealed the transformation of thermal environment intensity in the BTH region from 2005 to 2020.

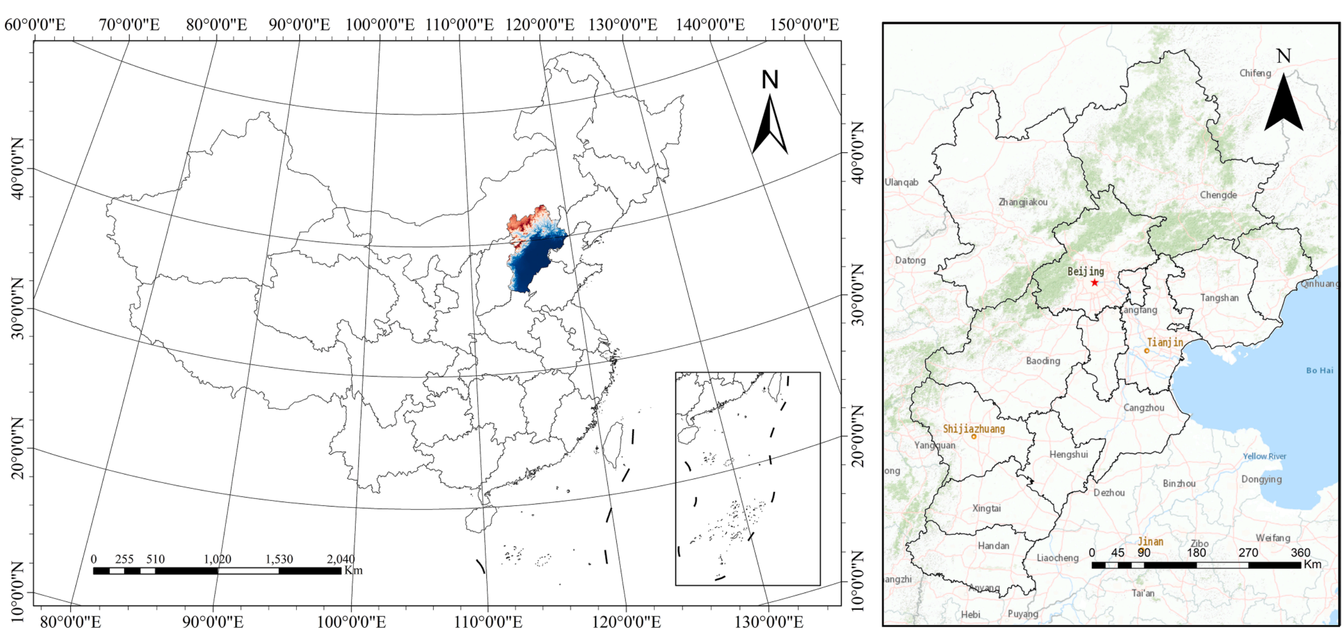

Fig. 1. Location of the BTH region.

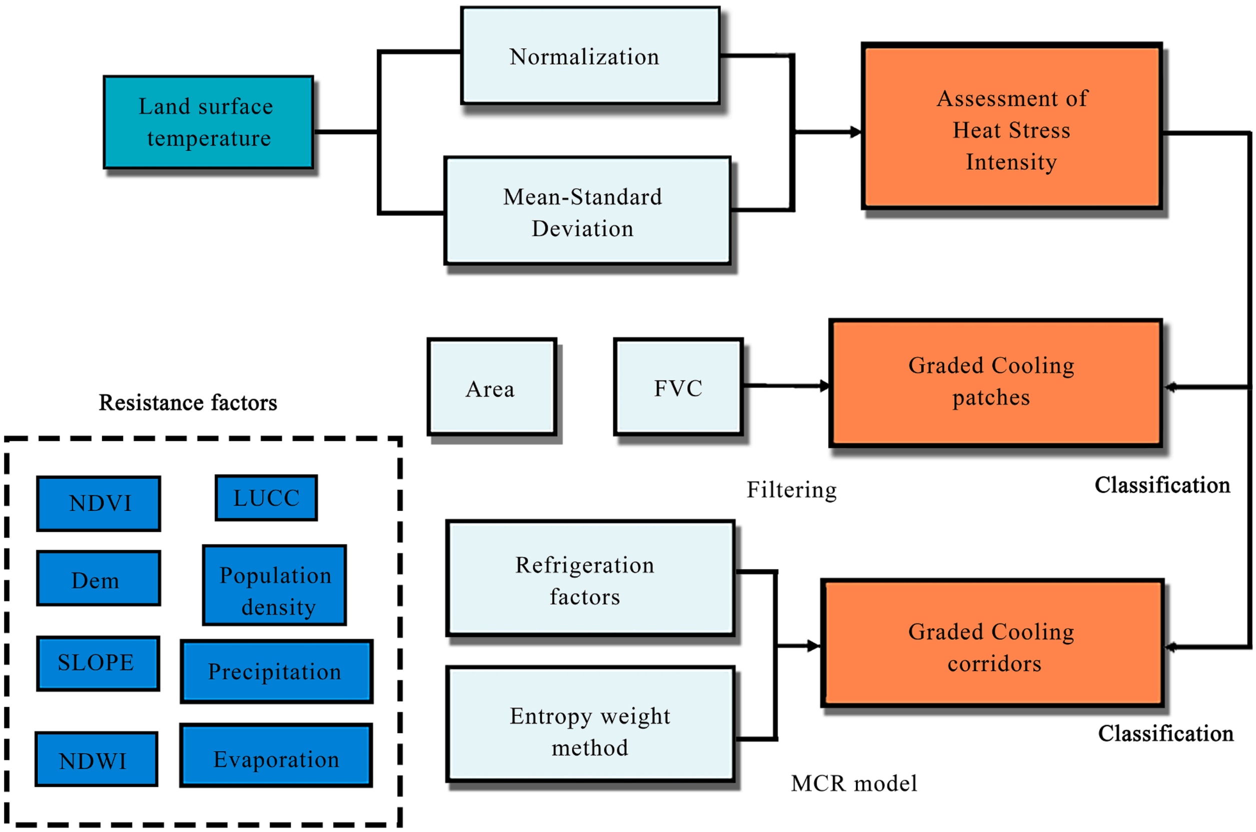

Fig. 2. Flowchart for constructing a graded refrigeration system.

Table 1
Urban thermal environment intensity.

Grading of thermal environmental strength.	LST range
Low temperature	$T_s < (T_o - 1\text{std})$
Sub-low temperature	$(T_o - 1\text{std}) < T_s < (T_o - 0.5\text{std})$
Normal temperature	$(T_o - 0.5\text{std}) < T_s < (T_o + 0.5\text{std})$
Sub-high temperature	$(T_o + 0.5\text{std}) < T_s < (T_o + 1\text{std})$
High temperature	$T_s > (T_o + 1\text{std})$

2.2. *Building a graded refrigeration system*

2.2.1. *Extraction of graded cooling patches*

We believe that the refrigeration effect of cooling patches is determined by their own characteristics. For cooling patches in forests, shrubs, and grasslands, the higher the fractional vegetation cover (FVC) and the better the vegetation growth, the easier it is to achieve regional cooling (Zhang et al., 2021c; Zhao et al., 2019). Therefore, we selected FVC as the screening indicator. For cooling patches in wetlands and lakes, research has shown that larger water bodies have a better cooling effect, so we selected area as the screening indicator (Peng et al., 2020). Finally, we selected the top 1% of ecological land for comprehensive evaluation as cooling patches. The greater the regional heat environment pressure, the higher the cooling responsibility and importance of the cooling patches. Therefore, we classify the cooling patches located in the high-temperature region, sub-high-temperature region, normal temperature region, sub-low-temperature region, and low-temperature region as Level 1, Level 2, Level 3, Level 4, and Level 5 cooling patches, respectively.

2.2.2. *Construction of potential cooling corridors*

In this study, we drew upon the source-sink theory, which suggests that the flow of material and energy information (including the potential transfer of cold air) tends to exchange through paths with the least resistance. The Minimum Cumulative Resistance (MCR) model precisely utilizes this concept for calculations. Hence, we employed the MCR model to simulate the potential transmission of cold air by constructing resistance surfaces for the formation and transmission of cold air. The formula for the MCR model is as follows.

$$V_{MCR} = f_{min} \sum_{j=n}^{i=m} (D_{ij} R_i) \tag{1}$$

where, V_{MCR} represents the minimum cumulative resistance, D_{ij} is the spatial distance from j to i for the cooling patches, and R_i is the resistance coefficient for passing through cooling patches i.

According to the refrigeration transmission process, we selected eight types of factors, and determined their corresponding weights using entropy weighting method. Among them, terrain factors such as DEM and slope directly affect the potential refrigeration system of urban agglomeration. Regions with high altitude generally have higher wind speeds, which make air exchange more fluent and beneficial for regional cooling. However, areas with high slopes may make air circulation more difficult, making it difficult for hot and cold air to exchange in the city. Regions with higher population density are more likely to accumulate heat and have higher temperatures, which is unfavorable for the transmission of cold air. Regions with high NDWI, NDVI, evapotranspiration, and rainfall have good vegetation growth conditions, abundant water vapor, and significant vegetation transpiration effects, which make it easier to achieve refrigeration effects and are suitable for the formation and transmission of cold air. For different land types, green spaces and water bodies can significantly reduce surface temperatures and alleviate urban heat environments. Therefore, we integrated the effects of all factors and constructed a comprehensive resistance surface. The higher the resistance of an area, the poorer the air flow, the higher the surface temperature, and the more difficult it is for hot air to be dissipated. The

Table 2
Evaluation factors for resistance of refrigeration systems.

Factor	Weight	Grade	Value	Factor	Weight	Grade	Value
DEM(m)	0.11	9	−52.00 ~ 231.00	LUCC	0.12	1	Water
		7	231.00 ~ 591.00			3	Forest, Grassland, Shrubland
		5	591.00 ~ 935.00			5	Cultivated land
		3	3025.62 ~ 1299.00			7	Bare land
		1	4353.55 ~ 2836.00			9	Artificial surface
SLOPE(°)	0.15	1	0 ~ 3.88	Population density	0.17	1	0 ~ 0.01
		3	3.88 ~ 10.18			3	0.01 ~ 0.04
		5	10.18 ~ 16.96			5	0.04 ~ 0.09
		7	16.96 ~ 25.20			7	0.09 ~ 0.19
		9	25.20 ~ 61.79			9	0.19 ~ 0.61
Evaporation (mm)	0.12	9	0 ~ 157.50	Precipitation	0.11	9	239.54 ~ 349.78
		7	157.50 ~ 169.60			7	349.78 ~ 423.88
		5	169.60 ~ 178.70			5	423.88 ~ 490.74
		3	178.70 ~ 186.90			3	490.74 ~ 563.03
		1	186.90 ~ 201.60			1	563.03 ~ 700.38
NDVI	0.11	9	-0.19 ~ 0.18	NDWI	0.11	9	-0.81 ~ -0.64
		7	0.18 ~ 0.29			7	-0.64 ~ -0.53
		5	0.29 ~ 0.37			5	-0.53 ~ -0.49
		3	0.37 ~ 0.44			3	-0.49 ~ -0.13
		1	0.44 ~ 0.69			1	-0.13 ~ 0.56

lower the resistance, the stronger the air flow, and the easier it is to form a cooling corridor. The assignment of each factor is as follows (Table 2):

Based on this, we classify the corridors connecting Level 1 cooling patches, Level 2 cooling patches, Level 3 cooling patches, Level 4 cooling patches, and Level 5 cooling patches as Level 1 cooling corridors, Level 2 cooling corridors, Level 3 cooling corridors, Level 4 cooling corridors, and Level 5 cooling corridors, respectively.

2.3. Landscape pattern index of cooling patches

The size and geometry of cooling patches are important factors affecting their cooling effect (Chen et al., 2014). In this study, we quantified the geometric information and landscape pattern characteristics of patches using landscape pattern index analysis. Based on the ecological significance of landscape pattern indices, we considered the functional features, shape features, and connectivity features of cooling patches, and prioritized landscape variables that had a significant impact on the patches. Using Fragstats5 software, we calculated the Shannon's diversity index (SHDI), Landscape shape index (LSI), Edge density (ED), Landscape Division index (Division), and Contagion index (Contag) indices of cooling patches of different grades from 2005 to 2020, as well as their spatiotemporal evolution patterns. We further explored the relationship between graded cooling patches and surface temperature, with the ecological significance of landscape pattern indices as follows (Table 3).

2.4. Stability and connectivity analysis of the refrigeration system

To verify the stability and connectivity of the refrigeration system from 2005 to 2020 and explore its structural and temporal characteristics, we introduced the theory of complex networks (Lu et al., 2023; Qiu et al., 2023; Strogatz, 2001). We abstracted the cooling patches as nodes in the complex network and the cooling corridors as edges. We used malicious attacks on node degree, betweenness centrality, closeness centrality, and clustering coefficient to evaluate the stability and connectivity of the refrigeration system. In addition, we used random attacks for comparison. Degree represents the number of cooling corridors connected to a refrigeration patch. A larger degree indicates better heat exchange and stronger air flow between the patch and other patches. Betweenness centrality refers to the number of shortest paths that pass through a cooling patch in the refrigeration system. A higher betweenness centrality means that the patch plays a stronger role in buffering and connecting the system. Closeness centrality represents the inverse of the sum of the shortest distances from a cooling patch to all other reachable patches. A high closeness centrality indicates that the patch is located in a central position in the refrigeration system. Clustering coefficient measures the degree of clustering between cooling patches. A higher clustering coefficient indicates stronger stability in the function and structure of cooling patches. The connectivity formula for the system is as follows:

Table 3
Ecological significance of the Landscape Pattern Index.

Type of feature	Landscape Pattern Index	Ecological implications
Ecological functional characteristics of cooling patches	Shannon's diversity index (SHDI)	This value reflects the diversity and heterogeneity of the landscape. The higher the value, the richer the landscape diversity, and the more stable the landscape ecosystem, which is conducive to the cooling patches to exert their cooling effect.
Shape characteristics of cooling patches	Landscape shape index(LSI)	This value reflects the morphological characteristics of the landscape. The larger the value, the more complex the shape of the cooling patches, and the more obvious the edge effect, which is conducive to the exchange and transfer of material energy within the patches.
	Edge density(ED)	This value reflects the degree of landscape fragmentation. The larger the value, the higher the degree of fragmentation, and conversely, the lower the degree of fragmentation.
Connection characteristics of cooling patches	Landscape Division index (Division)	This value reflects the degree of separation of patches in the landscape. The larger the value, the more fragmented the cooling patches in the landscape, and the more complex the landscape.
	Contagion index (Contag)	This value describes the degree of aggregation or dispersal trend of different patch types in the landscape. The larger the value, the better the connectivity of cooling patches, and the smaller the value, the more isolated the cooling patches.

$$\varepsilon_{ij} = 1/D_{ij} \tag{2}$$

$$E(G) = \sum_{i \neq j \in G} \varepsilon_{ij} \Big/ N\ (N-1) \tag{3}$$

where, D_{ij} represents the shortest path between cooling patches i and j, E(G) represents the connectivity of the system, and N represents the number of cooling patches in the system.

The formula for the robustness of the system is as follows:

$$D = \ (N - N_r + N_d)/N \tag{4}$$

where, D represents the robustness of the system, N_r represents the number of cooling patches subject to malicious attacks, and N_d represents the number of nodes that can be recovered after removing N_r nodes

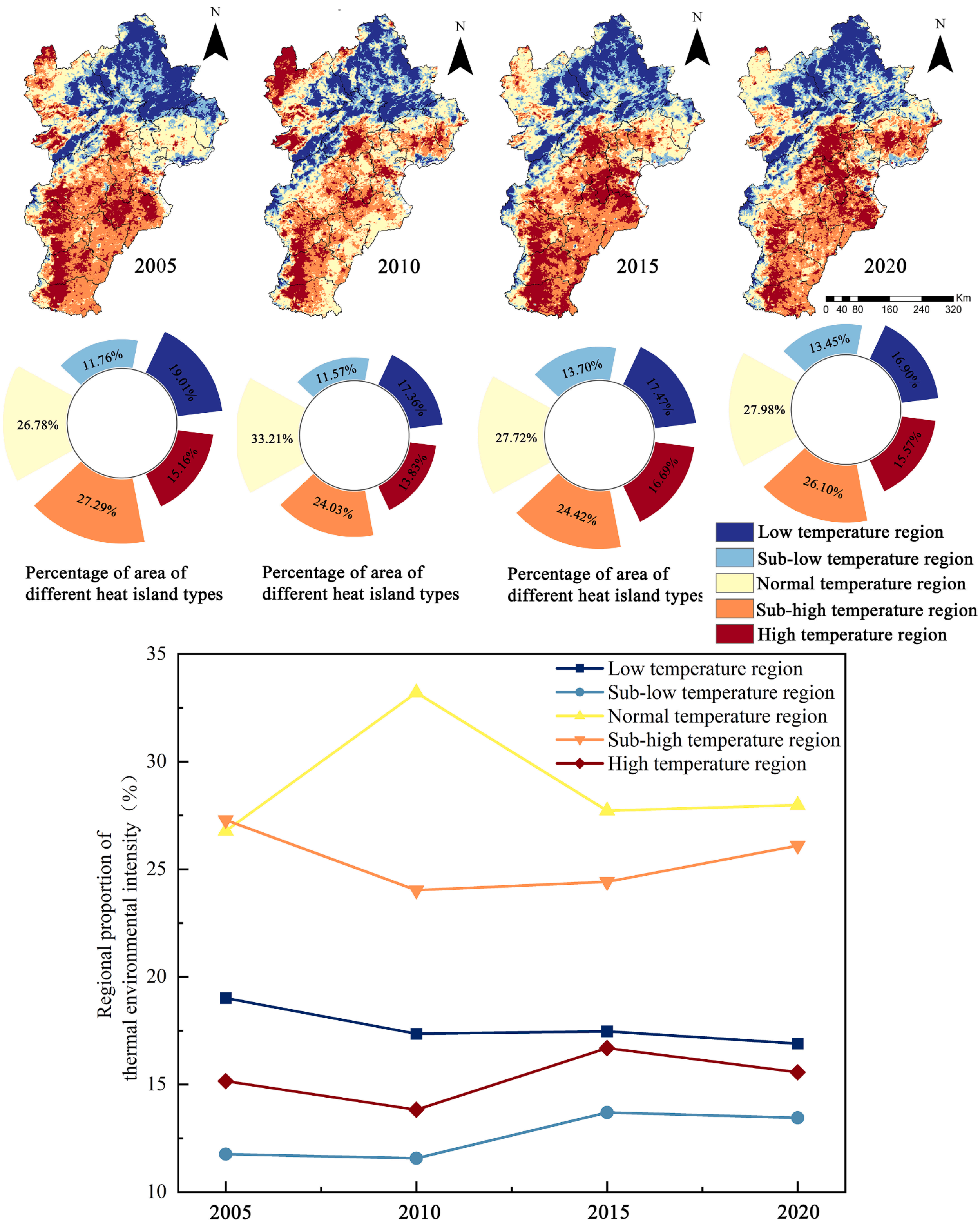

Fig. 3. Intensity and trend of heat environment in BTH region.

from the network.

3. Results

3.1. Spatiotemporal characteristics of urban thermal environment

After assessing the intensity of the thermal environment, we found that the southwestern region of BTH and some parts of the northeastern region have been in a high-intensity state from 2005 to 2020, with most areas showing sub-high temperature and high temperature (Fig. 3). In particular, the urban center areas mostly exhibit high temperature, indicating that human activities are important factors affecting the urban thermal environment. The northern and eastern regions of BTH, on the other hand, show sub-high temperature and high temperature. These areas are mostly mountainous or ecological lands with relatively little human activity, leading to a lower overall thermal intensity. By analyzing the proportion of thermal environment intensity and its trends, we found that the area proportion of the normal temperature region and sub-high temperature region is significantly higher than that of other thermal environment intensity areas. This indicates that the temperature in the BTH urban agglomeration is generally high, and high-temperature areas are mostly distributed in urban areas, demonstrating a certain geographic distribution pattern. Furthermore, although the sub-high temperature region and high temperature region decreased from 2005 to 2010, they showed a fluctuating upward trend from 2010 to 2020, while the low-temperature region decreased year by year. Therefore, the urban thermal environment remains an urgent ecological and environmental problem that needs to be addressed in the BTH urban agglomeration.

We explained the changes in Fig. 3 better by constructing a transition matrix of heat environment intensity (Fig. 4). We found that during the period of 2005–2010, the heat environment intensity in the BTH region decreased, specifically, part of the Sub-high temperature region transformed into the Normal temperature region, and part of the High temperature region transformed into the Sub-high temperature region. However, during the period of 2010–2015, although the Sub-low temperature region grew, part of the Normal temperature region transformed into the Sub-high temperature region, and at the same time, part of the Sub-high temperature region transformed into the High temperature region, which worsened the heat environment situation in the BTH region during 2010–2015. During the period of 2015–2020, the heat environment situation in the BTH urban agglomeration did not change much, as both the High temperature region and Low temperature region decreased, while the Sub-high temperature region increased, which may be due to government regulation slowing down the growth trend of urban heat environment in the BTH region, but the intensity of the urban heat environment remains at a high level.

3.2. Spatio-temporal evolution characteristics of graded refrigeration system

We found that from 2005 to 2020, most of the cooling patches in the BTH region were distributed in the western and northern regions in large contiguous areas, with a large patch area, and most of the patches were Level 5 cooling patches (Fig. 5). The number of cooling patches in the central, eastern, and southern regions was relatively small, mainly distributed in a point-like manner, with Level 1 and Level 2 cooling patches being the main types, indicating the high importance of cooling patches in these areas, and their important role in mitigating the urban heat environment. We also found that the number of patches showed a trend of first decreasing and then increasing during 2005–2020, especially in 2010 and 2015, when the number of patches in the central region of BTH decreased significantly, while the number of cooling patches increased slightly in 2020. The trend of change in cooling corridors was similar to that of cooling patches, both showing a trend of first increasing and then decreasing. In 2010 and 2015, due to the small number of cooling corridors in the central region, the heat in the city was difficult to dissipate through effective paths, making it difficult to alleviate the heat environment situation in the central region. However, in 2020, the number of cooling corridors in the central region of the urban

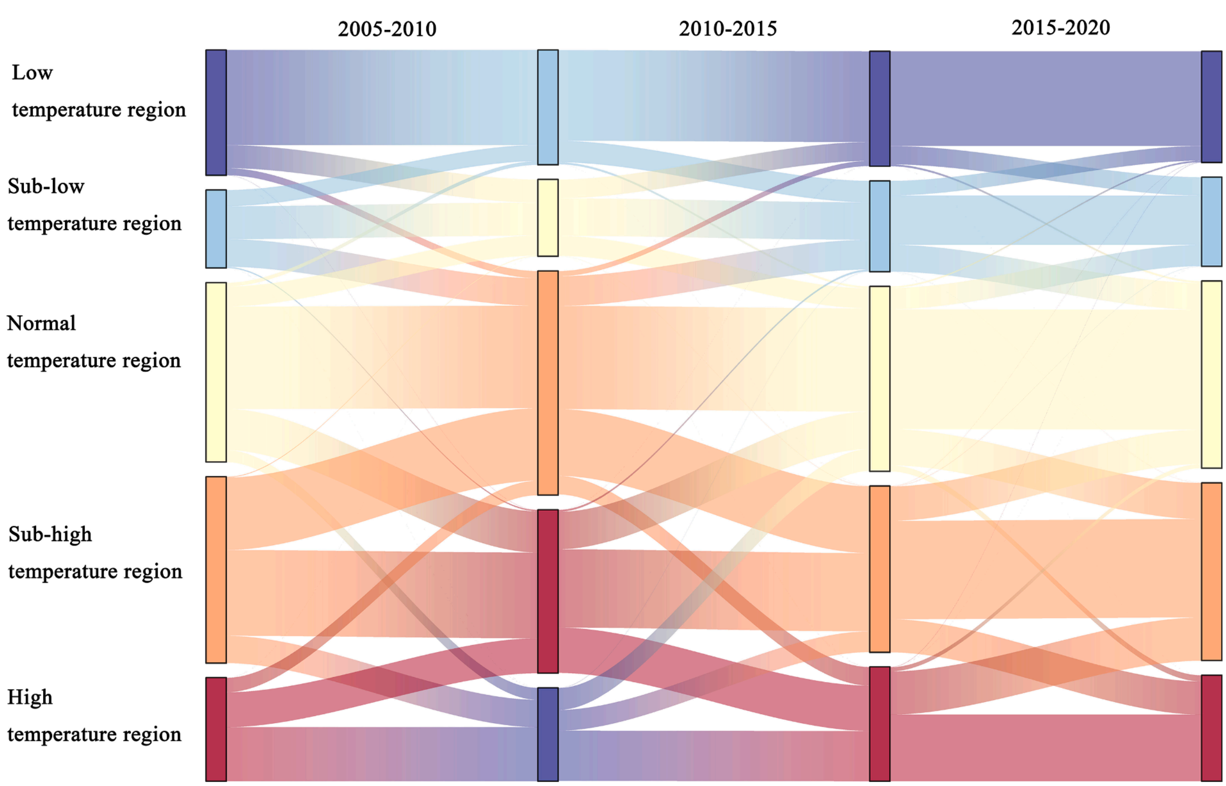

Fig. 4. Transformation of different heat environment intensity regions.

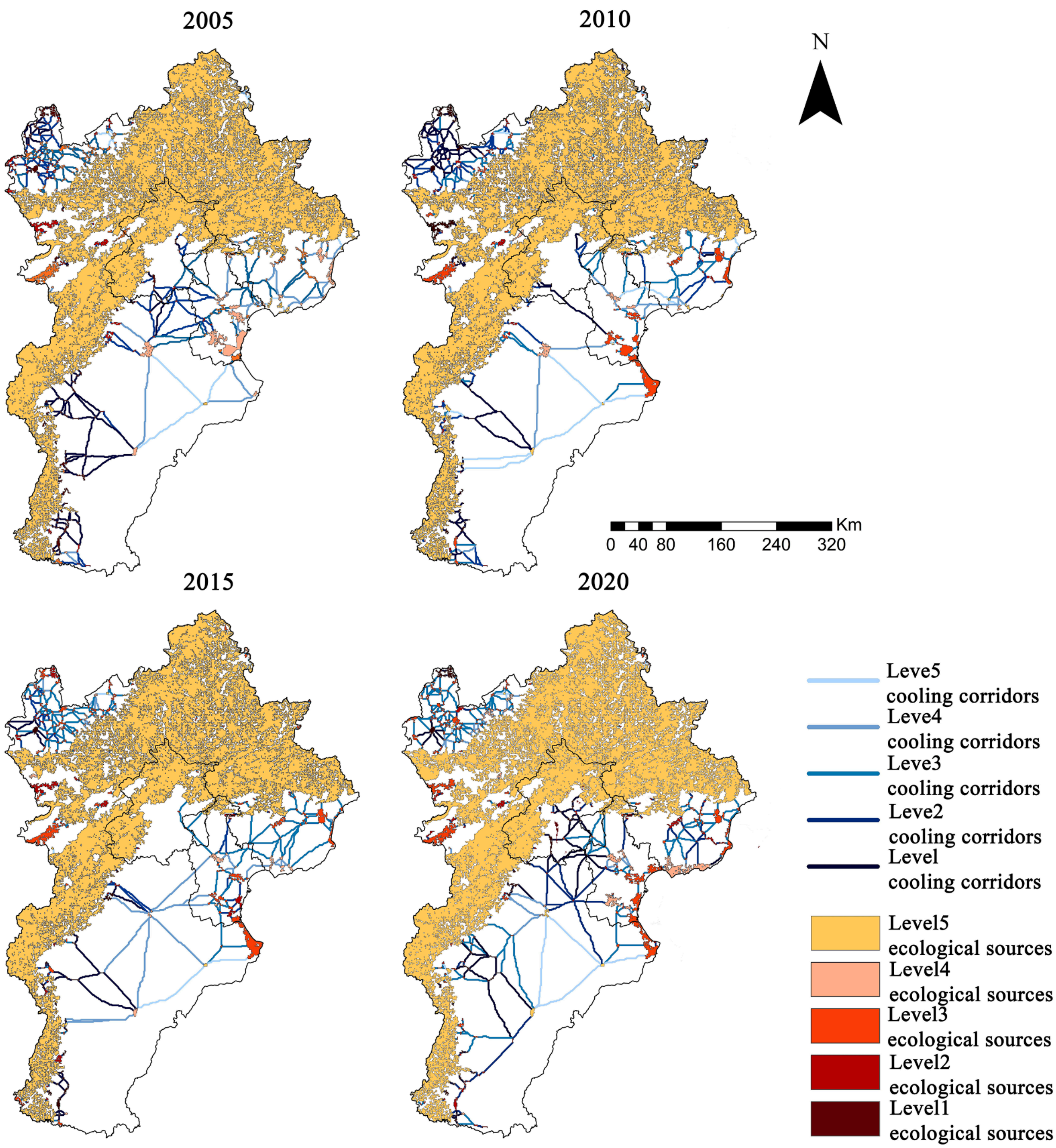

Fig. 5. 2005–2020 Graded refrigeration system.

agglomeration has increased significantly, greatly improving the ventilation, heat flow, and exchange in the city.

We compared the changes in the number of graded cooling corridors and graded cooling patches between 2005 and 2020, and found that during the 15-year period, Level 3 cooling corridors and cooling patches had the highest proportion, showing a fluctuating upward trend (Fig. 6). In 2015 and 2020, the proportion of cooling patches and cooling corridors reached more than 50%, indicating that cooling corridors and cooling patches can better alleviate the thermal environment in the Normal temperature region. The proportion of Level 5 cooling corridors and cooling patches was the lowest and showed a decreasing trend overall, and the proportion of Level 2 corridors and patches was also low, with little change in proportion between 2005 and 2020. In addition, the proportion of Level 1 and Level 2 corridors and patches was relatively high, increasing between 2005 and 2010, but decreasing between 2015 and 2020. This indicates that in recent years, the heat in the Sub-high temperature region and High temperature region of the BTH urban agglomeration is not easily dissipated outward, and the exchange of cold and hot air is not easily achieved effectively, which will cause heat accumulation. Therefore, it is necessary to artificially construct corresponding cooling corridors or increase corresponding cooling patches.

The length of cooling corridors will also affect the overall cooling effect of the urban agglomeration. Narrow corridors allow fresh cold and humid air to reach further areas, and hot air can also be exchanged through the corridors. We found that the length of Level 1- Level 3 cooling corridors did not change much from 2005 to 2010, with an average length of about 12 km, but during 2015–2020, the length of cooling corridors showed a significant increase, reaching up to 16 km (Fig. 7). The length of Level 4 and Level 5 cooling corridors was longer

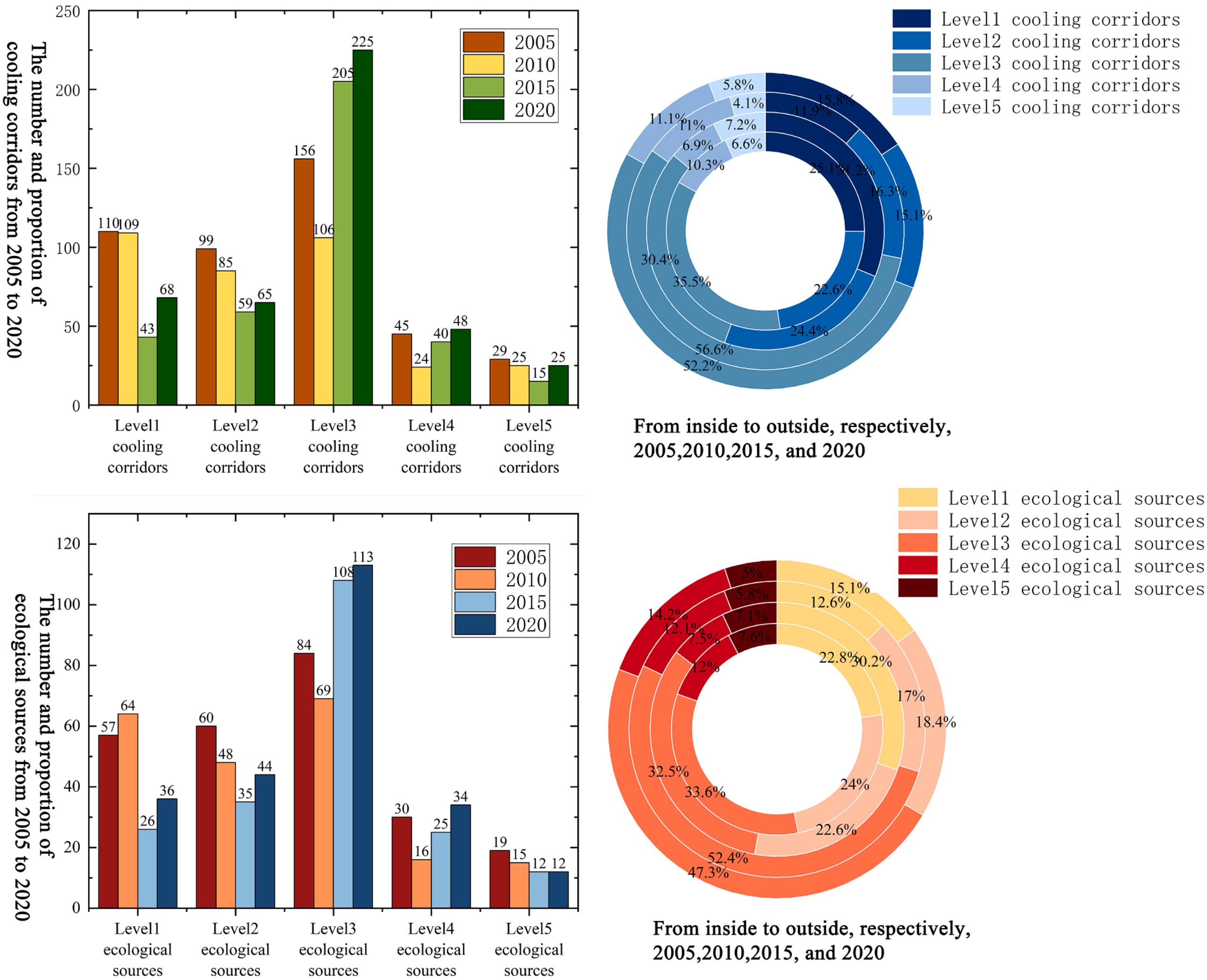

Fig. 6. The number and proportion of cooling patches and cooling corridors.

each year, with a length of 15 km or more, and the average length of Level 4 cooling corridors in 2015 was as high as 30.08 km. Overall, the length of cooling corridors increased for Level 1 and Level 2, remained stable for Level 3 and Level 5, and decreased significantly for Level 4. This indicates that the air circulation and exchange capacity of cold and hot air have been enhanced in areas with high heat intensity in the BTH urban agglomeration, which can further alleviate the intensity of urban heat environment. However, the range of cold air spreading in areas with lower heat intensity has decreased, and the radiative influence has weakened.

3.3. Analysis of the landscape pattern of a graded refrigeration system

From the perspective of the functional characteristics of patches, we found that the SHDI of graded cooling patches showed some growth during specific periods from 2005 to 2020 (Fig. 8). However, from an overall perspective, the SHDI values showed a fluctuating downward trend, indicating a decrease in the stability of cooling patches during this period. From the perspective of the shape characteristics of patches, the LSI values fluctuated less, but the LSI values of Level 2 and Level 3 cooling patches showed a decreasing trend. The ED values fluctuated more, and most cooling patches showed a downward trend, indicating a decrease in the edge effect and an increase in fragmentation from 2005 to 2020. From the perspective of the connectivity characteristics of patches, the Divison values showed a trend similar to the ED values, with Level 1, Level 2, and Level 3 patches showing a significant decrease. Although the Contag values fluctuated between 2005 and 2020, the value in 2020 remained similar to that of 2005, indicating an increase in the separation degree of cooling patches and a decrease in their connectivity. Based on the five landscape pattern indices, we found that the functional, shape, and connectivity characteristics of graded cooling patches showed varying degrees of decrease from 2005 to 2020, making it difficult for the refrigeration system to fully exert its cooling effect, resulting in a decrease in its overall refrigeration function.

3.4. Robustness and connectivity analysis of refrigeration systems

Through random attacks, we compared five types of malicious attacks and found that under malicious attacks in degree, betweenness centrality, and closeness centrality, the robustness and connectivity of the refrigeration system decreased more rapidly (Fig. 9). The clustering coefficient malicious attack initially showed better robustness and connectivity than random attacks, but quickly dropped once a certain threshold was reached. Therefore, under malicious attacks, the refrigeration system will collapse more quickly. In addition, when facing different malicious attacks, the system has the highest resistance to clustering coefficient malicious attacks, followed by degree malicious attacks, closeness centrality malicious attacks, and betweenness centrality malicious attacks.

From a time series perspective (2005–2020), we found that under

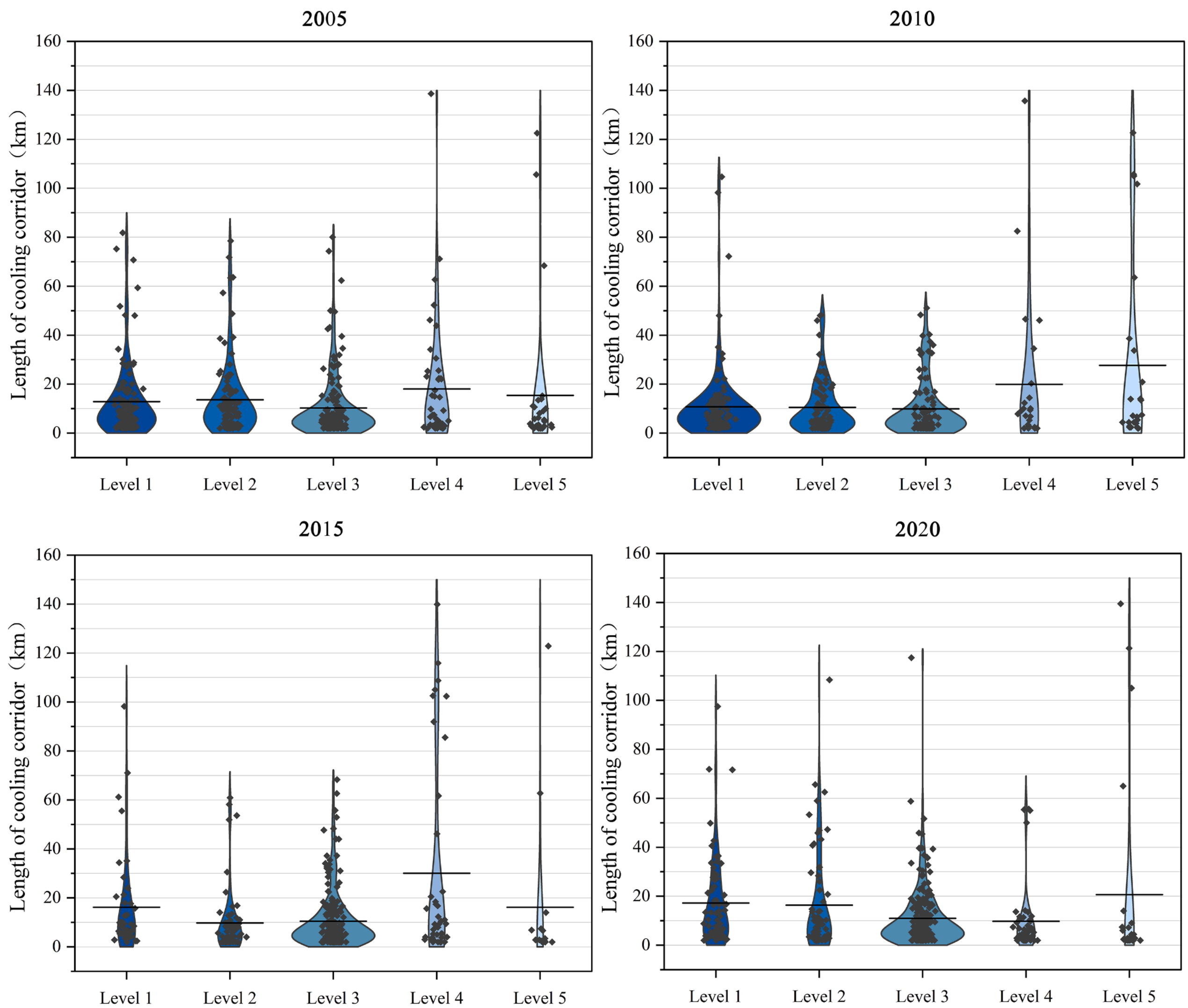

Fig. 7. The length of a graded cooling corridors.

degree malicious attacks, the robustness and connectivity of the refrigeration system were enhanced. Although the initial connectivity decreased in 2020, it was still higher than the initial connectivity in 2005, and the rate of decrease slowed down. Under betweenness centrality malicious attacks and closeness centrality malicious attacks, the robustness of the refrigeration system showed a trend of first increasing (2005–2015) and then decreasing (2015–2020), while the initial value of connectivity first increased and then decreased. Under clustering coefficient malicious attacks, the robustness showed a trend of first increasing and then decreasing, while connectivity increased year by year, and when 80% of the nodes were attacked, connectivity could still maintain a high value. Overall, from 2005 to 2020, both the robustness and connectivity of the refrigeration system were improved, with the best performance in 2015. In future planning and protection of the refrigeration system, optimization and improvement of the robustness and connectivity of the refrigeration system are still needed, so that the exchange of hot and cold air in the BTH urban agglomeration can be more stable, further reducing the intensity of the urban heat environment.

3.5. Advantages of building urban agglomeration refrigeration system

The urban thermal environmental is a phenomenon where the temperature in urban areas is elevated due to the release of large amounts of heat from various activities such as building construction, transportation, and industrial processes during urban development. This effect results in a series of adverse impacts. In response to this issue, scholars have attempted to mitigate the urban heat island effect through human intervention, such as changing the external material of urban buildings, the width of streets, and the height of buildings. In fact, the ecological land within urban agglomeration can be connected through potential cooling corridors, which can achieve a comprehensive cooling effect of different patches, indicating a more natural way to address the urban heat environment problem. Viewing each cooling patch within an urban agglomeration from a connected perspective, natural wind can be introduced into the urban agglomeration through cooling corridors. This allows the cold air from low-intensity heat environment areas to spread to high-intensity heat environment areas through cooling corridors, while the hot air from high-intensity heat environment areas can be evacuated to other areas. In addition, longer cooling corridors can also radiate cooling benefits to farther areas, maximizing the cooling effect. This nature-led approach can effectively alleviate the adverse impacts of the urban heat island effect and is expected to reduce adverse impacts on the environment. As a result, it represents a research direction with broad application prospects.

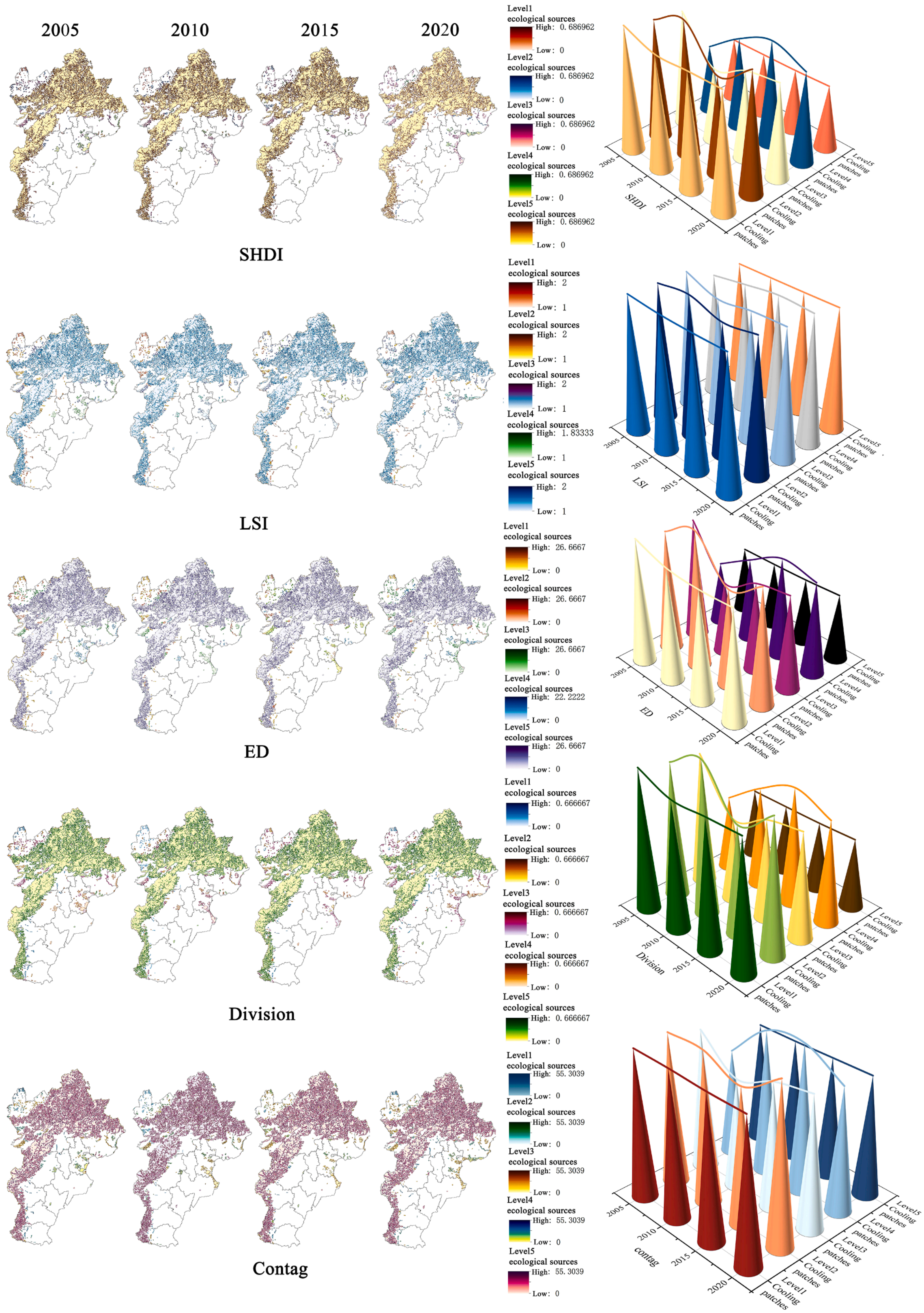

Fig. 8. Landscape pattern index of graded cooling patches.

3.6. *Priority for the protection and construction of cooling patches and cooling corridors*

Currently, the thermal environment pressure in the BTH region remains a key issue that affects the sustainable development of the urban agglomeration. Compared to relying on the restoration and optimization of patches and corridors themselves, human protection and planning can significantly improve the cooling effect and produce faster results. However, the construction and optimization of a city-wide cooling patch and corridor system clearly require significant economic costs.

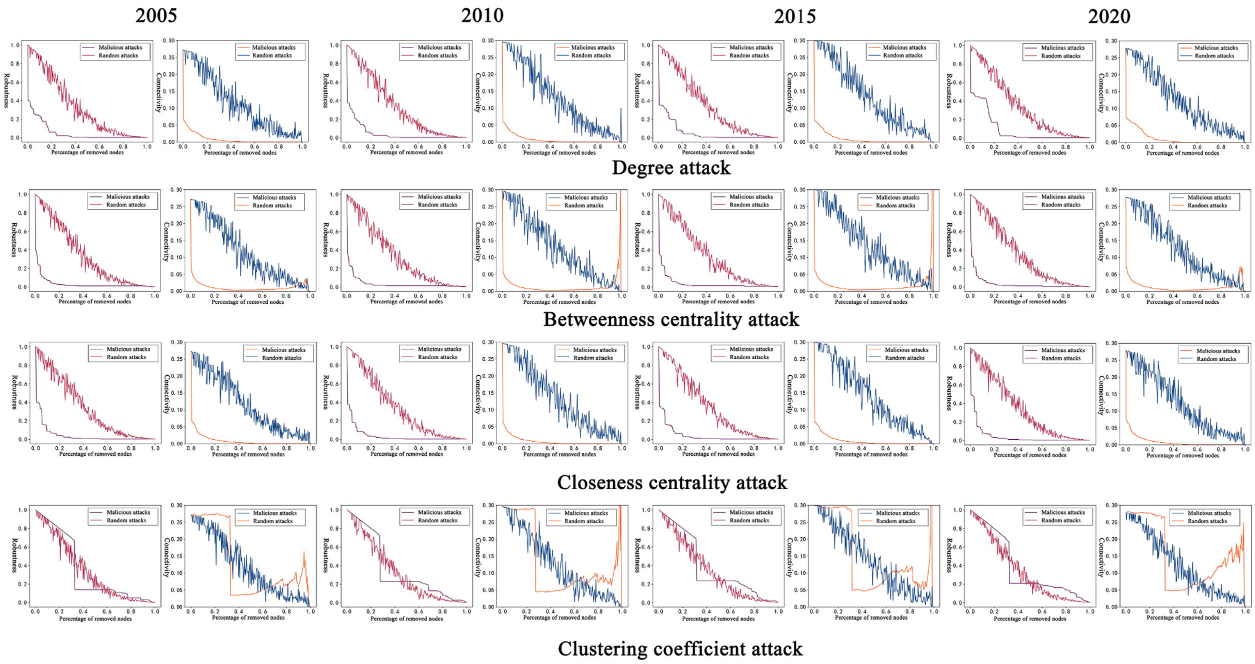

Fig. 9. Landscape pattern index of graded cooling patches.

Therefore, it is necessary to first identify the corridors and patches that contribute the most to the urban thermal environment and then grade their protection and improvement accordingly. However, few scholars have focused on the hierarchical protection of cooling systems. In order to achieve precise identification of critical patches and corridors, we combined thermal environment intensity assessment and the MCR model to connect patches dispersed throughout the urban agglomeration through cooling corridors, forming a complete cooling system. Compared to analyzing the cooling effect of patches based on landscape pattern indices such as area, shape, and fractal dimension, we elevated the research perspective to the entire city-wide cooling system, conducting a comprehensive evaluation and grading of the cooling patches and corridors in the system based on thermal environment intensity, thus identifying key patches and corridors that can alleviate thermal environment pressure. From the perspective of cooling patches, those closer to the city center have a higher priority, and thus should be protected first. In addition, small patches surrounding the city should also be improved and integrated to become important patches for alleviating urban thermal environment pressure. From the results of this study, the central and southern regions of BTH have fewer and smaller cooling patches, but their protection priorities are higher. Therefore, the government should appropriately optimize and upgrade the patches in these areas, increase suitable vegetation species, and delineate boundaries to prevent human activities from affecting these patches. From the perspective of cooling corridors, those connected to high thermal environment intensity areas have a higher priority. Therefore, the number of cooling corridors connected to the city can be artificially increased. The results show that there are fewer cooling corridors in the southeast region of BTH. Furthermore, for the low thermal environment intensity areas in the northern region of BTH, constructing cooling corridors that extend to the city can further enhance the exchange of cold and hot air.

3.7. Updates and future planning of urban spatial patterns

The construction of a natural cooling system for the BTH urban agglomeration has a certain guiding effect on urban planning and construction. The formation of the urban natural cooling system is influenced by the spatial configuration of green patches and the natural environment. To further enhance or improve the urban cooling system, human planning and construction are fundamentally necessary. With the intensification of urbanization, cities no longer focus solely on economic development but also need to value livability, ecology, and sustainability, and build cities that promote a harmonious coexistence between humans and nature. From the perspective of this study, alleviating the heat environment pressure in cities requires the determination of the hierarchy and protection priority of patches and corridors, and the pursuit of a more reasonable spatial layout, in order to minimize the impact of the urban thermal environment at a lower cost. In fact, both increasing the number and area of cooling patches and increasing the number and length of cooling corridors are updates to the urban land use, spatial pattern, and form. For the existing urban cooling system, the focus is on improving and enhancing the quality and cooling efficiency of cooling patches and increasing the construction of cooling corridors in local areas. For the future urban cooling system, the focus is on planning and construction. Based on the current ecological environment, using the heat environment intensity assessment and MCR model in this study, a simulated urban cooling system can be constructed, providing certain prerequisites for future urban planning and construction. It is certain that whether in the present or the future, urban spaces need to strengthen the deep intersection and full integration of natural cooling system construction and urban planning on the basis of fully understanding the intensity of the urban heat environment, in order to improve the applicability, professionalism, and interpretability of research results and provide a scientific and reasonable basis for planning practices and decision-making such as urban agglomeration planning, urban green space system planning, and overall design of urban agglomerations.

3.8. Outlook and limitations

We found that there is limited research on urban hierarchical cooling systems, with most studies focusing on isolated patch characteristics rather than a comprehensive regional analysis. Introducing the concept of hierarchical cooling systems provides a reference for developing strategies to alleviate interregional thermal environmental pressure. Furthermore, the method used in this study can be applied to constructing hierarchical cooling systems for other urban agglomerations. We observed that the urban hierarchical cooling system is a dynamic process, in which the roles played by each patch and corridor are continuously changing. Therefore, the construction of a hierarchical cooling system for urban agglomerations should be viewed from a more real-time perspective. The data used in this study can be monitored dynamically through remote sensing imagery. Therefore, we suggest the possibility of constructing a monitoring platform for cooling systems to simulate the spatial position and quantity of key cooling patches and corridors in real-time, to aid government decision-making on timely protection and optimization strategies.

This study also has limitations. Currently, it appears that the cooling elements in urban agglomerations are highly complex. Different building forms, road characteristics, and wind speeds also affect the construction of cooling systems. However, these characteristics are still difficult to quantify in detail, or the data precision is insufficient. Additionally, hierarchical cooling systems still need further validation, with observations and modeling results combined to provide data support for large-scale mitigation of thermal environmental pressure in urban agglomerations. We suggest constructing small-scale monitoring facilities at a distance in urban agglomerations to monitor changes in environmental temperature and natural factors in real-time.

4. Conclusion

This study proposes the construction of a graded refrigeration system for urban agglomerations to alleviate the pressure of summer heat environment. Based on thermal environment assessment and the MCR model, the spatiotemporal evolution characteristics of the graded refrigeration system and its internal functional features in the BTH urban agglomeration from 2005 to 2020 were analyzed. The results indicate that the thermal environment in the southwestern region of the BTH area and some parts of the northeastern region has remained in a high-intensity state, and the area of high-temperature regions is showing a fluctuating increasing trend. The number of cooling patches and corridors has shown a trend of first increasing and then decreasing, with fewer patches and corridors in the central and southern regions, making it difficult for cold and hot air to exchange, and requiring improvement. Although the average length of high-grade cooling corridors has increased, almost all landscape pattern indices of cooling patches have decreased, resulting in a decrease in cooling efficiency. The northwestern region has larger cooling patch areas, more concentrated distribution, while the southeastern region has smaller cooling patch areas and more scattered distribution. However, their protection priority is higher, and they play a crucial role in alleviating regional heat intensity. Additionally, the robustness and connectivity of the cooling system have increased under malicious attacks, but future optimization and improvement are still needed. This study provides new solutions and research methods for solving urban heat stress from a natural perspective, as well as valuable information for the ecological planning and management of urban agglomeration, and serves as a reference for other rapidly developing urban agglomeration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

This work was supported by the Beijing Natural Science Foundation Project (No. 8212031). Special thanks are given to the anonymous reviewers and editors for their constructive comments that greatly enrich the manuscript. The authors acknowledge the providers of SPOT/VEGETATION NDVI (doi:10.12078/2018060602) data for their valuable and accessible information.

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