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Construction of Climate Adaptability Evaluation Indicator System for Urban Spaces in the Severe Cold Zones of China —A Case Study on the Central Area of Harbin

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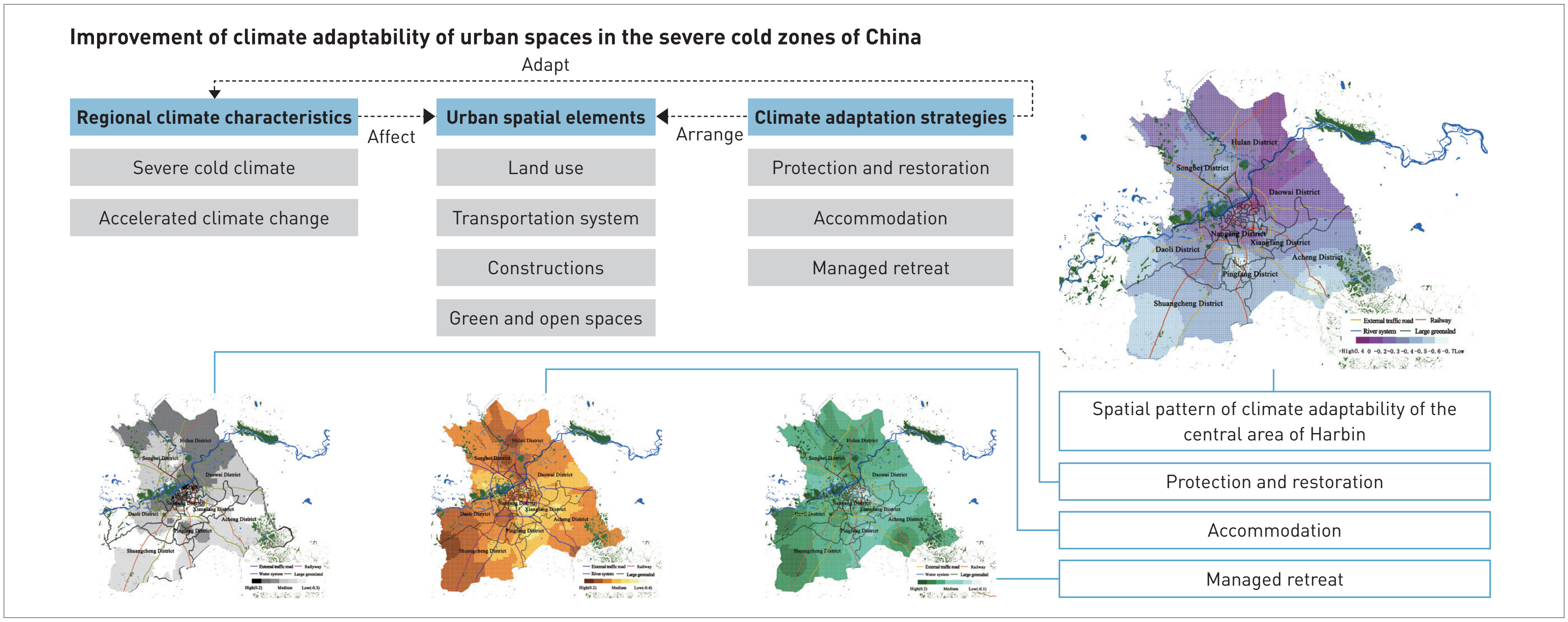
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Considers both climate change and regional climate contexts
- Adapts through protection and restoration, accommodation, and managed retreat
- Constructs climate adaptability evaluation indicator system for severe cold zones of China
- Evaluates climate adaptability of urban spaces in Harbin
- Proposes climate adaptation strategies for severe cold zones of China

KEYWORDS

Severe Cold Zones;
Urban Spaces;
Climate Adaptability;
Evaluation Indicator System;
Adaptation Strategies

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ABSTRACT

Climate adaptation research should consider both climate change and regional climate contexts. Research evaluating the regional climate adaptability of urban spaces helps identify weaknesses of climate resilience in spatial planning. This paper constructs a climate adaptation evaluation indicator system for cities in the severe cold zones of China, and evaluates the temporal-spatial changes of climate adaptability in the central area of Harbin. The evaluation outcome reveals that the overall climate adaptability of the study area generally improved from 2008 to 2017 despite staying at a relatively lower level. There are significant differences in spatial pattern and development of spatial elements of climate adaptability by districts. Accordingly, this paper proposes countermeasures supporting future decision-making on climate adaptation planning for the study area, offering a reference for other cities in the severe cold zones of China.

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1 Introduction

Climate change has lasting effects on the environment due to the inertia of climate system[1][2]. Intergovernmental Panel on Climate Change (IPCC) pointed out that climate adaptation measures are important in dealing with future climate change impacts[1][3], particularly for urban areas[4]. At present, researchers worldwide have contributed to the studies on climate change adaptability, and countries such as Denmark, New Zealand, and Canada have proposed climate adaptation strategies or action frameworks for domestic major cities[5]~[8].

Defining and evaluating the climate adaptability of cities is the basis for the development of adaptive planning and decision-making[9]. In recent years, scholars in related fields have mainly carried out research on the evaluation of urban climate adaptability through two approaches. 1) Evaluation of climate adaptation actions. Karianne de Bruin et al. conducted a quantitative assessment on the incremental costs and benefits of climate adaptation policies in the Netherlands[10]. Benjamin L. Preston et al. and Ingrid Baker et al. respectively developed and applied evaluation frameworks on 57 and 7 climate adaptation plans concerning public health and ecological environment[11][12]. Both studies evaluated plan components such as information base and risk assessments. In two cases, Elisabeth M. Hamin et al. assessed whether the climate adaptation and mitigation policy goals of some cities conflict with each other in transportation, water resources, biodiversity, and energy utilization, and proposed suggestions for a synergic urban development[13]. 2) Evaluation of the interactions between urban spatial elements and thermal climate factors. Brain Stone et al. studied the impact of urban form and land development density on urban heat island effect and extreme heat events[14]~[16]. Claire L. Walsh applied an urban integrated assessment facility to simulate land use change, climate impact, and greenhouse gas emissions in London over the 21st century[17]. Based on the EPICEA project in Paris, Jean-Luc Salagnac assessed the increased albedo of urban building surface, enlarged green area, and other climate adaptation strategies on urban heat balance[18].

To sum up, the first approach mostly assesses the economic and ecological benefits of government-led adaptation actions[19], which has become mainstreaming in climate adaptation planning at home and abroad[20]. The second mainly measures whether and how urban spatial elements can adapt to the increasing climate changes. However, little research systematically evaluates climate adaptability from the perspective of urban spaces or establishes climate adaptability evaluation systems for urban spaces[19][21].

Urban meteorologist Tim Oke believes that the impacts of climate change vary by regions[22], suggesting that climate adaptability research should consider both climate change and regional climate contexts. For cities in severe cold zones that are facing combined impacts of climate change and regional climate[23], their main climatic problems mostly occur in winter despite intensified heat island effect in recent years[24][25]. Long time of low temperature and frequent snowfalls in winter greatly reduces citizens' living comfort and impedes domestic production. Collymore Peter, Jan Gehl, Norman Pressman, and other scholars conducted in-depth research on urban and architectural design countermeasures in line with severe cold climates[26]~[28]. Although climate warming in winter brings about benefits such as improving outdoor thermal environment and facilitating the diffusion of water pollutants[29][30], it enlarges the temperature difference between day and night after snow, accelerates the formation of icy surface, and increases sand and dust weather in spring due to the decrease of snow retention[31].

Across the world, the number of research on urban spatial planning that responds to climate change is increasing. However, little research studies the mechanism of climate adaptation planning upon regional climate conditions[32], not to mention regional climate adaptability. Evaluating the regional climate adaptability of urban spaces helps identify weaknesses of climate resilience in spatial planning. This paper constructs the climate adaptability evaluation indicator system for cities in the severe cold zones of China (where the lowest monthly average temperature over years is no higher than –10℃[33]), by demonstrating the case of the climate adaptation planning for the central area of Harbin—a typical city in the severe cold zones of China. This paper then proposes countermeasures according to the evaluation results, supporting future decision-making on climate adaptation planning for cities in the severe cold zones of China.

Table 1: Climate problems of urban spaces in winter in the severe cold zones of China

Impacted facet	Specific problem
Transportation	Increased carbon emission from traffic; frequent traffic congestion and icy surfaces after snow; reduced overall public transportation capacity, especially during peak hours
Landscape	The lack of greenery and outdoor environmental attraction to citizens; lowered carbon sequestration by soil and vegetation
Energy consumption	Increased energy consumption for domestic heating and clearing snow on roads, and growth of the use of construction materials; aggravated air pollution
Living and production	Limited outdoor activities; lowered jobs of outdoor work

2 Climate Adaptability of Urban Spaces in the Severe Cold Zones of China

This paper summarizes the climate problems of urban spaces under the combined contexts of climate change and regional climate, explores the concept of climate adaptability of urban spaces in the severe cold zones, and proposes the paths of improving climate adaptability of urban spaces.

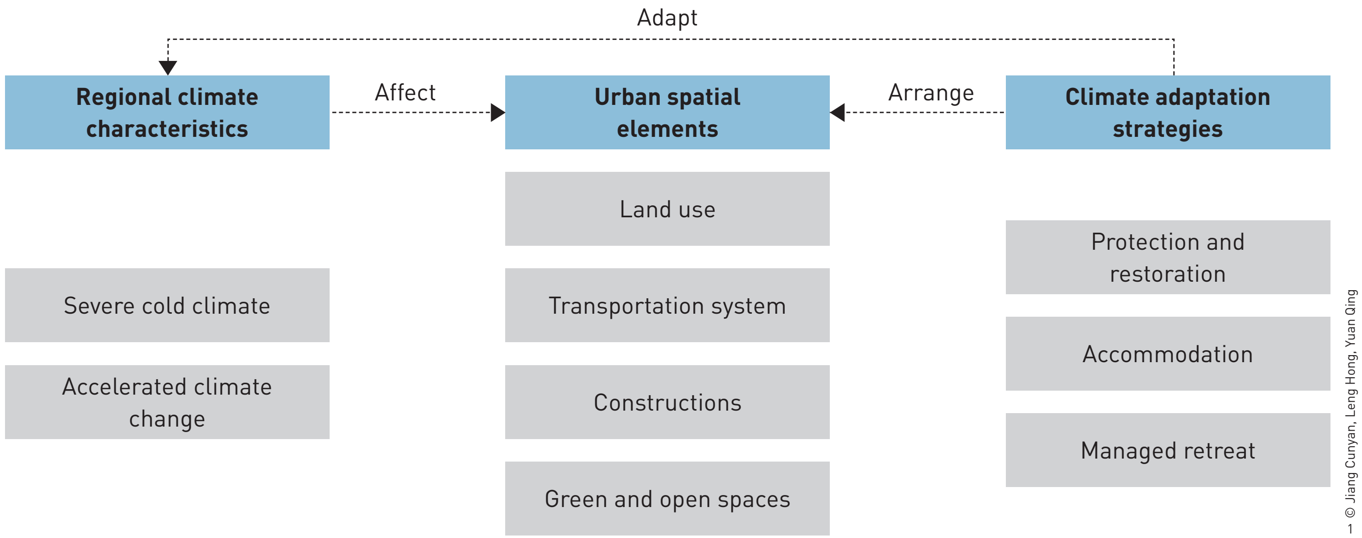
2.1 Climate Problems of Urban Spaces in Severe Cold Zones of China

Compared with China's other climatic zones (including cold zones), severe cold zones are more profoundly impacted by combined impacts of climate change and regional climate since they suffer from longer harsh winters. The paper characterizes the climate problems of urban spaces in winter in the severe cold zones of China (Table 1)[31][34] to inform the development of climate adaptation paths.

2.2 Climate Adaptation Paths for Urban Spaces in Severe Cold Zones of China

One of the essential components in urban planning is the arrangement of physical spatial elements (such as land use, transportation system, constructions, and green and open spaces)[35]. Therefore, research on climate adaptation planning from the perspective of urban spaces needs to focus on the improvement of climate adaptation through planning approaches.

IPCC classifies adaptation strategies to cope with climate change and extreme weather events into three types—protection, accommodation, and managed retreat[36][37]. Considering both climate change and regional climate, this paper extends the application scenarios of these strategies to urban spaces, and defines three types of climate adaptation paths, namely protection



1. Interactions between climate characteristics, urban spatial elements, and climate adaptation paths in the severe cold zone.

and restoration, accommodation, and managed retreat. The interactions between regional climate characteristics, urban spatial elements, and climate adaptation paths in the severe cold zones are displayed in Figure 1.

1) Protection and restoration. Protect vulnerable urban spaces with engineering measures to guarantee city's basic services and residents' daily life[38]. It also requires to restore the urban systems in impacted areas back to the condition before the external stress with planning interventions. In this paper, protection and restoration means include improving energy efficiency of transportation and construction industries, and protecting urban systems vulnerable to the severe cold climate in winter.

2) Accommodation. Urban systems can enhance their adaptation capacities to withstand moderate climate impact caused by accelerated climate change and maintain city functions without additional human intervention[39]. In this paper, accommodation means include ensuring transportation efficiency in winter, increasing green and open spaces, and promoting the micro-climate regulation and carbon sequestration function of soil and vegetation.

And 3) managed retreat. When the external stress exceeds the combined adaptation capacity of urban systems and engineering constructions, retreat from areas of high vulnerability or exposure risk through planning approach to minimize the potential impact of climate problems[40]. In this paper, managed retreat means include early warning and emergency response programs for disastrous weather events and the transition of urban systems (e.g. replacement of vegetation species) responding to adverse climate impacts.

3 Construction of Climate Adaptability Evaluation Indicator System for Urban Spaces in the Severe Cold Zones of China

To evaluate climate adaptability of urban spaces in the severe cold zones of China, this paper first establishes an indicator system measuring the city's capacities of protection and restoration, accommodation, and managed retreat in land use, transportation system, constructions, and green and open spaces. The quantitative method for each indicator is put forward as well.

3.1 Selection of Evaluation Indicators

By reviewing research on the correlations between urban spaces and climate environments in severe cold zones across the world[41][42], climate regulation policies for cities in severe cold zones in developed countries[43][44], and evaluation indicator systems of urban climate carrying capacity and climate change vulnerability[45][46], this paper identifies 21 evaluation indicators (Table 2). In the synthesized selection process, data accessibility is considered, relevant categories are consolidated, and indicators with relatively lower correlation coefficients are eliminated.

3.2 Calculation Methods of Indicators

3.2.1 Indicator Quantitation Equations

The quantitation of each indicator in this research adopts three

Table 2: Climate adaptability evaluation indicator system for urban spaces in the severe cold zones of China

Capacity	Element	Indicator
Protection and restoration	Land use	Development and utilization rate of underground space
	Transportation system	Indoor accessibility
		Degree of road snow removal and antifreeze treatment in winter
	Construction	Building clean heating ratio
		Ratio of water- and energy-saving old buildings
	Green and open spaces	Implementation ratio of green buffer
Accommodation	Land use	Land use compatibility
		Land development intensity
	Transportation system	Proportion of rail transit trips
		Winter traffic performance index
		Public transport accessibility
	Construction	Building shape factor
		Proportion of buildings with vertical planting
	Green and open spaces	Greenery coverage
		Ventilation channel construction level
		Popularity of winter activities in public spaces
Managed retreat	Land use	Afforestation area in the current year
	Transportation system	Emergency access network coverage
		Winter disaster early warning coverage
	Construction	Proportion of green buildings in newly-built buildings
	Green and open spaces	Planting ratio of native species of severe cold zones

methods (Table 3)[43][44][47]~[63].

1) Eleven indicators have clearly defined quantitative equations by planning documents, laws, or management regulations. They are building clean heating ratio, ratio of water- and energy-saving old buildings, implementation ratio of urban buffer, land development intensity, proportion of rail transit trips, winter traffic performance index, public transport accessibility, building shape factor, greenery coverage, proportion of green buildings in newly-built buildings, and planting ratio of native species of severe cold zones.

2) This research uses referred quantitative methods for the indicators without clear quantitative equations from similar well defined ones. They are development and utilization ratio of underground spaces, and proportion of buildings with vertical planting. For example, the annual average development growth

Table 3: Quantitative equations of the evaluation indicator system

Indicator	Attribute	Reference	Threshold/level	Weight
Development and utilization ratio of underground spaces	Quantitative	Annual average development growth ratio of underground spaces by The 13th Five-Year Plan for the Development and Utilization of Urban Underground Space (Source: Ref. [47])	≥ 20%	0.026
Indoor accessibility	Qualitative	Minneapolis Climate Action Plan (Source: Ref. [44])	Low—medium—high	0.084*
Degree of road snow removal and antifreeze treatment in winter	Qualitative	Technical Specification of Snow Remove Operation for City Road, NO. CJJ/T 108—2006 (Source: Ref. [48])	Low—medium—high	0.026
Building clean heating ratio	Quantitative	Planning of Clean Heating in Winter in Northern China (2017—2021) (Source: Ref. [49])	≥ 70%	0.062*
Ratio of water- and energy-saving old buildings	Quantitative	Technical Guidelines for the Comprehensive Improvement of Old Residential Areas of State Organs in China (Source: Ref. [50])	≥ 65%	0.047
Implementation ratio of green buffer	Quantitative	National Garden City Standards in National Garden City Series Standards, NO. (2016) 235 (Source: Ref. [51])	≥ 80%	0.036
Land use compatibility	Qualitative	Code for Classification of Urban Land Use and Planning Standards of Development Land, NO. GB50137—2011 (Source: Ref. [52])	Low—medium—high	0.055*
Land development intensity	Quantitative	Technical Release 55 stipulates that if the total impervious area exceeds 30% of a site, the infiltration of the pervious area will be nominal (Source: Ref. [53])	≤ 30%	0.047
Proportion of rail transit trips	Quantitative	Standard for Urban Rail Transit Network Planning, NO. GB/T50546—2018 (Source: Ref. [54])	Population above 5 million, > 50% Population 1.5 ~ 5 million, > 30%	0.057*
Winter traffic performance index	Quantitative	Specification for Urban Traffic Performance Evaluation, NO. GB/T33171—2016, stipulates that the traffic performance index of uncongested roads is not higher than 4 (Source: Ref. [55])	≤ 4	0.061*

Continued

rate of underground spaces should be more than 20%, according to the 13th Five-Year Plan for the Development and Utilization of Urban Underground Space[47], and this research thus takes 20% for the indicator of development and utilization ratio of underground spaces.

And 3) for the other eight indicators without defined equations (i.e. qualitative indicators), such as indoor accessibility, popularity of winter activities in public spaces, and afforestation area in the current year. The quantitative equation for each indicator is assigned to a certain predefined level (i.e. low—medium—high) by its value or cross-comparison with its previous year.

3.2.2 Indicator Weights

Since this evaluation system contains both qualitative and

Table 3: Quantitative equations of the evaluation indicator system

Indicator	Attribute	Reference	Threshold/level	Weight
Public transport accessibility	Quantitative	Public transport accessible levels no less than 3 are considered medium or good according to Hammersmith & Fulham Local Plan (Source: Ref. [56])	≥ 3	0.047
Building shape factor	Quantitative	Design Standard for Energy Efficiency of Residential Buildings in severe cold and cold zones, NO. JGJ26—2018 (Source: Ref. [57])	≤ 0.55 (stories ≤ 3); ≤ 0.3 (stories ≥ 4)	0.034
Proportion of buildings with vertical planting	Quantitative	Minimum proportion of roof greening area of new buildings required by the Opinions on Strengthening Vertical Planting in Shandong Province (Source: Ref. [58])	≥ 30%	0.043
Greenery coverage ratio	Quantitative	National Garden City Standards in National Garden City Series Standards, NO. (2016) 35 (Source: Ref. [51])	≥ 36%	0.062*
Ventilation channel construction level	Qualitative	Technical Guidelines for Urban Ventilation Channel Planning (Source: Ref. [59])	Low—medium—high	0.147*
Popularity of winter activities in public space	Qualitative	Winter Design Guidelines: Transforming Edmonton into a Great Winter City (Source: Ref. [43])	Low—medium—high	0.011
Afforestation area in the current year	Qualitative	Implementation Regulations of the Forestry Law of the People's Republic of China (Source: Ref. [60])	Less than—the same as—more than the previous year	0.010
Emergency access network coverage	Qualitative	Comprehensive Disaster Prevention and Reduction Planning of Heilongjiang Province (2016—2020) (Source: Ref. [61])	Low—medium—high	0.050*
Winter disaster warning coverage	Qualitative	Measures for Meteorological Disaster Early Warning by the Central Meteorological Office (Source: Ref. [62])	Low—medium—high	0.011
Proportion of green buildings in newly-built buildings	Quantitative	The 13th Five-Year Plan for Building Energy Conservation and Green Building Development (Source: Ref. [63])	≥ 50%	0.047
Planting ratio of native species of severe cold zones	Quantitative	National Garden City Standards in National Garden City Series Standards, NO. (2016) 35 (Source: Ref. [51])	≥ 80%	0.037

NOTES

1. For the indicator "proportion of rail transit trips," the minimum population required for the construction and development of urban rail transit is 1.5 million.
2. "*" refers to the weights greater than the ratio of the sum of all indicator weights (1) to the total indicator number (21), that is, 0.0476.

quantitative indicators, this paper adopts an integrated method to weigh the indicators[64]. Firstly, the data for the 13 quantitative indicators are sourced from different official documents of Harbin city from 2008 to 2017. Through KMO test, three principal components with characteristic roots bigger than 1 are determined, and the cumulative variance contribution rate is 84.358%. Then varimax rotations are used to determine the linear equations of the three principal components, and the load factor of each indicator is obtained as the initial weight.

Secondly, this paper adopts proportional scaling, a weighting method based on the subjective identified level of each indicator, which usually uses a 5-level 9-point scale[65] to determine the relative weight of each indicator through pairwise comparison. In this paper, the judgment matrix constructed upon expert scoring has a maximum characteristic root of 8.3921 and a CI value of 0.056, suggesting that this matrix is consistent. Then, the initial weights of the 8 qualitative indicators are obtained.

Finally, the initial weights of all 21 indicators are normalized to obtain the final weights. In this paper, the indicators whose weights are greater than the average (the ratio of the sum of all indicator weights to the total indicator number, 0.0476) are considered the major factors of climate adaptability of urban spaces in the severe cold zones of China. They are indoor accessibility, building clean heating ratio, land use compatibility, proportion of rail transit trips, winter traffic performance index, greenary coverage ratio, ventilation channel construction level, and emergency access network coverage, which are analyzed in the following sections.

3.2.3 Indicator Calculation

All indicators are normalized and nondimensionalized. A quantitative indicator which meets the corresponding threshold (Table 3) is audited with 1 point, otherwise –1 point. For example, the winter traffic performance index is audited with 1 point when its value is no more than 4, otherwise –1 point; the proportion of green buildings in newly-built buildings is audited with 1 point when its value not less than 50%, otherwise –1 point.

A qualitative indicator is audited with –1, 0, or 1 point when it is less than, the same as, or more than the previous year (afforestation area in the current year) or when its level is low, medium, or high (other indicators), respectively. It is worth noting that the building shape factor is determined by the dominated building-storey type within the study area.

The overall climate adaptability is evaluated based on all the 21 indicators, as shown in equation (1):

$$C = f\left(I_{PA}, I_{AA}, I_{MA}\right), \tag{1}$$

where C is the overall climate adaptability index of urban spaces—the larger value the index, the stronger the climate adaptability. I_{PA}, I_{AA}, *and* I_{MA} represent the capacities of protection and restoration, accommodation, and managed retreat, respectively. In view of the complexity of climate adaptability, this research regards the three capacities equally important, and the weights of the three criterion are also equal.

This paper uses the linear weight sum method, which is widely used in the evaluation function series to solve multi-objective planning problems[66][67]: the overall climate adaptability of urban spaces equals the summed capacity in protection and restoration, accommodation, and managed retreat. The climate adaptability of urban spaces is calculated with equations (2) ~ (5):

$$C = I_{PA} + I_{AA} + I_{MA}, \tag{2}$$

$$I_{PA} = \sum_{i=1}^{n} I_{P_i} \times W_{P_i}, \tag{3}$$

$$I_{AA} = \sum_{i=1}^{m} I_{A_i} \times W_{A_i}, \tag{4}$$

$$I_{MA} = \sum_{i=1}^{k} I_{M_i} \times W_{M_i}, \tag{5}$$

where n, m, and k are the number of indicators in the criteria of protection and restoration, accommodation and managed retreat, respectively. I_{P_i} and W_{P_i}, I_{A_i} and W_{A_i}, and I_{M_i} and W_{Mi} are the ith indicator in criteria of protection and restoration, accommodation and managed retreat and the corresponding weight, respectively. The resultant score of each criteria and overall climate adaptability of urban spaces in the study area can be obtained.

4 Climate Adaptability Evaluation of Urban Spaces in Harbin

Relying on the climate adaptability evaluation indicator system of urban spaces in the severe cold zones of China, this paper evaluates the climate adaptability of the central area of Harbin—a typical severe-cold-climate city—based on official statistics and spatial data.

4.1 Study Area

Located in the northeast of the Northeast Plain of China, Harbin is the capital of Heilongjiang Province, the regional hub in transportation, politics, economy, culture, and finance, and a super-large city with the highest latitude and the lowest winter temperature in China. The central area of Harbin consists of Nangang, Daoli, Xiangfang, Daowai, Pingfang, and Songbei Districts, and parts of Hulan, Shuangcheng, and Acheng Districts, covering a total area of about 4,187 km^2.

4.2 Data Sources

The data used in this paper are mainly sourced from official statistics, spatial planning documents, literature, and guidelines. Statistical data for 14 indicators, including afforestation area in the current year and winter traffic performance index, are collected from Heilongjiang Statistical Yearbooks (2008 ~ 2017), Harbin Statistical Yearbooks (2008 ~ 2017), Government Work Reports (2008 ~ 2017), the official website of Harbin Municipal People's Government, news, as well as analysis reports on urban infrastructure released by AMap, Tuniu.com, and other transportation and tourism applications. The spatial data for development and utilization ratio of underground spaces, land use compatibility, and land development intensity are mainly sourced from the open-access planning documents on the official website of Harbin Municipal People's Government, the official website of Harbin Urban and Rural Planning Bureau (before 2017), etc. In terms of the data for antifreeze treatment in winter and indoor accessibility, degree of road snow removal, building shape factor, and proportion of buildings with vertical planting, this study conducts the assignment by reviewing relevant research and guidelines, empirical experience, and available data.

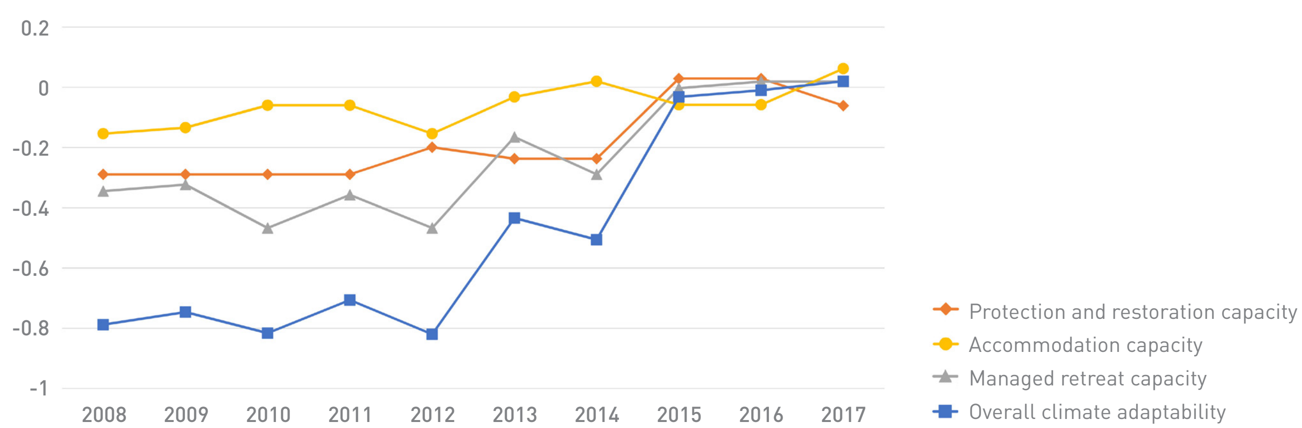
4.3 Evaluation Results and Discussion

4.3.1 Temporal Changes of Climate Adaptability

The temporal changes of climate adaptability of the study area from 2008 to 2017 are shown in Figure 2. During this period, relevant national and local policies were issued and the urban socio-economic development advanced; government departments have increasingly recognized the importance of enhancing the climate adaptability of urban spaces, taken positive countermeasures in all aspects of urban construction, and invested in ecological and environmental governance. Accordingly, all the three capacities and the overall climate adaptabilities in the study area were generally improved. However, drawbacks such as high energy consumption of transportation and industrial buildings, loose urban spatial pattern, and weak carbon sequestration of green space[68] have been challenging the overall climate adaptability of the study area, which largely fluctuated and was not scored positively until 2017.

The evaluation outcome reveals that the protection and restoration capacity of the study area witnessed a gradual increase since 2011. In terms of the major factors, indoor accessibility was far less than other severe-cold cities in developed countries[69]. The construction project of indoor overpass in Qiulin Business District of Nangang District was initiated in 2008 by the government, but then was halted for safety and management reasons. The insufficient indoor accessibility led to a low efficiency of winter climate protection, which might have restricted the improvement of protection and restoration capacity. In 2016, the Harbin City Special Action Plan for Air Pollution Prevention and Control (2016—2018)[70] promoted forbidding the use of lignite boilers for winter heating. Both Harbin Clean Heating Implementation Plan (2019—2021)[71] issued in 2019 and the 14th Five-Year Plan for Ecological Environment Protection in Harbin (draft for comments)[72] issued in 2022 promote the development of clean energy. Buildings clean heating ratio is expected to continue to grow, strengthening the climate adaptability of the study area.

Compared with the other two, the accommodation capacity of the study area is the lowest—this significantly compromises the integrated climate adaptability score, showing a general growth though. Among the major factors, the proportion of rail transit trips has gradually increased since 2013, when three subway lines



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2. Temporal changes of climate adaptability of urban spaces in the study area

were put into operation, and contributed to the improvement of the climate adaptability of urban spaces. This paper uses the analysis reports from AMap on the traffic performance of Harbin for an approximate measurement of the winter urban traffic performance index of the study area. Considering that the traffic congestion index of Harbin in the first quarters of 2016 and 2017 ranked the first and the second nationally, and the peak congestion delay index in both years exceeded 1.9[73]. There is great potential in enhancing the accommodation capacity of the study area by improving the winter traffic performance (increasing the operation efficiency in winter, reducing the peak congestion time, etc.). In addition, the recent development of multifunction land use pattern has improved the land use compatibility, but has limited effect on the improvement of protection and restoration capacity. Although the greenery coverage has generally risen in the research period and has reached the national garden city standard (36%) since 2015, it was still far behind the national eco-garden city standard (45%). The regional severe cold climate hinders the function of the accommodation capacity of urban green spaces. The construction of ventilation channel has gradually attracted the attention of government departments in recent years. In April 2018, with the issue of Planning of Ventilation channel in Harbin[74], the city started to strictly control the construction area and density of the ventilation channel sites, and clear the key nodes hindering the channel connectivity as many as possible. However, it will take some more time to complete the construction of ventilation channels and for an overall improvement of the accommodation capacity of the study area.

Managed retreat capacity improved mildly—it is scored −0.2 to 0 point except for the years of 2014 and 2017. This may be caused by the long-time neglect by government departments of the indicators of managed retreat capacities such as the emergency access network coverage. The Harbin Contingency Plan issued in 2022[75] specifies disaster emergency response measures, but does not designate any emergency paths or shelters at the level of urban space. The historically inadequate managed retreat capacity of the study area needs strengthening urgently.

4.3.2 Spatial Pattern of Climate Adaptability

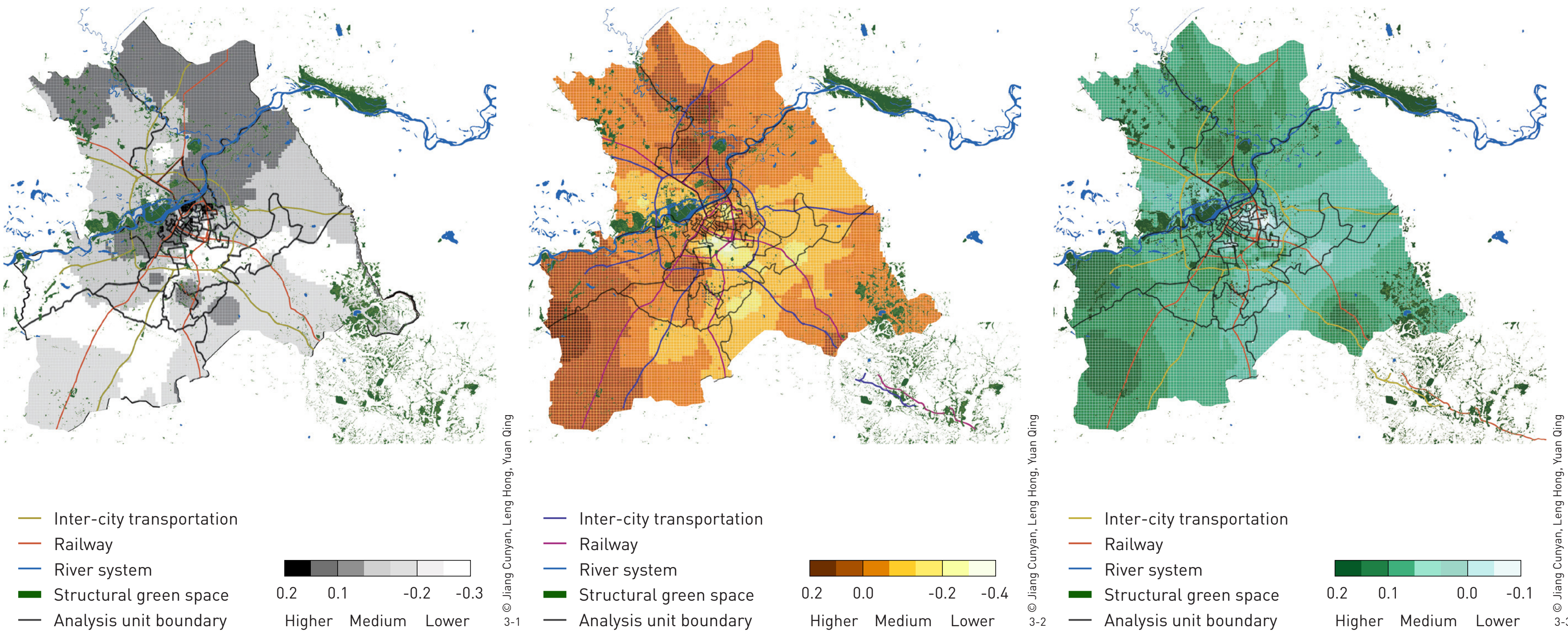
For a refined analysis, the central area of Harbin is divided into 48 units bounded by arterial roads, expressways, and district/town boundaries. The spatial analysis of climate adaptability used the data of 2017, the last year of the study time span. Since urban climate adaptability ignores spatial boundaries between units, interpolation analysis can be used to accurately predict the unknown data value[76]. Therefore Kriging (a method of interpolation analysis) in ArcGIS 10.3[77] is used to visualize the spatial pattern of climate adaptability of the study area. In addition, this research employed the widely-used natural breakpoint classification system in ArcGIS 10.3[78][79] to classify the evaluation results, which are divided into 7 grades. Then the division results were rounded to the nearest tenth for a better visualization (Fig. 3).

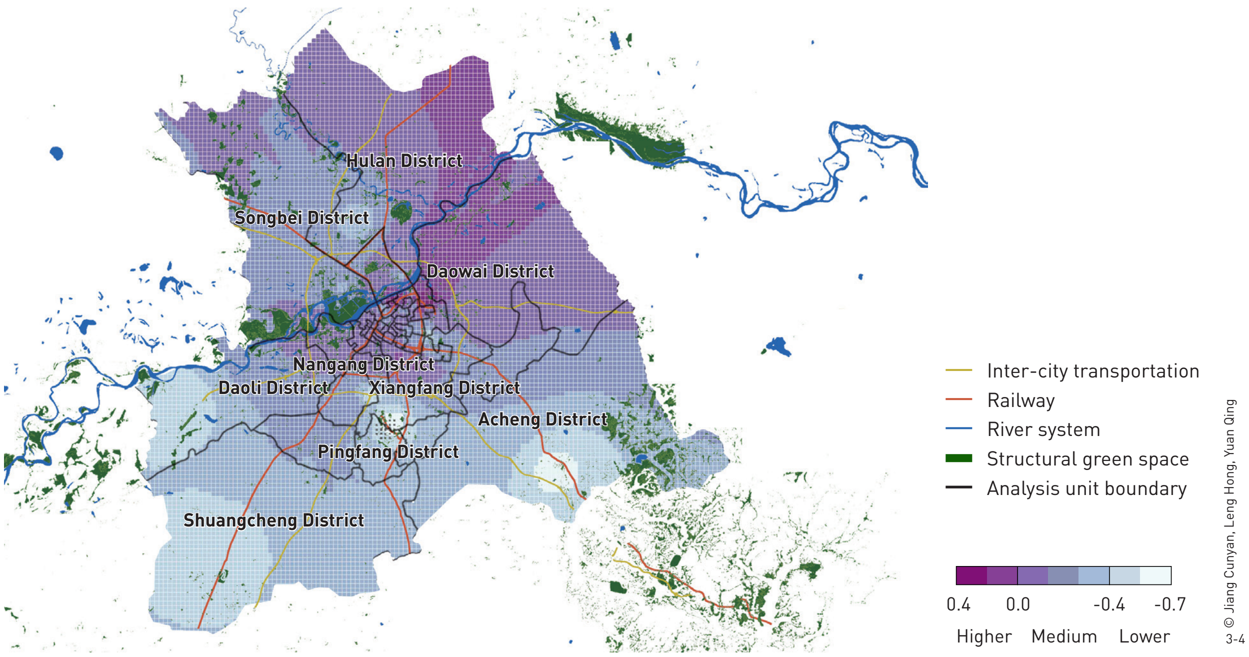
The overall climate adaptability of the study area is considered low: areas with positive scores account for less than 1% of the total area, and areas with scores below −0.4 account for more than 70%. There are significant differences in spatial pattern and development of spatial elements in the overall climate adaptability by districts: generally, the northern area has a higher climate adaptability than the southern part, and that of the downtown area is higher than the others, showing a radial pattern from the city center to the surrounding.

Lower scored units ($-0.7 < \text{score} \le -0.4$) concentrates in the south of the study area where heavy industrial land use dominates, including heavy machinery manufacturers, pharmaceutical companies, and industrial logistics parks. Heavy energy consumption and long-term job-housing separation also account for the low score of the protection and restoration capacity of this area. In the southeast and southwest of the study area, the recent “county to district” reform of Acheng and Shuangcheng have reshaped the local land use and disturbed the ecological environment. In Acheng District, the arable area decreased from 93,400 hm^2 in 2006 to 72,500 hm^2 in 2018, which considerably compromised the accommodation capacity of the area.

Units with medium scores ($-0.4 < \text{score} \le 0$) are mainly found in the north, south-central, and east of the study area, where the historic city areas of Harbin are located in. The high population density, lack of infrastructure, heavy building energy consumption, and low transportation accessibility have together resulted in relatively lower accommodation and managed retreat capacities. In the downtown area, the dense road network, insufficient emergency accesses, and lack of large emergency shelters lead to a relatively low managed retreat capacity.

Higher scored units (> 0) are all located along the Songhua River, mostly developed in the recent 15 years, and some sit in the key development areas. Developed infrastructure, higher greenery coverage, less industrial pollution, as well as cold island elements such as ventilation channels along the rivers, green spaces, and squares, lead to a better accommodation capacity.





3. Spatial pattern of climate adaptability of the study area: protection and restoration capacity (Fig. 3-1); accommodation capacity (Fig. 3-2); managed retreat capacity (Fig.3-3); spatial pattern of the overall climate adaptability (Fig. 3-4).

5 Strategies for Improving the Climate Adaptability for Urban Spaces in the Central Area of Harbin

The evaluation results show the temporal–spatial disparity in climate adaptabilities. During the research period, the climate adaptabilities of the study area was low, gradually improved though. While most urban spaces in the study area face with problems such as heavy energy consumption of transportation and industrial buildings, loose urban spatial pattern, and weak carbon sequestration of green spaces[68], local challenges can be identified by analysis through climate adaptation zoning. In the future, planning and design countermeasures should be put forward according to the climate adaptability evaluation results, and provide reference for climate adaptation planning, actions, and decisions for cities in the severe cold zones of China.

5.1 Integrating the Concept of Climate Adaptation Into the Compilation of Territorial Spatial Planning

In recent years, climate adaptation has been integrated into urban planning systems of some Chinese cities mainly in forms of ideological principles or macro guidance and suggestions, less in specific planning outcome. This paper attempts to integrate the concept of climate adaptation into the compilation of territorial spatial planning by supplementing the existing planning system with the major factors of climate adaptability evaluation indicator system (Table 4), upon the requirements of municipal territorial spatial planning by the Notice of Territorial Spatial Planning by the Ministry of Natural Resources of the People's Republic of China[80], and the urban planning measures at varied levels in respond to climate change through literature review[81][82].

Main possible means to improving the protection and restoration capacity include providing citizens with underground spaces or indoor overpasses, improving the utilization efficiency of land use through land compatibility control, and proactively increasing building clean heating ratio through application of new energy technology. Main possible means to improving accommodation capacity include promoting the construction of urban rail transit and guaranteeing the transportation efficiency in winter, determining the spatial layout and planting structure of green spaces in line with macro principles on ecological

Table 4: Supplementary of climate adaptation in territorial master planning of Harbin

Requirement	Main factors	Supplementary	Climate adaptation path
Layout of urban and rural public service facilities	Indoor accessibility	Identify the key distribution areas and determine the construction forms of indoor overpasses, and proactively explore new types of climate protection measures	Protection and restoration
Functional layout of the central area	Land use compatibility	Identify the key areas and determine measures for compatible land use	
Important linear engineering network	Building clean heating ratio	Set goals for building clean energy heating ratio and clean energy consumption	
	Proportion of rail transit trips	Increase the accessibility of urban rail transit and provide climate protection for rail transit facilities	Accommodation
	Winter traffic performance index	Improve public transportation accessibility and focus on ensuring transportation efficiency in winter	
Scope and distribution requirements of urban structural green spaces	Greenery coverage	Improve greenery coverage and determine the proportion of arbor planting and main planting areas	
Pattern and control requirements of ventilation channels	Ventilation channel construction ratio	Build ventilation channels on both sides of Songhua River and Majiagou River as major ecological barriers, and establish a hierarchical and interconnected ecological spatial system	
Security and disaster prevention system	Emergency channel network coverage	Build emergency shelters and routes for evacuation based on arterial roads, green and open spaces, etc.	Managed retreat

and environmental protection against severe cold climate, and improving the overall greenery coverage of the city while delimiting ventilation channel areas based on the existing river system and riverside green buffer belts. Main possible means to improving the managed retreat capacity and provide practical measures for evacuation include establishing meteorological disaster early warning systems and building emergency escape networks.

5.2 Formulating District-Level Management Measures for Climate Adaptation

According to the evaluation results of climate adaptability, district-level management measures are put forward to synergize the climate adaptation effect of each district and improve the overall climate adaptability of Harbin: central Nangang District and northern Daoli District should aim at optimizing land use pattern and lowering population density to alleviate the adverse impact of regional climate environment; Songbei District and eastern Daowai District should target increasing land use compatibility and efficiency to enhance climate adaptation; for the vast areas of destructed arable land in Shuangcheng and Acheng districts, climate security should be maintained by restoring arable lands; at last, Pingfang and Xiangfang districts should focus on enhancing climate adaptation by tackling serious problems of energy consumption.

6 Conclusions and Prospects

Severe cold zones facing complex climate conditions are more vulnerable to climate change. Summarizing the climate characteristics of these areas, this paper responds to the combined effects of climate change and regional climate with three strategies, namely protection and restoration, accommodation, and managed retreat, and constructs a climate adaptability evaluation indicator system for urban spaces in severe cold zones of China. In the case study of the central area of Harbin—a typical severe-cold city, planning and design countermeasures are put forward based on the evaluation results. The local difference and insufficient synergy between districts in climate adaptation shown in the study area are also challenging other severe-cold Chinese cities. Since the studied period of time spans from 2008 to 2017, some indicators (e.g. building clean heating ratio and the proportion of rail transit trips) have significantly improved in the past few years due to the promotion of national and local policies, and greatly enhanced the overall climate adaptability of urban spaces. In the future, measures to promote the construction of urban rail transit, guarantee the transportation efficiency in winter, and build urban ventilation channels should be taken. Integrating the concept of climate adaptation into the compilation of territorial spatial planning, and formulating forward-looking climate adaptation planning and synergetic policies are key to strengthening urban spatial climate adaptation in the severe cold zones of China. The research team will continue to pay attention to relevant policies and urban spatial construction in future efforts.

Due to the complexity of urban systems, cities at different scales vary widely in climate problems. This paper conducts an exploratory research on the climate adaptability evaluation of urban spaces in severe cold zones, and sees deficiency in the structural design and quantification method of the indicator system. For example, refined indicators to specific climate risks need to be introduced[83], and the research scientism can be improved by adopting more objective weighing methods instead of the linear weight sum method. Also, the research results need to be verified by future (comparative) evaluation research on climate adaptability in different severe-cold Chinese cities.

This paper provides reference for future compilation of territorial spatial planning and special planning and research responding to climate adaptation under severe cold climates, promotes the development of climate adaptation of cities in severe cold zones of China, and supports the ongoing pilot projects of climate adaptability city construction throughout the country.

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中国严寒地区城市空间的气候适应性评价指标体系构建研究——以哈尔滨市中心城区为例

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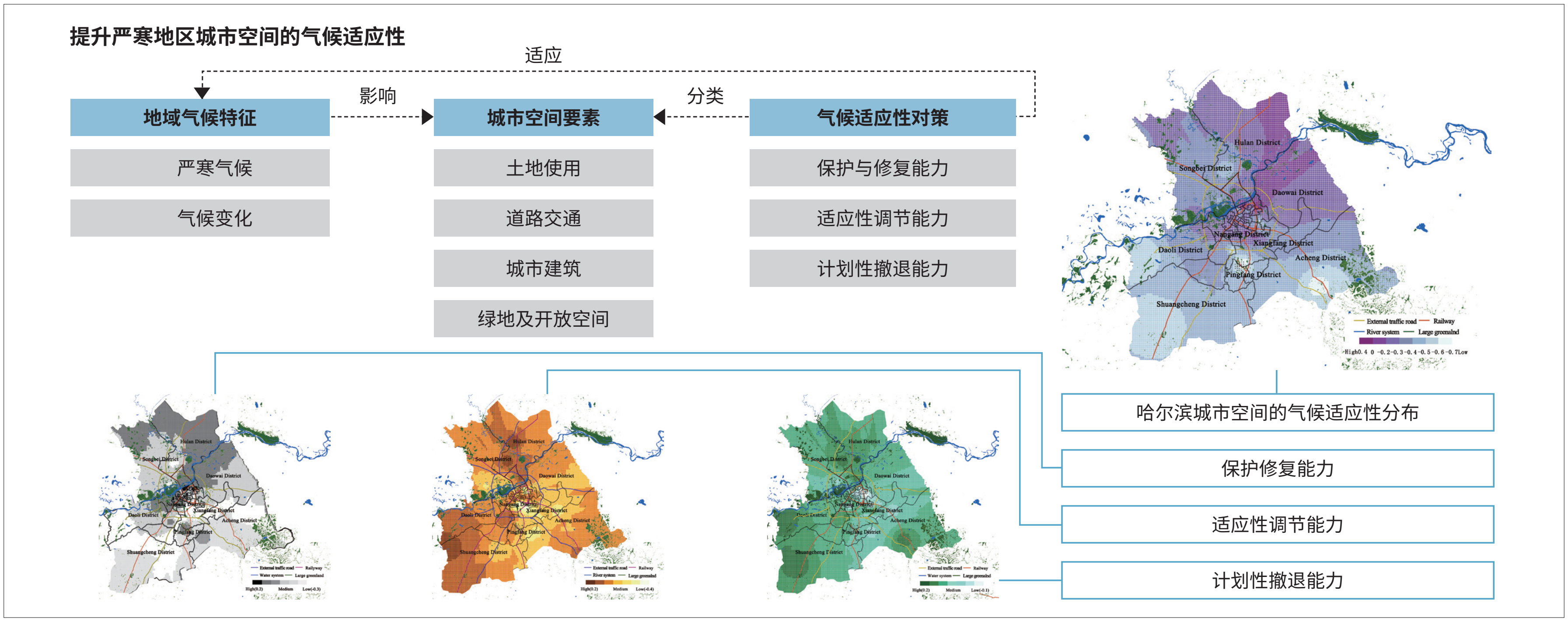
图文摘要



文章亮点

- 本气候适应性研究同时涵盖气候变化与地域气候背景
- 提出三类气候适应性途径：保护修复、适应性调节、计划性撤退
- 构建中国严寒地区城市空间的气候适应性评价指标体系
- 评价中国典型严寒地区城市空间的气候适应性
- 提出中国严寒地区城市空间的气候适应性提升策略

关键词

严寒地区；
城市空间；
气候适应性；
评价指标体系；
适应策略

摘要

气候适应性研究应该同时涵盖气候变化与地域气候背景两方面因素。从城市空间角度进行气候适应性的研究并对其展开评价，有助于明确城市空间建设在应对气候问题方面的薄弱环节。本文构建了中国严寒地区城市空间的气候适应性评价指标体系，并以哈尔滨中心城区为例进行气候适应性的时空分异评价。结果表明，研究区域城市空间的综合气候适应性能力在2008~2017年间基本呈提升趋势，但总体仍处于较低水平，同时各市辖区的气候适应性存在较为显著的空间差异和要素发展不均衡现象。本文据此提出相应对策，以期为未来中国严寒地区城市制定气候适应性规划和建设决策提供支撑。

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1 引言

由于气候系统的惯性，气候变化将带来持久的影响[1][2]。为此，政府间气候变化专门委员会（IPCC）指出，在未来的一段时间内，应将气候适应作为应对气候变化的重要手段[1][3]，且城市属于实行气候适应措施的重要作用区域[4]。目前，世界各国针对气候适应性的研究成果颇丰，丹麦、新西兰、加拿大等国均为本国重点城市编制了应对气候变化的战略或行动框架[5]-[8]。

界定和评价不同城市的气候适应性是城市开展适应性规划和决策制定的基础[9]。近年来，相关领域学者主要通过两种途径对城市气候适应性进行评价研究：1）评价气候适应行动方案，如卡利安·德·布鲁因等人对荷兰适应气候变化政策的增量成本及收益情况开展了评估[10]；本杰明·李·普雷斯顿等人、英格里德·贝克等人分别针对57个和7个涉及公共卫生、生态环境等领域的气候适应性方案制定了气候适应性评估框架，并对信息收集、规避风险等方案实施步骤的周全性进行了评估[11][12]；伊丽莎白·M·哈敏等人从城市交通、水资源、生物多样性、能源利用等方面评估了两项城市气候适应行动与相应缓解气候变化影响的目标间的冲突，并初步归纳出协同二者的方法[13]。2）评估城市空间要素与气候要素的相互作用，如布莱恩·斯通及其团队陆续探索城市形态、土地开发密度等对城市热岛效应和极端热事件的影响[14]-[16]；克莱尔·L·沃尔什采用城市综合评估设施模拟了伦敦市21世纪的土地利用、气候变化影响和温室气体排放等变化状况[17]；让-卢克·萨拉尼亚克依托法国巴黎的EPICEA项目，评估了城市建筑表皮、植被绿化等气候适应性措施对于热平衡的改善情况[18]。

综上，第一种途径关注政府部门主导的气候适应行动[19]，重在评价行动的经济和生态效益，目前已成为国内外气候适应性规划体系主流做法的一部分[20]；第二种途径主要衡量城市空间要素能否以及如何适应不断加剧的气候变化。然而，目前国内外从城市空间视角展开系统性气候适应性评价的研究仍十分有限，且尚未建立针对城市空间的气候适应性评价体系[19][21]。

城市气象学家蒂姆·奥克认为，不同地域所遭受的气候变化影响存在较大差别[22]，因此气候适应性研究应同时涵盖气候变化与地域气候两方面因素。其中，地处严寒地区的城市同时面临地域严寒气候与气候变化的双重影响[23]。虽然近年来城市热岛效应有一定程度的加剧[24][25]，但严寒地区城市空间所面临的主要气候问题仍集中在冬季：持续低温及频繁降雪使得严寒地区城市环境的宜居性大幅下降，对城市居民的生产生活影响重大。科利·莫尔彼得、扬·盖尔、诺曼·普莱斯曼等学者对符合严寒地域气候特点的城市与建筑设计对策进行了深入研究[26]-[28]。此外，既有研究表明，虽然气候变暖具有提升冬季城市室外体感舒适度、利于冬季水体污染物扩散（从而降低污染物浓度）等益处[29][30]，但也造成了雪后昼夜温差大、冰雪路面加速形成、积雪存留变少以致春季沙尘天气增多等问题[31]。

目前，国内外应对气候变化的城市空间规划研究日趋增多，然而基于地域气候背景探究气候适应性规划应对机制的研究十分有限[32]，以地域气候适应为切入点展开的相关研究几近空白。立足地域气候背景评价城市空间的气候适应性，有助于明确城市空间建设在应对气候问题方面的薄弱环节。本文旨在构建中国严寒地区（即累年最冷月平均温度不高于−10° C的地区[33]）城市空间的气候适应性评价指标体系，并以典型严寒地区城市哈尔滨的中心城区为例，针对评价结果提出相关对策，以期为未来中国严寒地区城市制定气候适应性规划和建设决策提供支撑。

2 中国严寒地区城市空间的气候适应性

在本研究中，研究团队总结了基于严寒气候与气候变化背景的城市空间气候问题的特殊性，并据此解析严寒地区城市空间气候适应性的内涵，进而提出了严寒地区城市空间应对气候问题的途径。

2.1 中国严寒地区城市空间气候问题的特征

相比于其他气候地区，严寒地区受到了更为深远的地域气候与气候变化双重影响；与处于寒冷气候区的中国华北与西北地区相比，由于冬季恶劣气候的持续时间更长，严寒地区城市空间所遭受的影响程度也更大。表1梳理了中国严寒地区城市空间冬季气候问题的特殊性[31][34]，作为探究城市空间应对气候问题适应途径的依据。

2.2 中国严寒地区城市空间的气候适应性途径

城市规划的核心内容之一是对城市物质空间要素（如土地利用、道路交通、城市建筑和绿地及开放空间）进行布局，而合理的布局与设计可以增强城市对气候问题的适应能力[35]。因此，从城市空间的角度研究气候适应性规划，是气候适应与城市规划的重要结合点。

IPCC将应对气候变化和极端天气事件的适应策略分为三类：保护（protection）、适应性调节（accommodation）和计划性撤退（managed retreat）[36][37]。立足地域气候与气候变化的双重背景，本文将这三类适应策略的应用场景在城市空间层面进行了延伸，界定了严寒地区城市空间的三类气候适应性途径，即保护修复、适应性调节、计划性撤退。在本文中，严寒地区城市空间的气候问题特征、城市空间要素，以及与气候适应性途径的相互作用关系如图1所示。

表 1：中国严寒地区城市空间冬季气候问题的特征

影响对象	具体表征
城市道路交通	交通碳排放量及道路清雪能耗大；雪后交通拥堵、路面结冰事件频发；公共交通运力降低，高峰时段运力不足
城市景观绿化	缺乏绿色植被景观，户外环境对城市居民的吸引力、土壤及植被的碳汇作用低
城市能源消耗	建筑供暖及道路清雪能耗大、城市环境污染加剧、建筑材料使用量大
居民生产生活	居民户外活动受限、活动时长少，部分涉及户外环境的就业受到影响

1）保护修复。采取工程措施保护城市内易受影响的城市空间，保障重要的社会服务和居民基本的生产生活[38]。此外，还需要修复已经受到影响的空间，通过干预措施将其调整为外界干扰胁迫之前的城市系统状态。在本文中，这类途径主要包括对城市能源消耗量大的交通、建筑产业进行节能修复；对易受冬季严寒气候影响的城市系统进行气候防护或保护等。

2）适应性调节。当气候变化趋势加剧但负面影响较轻时，依靠城市系统自身的韧性或自适应机制而不另外施加适应措施，就能有效调节气候变化所带来的影响，实现城市的照常运转[39]。在本文中，这类途径主要包括重点保障冬季城市交通的运行效率，增加绿地及开放空间以提升土壤及植被的碳汇和微气候调节功能等。

3）计划性撤退。当受到的胁迫超过自适应与人为适应能力之和时，应对气候脆弱性或风险性较大的城市空间进行撤退，以减少气候问题所带来的负面影响[40]。在本文中，这类途径主要包括冬季气候灾害发生时城市的预警及应急处理，以及为应对不利的冬季气候影响而进行的城市系统转型（如植被置换）等。

3 中国严寒地区城市空间气候适应性评价指标体系的建立

本研究将保护修复、适应性调节、计划性撤退三类途径设为准则层，将土地利用、道路交通、城市建筑、绿地及开放空间设为要素层，建立中国严寒地区城市空间的气候适应性评价指标体系，进而制定了各项指标内容的量化评价方法。

3.1 评价指标筛选

基于文献研究——参考世界其他严寒地区城市空间与气候环境相关性研究成果[41][42]、发达国家寒地城市气候调节政策[43][44]，同时借鉴城市气候承载力、气候变化脆弱性等评价指标体系的构建过程[45][46]——并综合考虑数据的可获得性，通过相关类目合并、系列相关剔除等步骤，最终确定了21项评价指标（表2）。

3.2 指标计算过程

3.2.1 指标取值依据

根据各项评价指标的不同属性，通过以下三种途径为各指标赋值（表3）[43][44][47]~[63]。

1）若评价指标在规划、法律条令、管理规定中已有明确的定义和计算方式，则据此方式计算获取指标的数值，由此确定建筑清洁取暖率、老旧建筑节水节能改造率、城市防护绿地实施率、土地开发强度、轨道交通出行比例、冬季交通运行指数、公共交通可达性、建筑体型系数、

表 2：中国严寒地区城市空间气候适应性指标评价体系

准则	要素	指标
保护修复	土地使用	地下空间开发利用率
	道路交通	室内步行系统覆盖率
		冬季道路除雪防冻处理程度
	城市建筑	建筑清洁取暖率
		老旧建筑节水节能改造率
	绿地及开放空间	城市防护绿地实施率
适应性调节	土地使用	用地兼容性
		土地开发强度
	道路交通	轨道交通出行比例
		冬季交通运行指数
		公共交通可达性
	城市建筑	建筑体型系数
		建筑立体绿化比例
	绿地及开放空间	绿化覆盖率
		城市通风廊道建设水平
		公共空间冬季活动普及程度
计划性撤退	土地使用	当年造林面积
	道路交通	城市应急通道网络覆盖率
		冬季灾害预警普及率
	城市建筑	新建建筑中绿色建筑比例
	绿地及开放空间	寒地乡土植物种植率

绿化覆盖率、新建建筑中绿色建筑比例和寒地乡土植物种植率，共计11项指标的赋值。

2）对于自身没有明确定义和计算方式、但可获取相似指标明确量化要求的评价指标，依据相似指标推断该指标的参考值。以地下空间开发利用率为例，本研究选取《城市地下空间开发利用“十三五”规划》[47]中对地下空间开发年均增速的规定（20%以上）作为该指标的量化阈值。由此确定地下空间开发利用率和建筑立体绿化比例两项指标的赋值。

3）对于暂无明确计算方式的指标（即定性指标），依据指标内涵或横向比较年度指标值的方式，将指标赋值划分为三个等级（如低—中—高、不全面—中等—全面）；由此确定室内步行系统覆盖率、公共空间冬季活动普及程度、当年造林面积等8项指标的分级规则。

3.2.2 指标权重

由于本评价体系中同时包含定性及定量指标，构成具有一定的复杂性，因此采用主客观综合集成赋权法[64]确定评价指标的权重。首先，对于13项定量指标，选取哈尔滨市2008~2017年的相应数据，通过KMO检验后，确定特征根大于1的三个主成分，累计方差贡献率达84.358%。继而选用最大方差法对各项指标进行旋转，确定三个主成分的线性组合方程，得到13项定量指标的荷载系数作为初始权重值。

其次，比例标度法是以对事物的差别评判标准为基础的主观权重确定方法，通常采用5等9级的方式来[65]确定每个指标的相对重要程度比较值。本研究以专家评分的方式构建判断矩阵，该矩阵最大特征根为8.3921，CI值为0.056，通过了一致性检验，因此由该判断矩阵确定8项定性指标的初始权重值。

最后，对全部21项指标的初始权重值进行归一化处理，获得每一项指标的综合权重值。本研究将权重值高于平均水平（各因子权重值的总和1与指标数量21的比值，即0.0476）的指标确定为严寒地区城市空间气候适应性主因子，共8项——室内步行系统覆盖率、建筑清洁取暖率、用地兼容性、轨道交通出行比例、冬季交通运行指数、绿化覆盖率、城市通风廊道建设水平，以及城市应急通道网络覆盖率。这些指标将在后续对哈尔滨城市空间的气候适应性评价中予以重点分析。

3.2.3 指标运算规则

为消除各项指标因子的数值及其单位差异，采用归一化对各项指标进行无量纲处理。对于13项定量指标，指标值满足表3中对应赋值规则的计1分，否则计—1分。以冬季交通运行指数为例，该指标值所属等级不大于4时计1分，反之计—1分；再如新建建筑中绿色建筑比例，该指标值不小于50%时计1分，反之计—1分。

在8项定性指标评价中，根据表3的分级规则依次分别计—1、0、1

表 3：评价体系中各项指标取值依据

指标	属性	参考依据	指标赋值／分级规则	权重
地下空间开发利用率	定量	《城市地下空间开发利用“十三五”规划》规定的地下空间开发年均增速（来源：参考文献 [47]）	⩾ 20%	0.026
室内步行系统覆盖率	定性	美国《明尼阿波利斯市城市设计导则》（来源：参考文献 [44]）	低—中—高	0.084*
冬季道路除雪防冻处理程度	定性	《城市道路除雪作业技术规程》CJJ/T 108—2006（来源：参考文献 [48]）	不及时彻底—中等—及时彻底	0.026
建筑清洁取暖率	定量	《北方地区冬季清洁取暖规划（2017—2021）》（来源：参考文献 [49]）	⩾ 70%	0.062*
老旧建筑节水节能改造率	定量	《中央国家机关老旧小区综合整治技术导则》（来源：参考文献 [50]）	⩾ 65%	0.047
城市防护绿地实施率	定量	《国家园林城市系列标准（建城〔2016〕235 号）》——国家园林城市标准（来源：参考文献 [51]）	⩾ 80%	0.036
用地兼容性	定性	《城市用地分类与规划建设用地标准》（GB50137—2011）（来源：参考文献 [52]）	低—中—高	0.055*
土地开发强度	定量	美国《第 55 号技术公报》指出，若不透水面积占比超过 30%，则其余透水区域的渗透作用将非常有限（来源：参考文献 [53]）	⩽ 30%	0.047
轨道交通出行比例	定量	《城市轨道交通线网规划规范（GB/T50546—2018）》（来源：参考文献 [54]）	>50%（人口 500 万以上） >30%（人口 150 ～ 500 万）	0.057*
冬季交通运行指数	定量	《城市交通运行状态评价规范（GB/T33171—2016）》规定交通运行指数等级不高于 4 为道路基本畅通或畅通状态，反之为拥堵状态（来源：参考文献 [55]）	⩽ 4	0.061*
公共交通可达性	定量	美国《哈默史密斯和富勒姆行政区规划》中规定公共交通可达性评级不小于 3 为中等及良好以上（来源：参考文献 [56]）	⩾ 3	0.047

续表见下页

分。以当年造林面积为例，比上一年度减少的计−1分，与上一年度持平的计0分，比上一年度增加的计1分。值得注意的是，对于建筑体型系数，以评价对象范围内符合两种情况的建筑数量为依据，估算确定取值。

本研究基于保护修复、适应性调节与计划性撤退3类途径与21项评价指标，构建了气候适应性评价函数，如公式（1）所示：

$$C=f\left(I_{PA},I_{AA},I_{MA}\right), \qquad (1)$$

式中，C表示城市空间的综合气候适应性指数，其值越大表示城市空间的气候适应能力越强；I_{PA}、I_{AA}、I_{MA}分别表示三类途径试图建设的能力——保护修复能力、适应性调节能力和计划性撤退能力。鉴于气候适应性构成的复杂性，保护修复能力、适应性调节能力与计划性撤退能力在气候适应性方面相辅相成、缺一不可。因此在本研究中，此三项的权重值相同。

同时，本研究采用评价函数方法中常用的线性加权和法求解多目标规划问题[66][67]，即认为城市空间的气候适应能力为保护修复能力、适应性调节能力与计划性撤退能力之和，由此得到严寒地区城市空间的气候适应性的具体计算公式，如公式（2）~公式（5）所示：

表 3：评价体系中各项指标取值依据

指标	属性	参考依据	指标赋值／分级规则	权重
建筑体型系数	定量	《严寒和寒冷地区居住建筑节能设计标准 JGJ26—2018》（来源：参考文献 [57]）	≤ 0.55（建筑层数不高于 3 层）；≤ 0.3（建筑层数不小于 4 层）	0.034
建筑立体绿化比例	定量	山东省《关于加强全省城市立体绿化工作的指导意见》规定条件适宜的新建建筑屋顶绿化应达比例（来源：参考文献 [58]）	≥ 30%	0.043
绿化覆盖率	定量	《国家园林城市系列标准（建城〔2016〕235 号）》——国家园林城市标准（来源：参考文献 [51]）	≥ 36%	0.062*
城市通风廊道建设水平	定性	《城市通风廊道规划技术指南》（来源：参考文献 [59]）	低—中—高	0.147*
公共空间冬季活动普及程度	定性	加拿大《埃德蒙顿冬季城市设计导则》（来源：参考文献 [43]）	低—中—高	0.011
当年造林面积	定性	《中华人民共和国森林法实施条例》（来源：参考文献 [60]）	比上一年度减少—持平—增加	0.010
城市应急通道网络覆盖率	定性	《黑龙江省综合防灾减灾规划（2016—2020）》（来源：参考文献 [61]）	低—中—高	0.050*
冬季灾害预警普及率	定性	《中央气象台气象灾害预警发布办法》（来源：参考文献 [62]）	不全面—中等—全面	0.011
新建建筑中绿色建筑比例	定量	《建筑节能与绿色建筑发展“十三五”规划》（来源：参考文献 [63]）	≥ 50%	0.047
寒地乡土植物种植率	定量	《国家园林城市系列标准（建城〔2016〕235 号）》——国家园林城市标准（来源：参考文献 [51]）	≥ 80%	0.037

注

1. 在“轨道交通出行比例”中，建设发展城市轨道交通的最低人口规模为 150 万人。
2. “*”表示该权重值大于各因子权重值的总和（1）与指标数量（21）的比值，即 0.0476。

$$C = I_{PA} + I_{AA} + I_{MA}, \quad (2)$$

$$I_{PA} = \sum_{i=1}^{n} I_{P_i} \times W_{P_i}, \quad (3)$$

$$I_{AA} = \sum_{i=1}^{m} I_{A_i} \times W_{A_i}, \quad (4)$$

$$I_{MA} = \sum_{i=1}^{k} I_{M_i} \times W_{M_i}, \quad (5)$$

式中，n、m、k分别为保护修复、适应性调节和计划性撤退途径所包含的指标个数。I_{P_i}、W_{P_i}分别为第i个保护修复指标及其对应的权重；I_{A_i}、W_{A_i}分别为第i个适应性调节指标及其对应的权重；I_{M_i}、W_{M_i}分别为第i个计划性撤退指标及其对应的权重。采用上述公式进行评价运算，可以得到研究对象城市空间三项适应能力各自的得分及其气候适应性总分。

4 哈尔滨城市空间气候适应性评价

依托中国严寒地区城市空间气候适应性评价指标体系，本研究选取典型严寒地区城市哈尔滨，并以其中心城区为研究对象，基于相关统计及空间数据，对研究区域城市空间开展气候适应性评价。

4.1 研究区域

哈尔滨地处中国东北平原东北部，是黑龙江省省会，东北地区的交通、政治、经济、文化、金融中心，同时也是中国纬度最高、冬季气

温最低的特大城市。哈尔滨的中心城区范围涵盖南岗区、道里区、香坊区、道外区、平房区、松北区的全部，以及呼兰区、双城区、阿城区的部分区域，总面积约4 187km^2。

4.2 数据来源

本研究的原始数据包括统计数据、时空数据及文献导则三类。其中统计数据来自《黑龙江省统计年鉴》（2008～2017年）、《哈尔滨市统计年鉴》（2008～2017年）、《哈尔滨市政府工作报告》（2008～2017年）、“中国·哈尔滨”政府门户网站、哈尔滨市当地新闻，以及高德地图、途牛网等交通业、旅游服务业应用程序所发布的有关城市建设的统计分析报告，共涉及当年造林面积、冬季交通运行指数等14项指标。空间数据主要来自“中国·哈尔滨”政府门户网站中政务信息公开栏目的市资源规划专栏、哈尔滨城乡规划局网站（2017年前）等，共涉及地下空间开发利用率、用地兼容性和土地开发强度3项指标。此外，由于可获取的统计、空间数据不能满足本研究的全部需要，本研究参考国内外相关研究成果、导则，结合研究经验和可获得的数据基础，选取部分相关指标进行处理和推算，以满足室内步行系统覆盖率、冬季道路除雪防冻处理程度、建筑体型系数和建筑立体绿化比例，共计4项指标的取值需求。

4.3 评价结果与讨论

4.3.1 气候适应性的时间变化特征

本文基于哈尔滨中心城区2008～2017年间的城市时空数据，对其气候适应性动态进行了分析与评估，结果如图2所示。在此期间，随着国家及地方相关政策陆续出台，城市社会经济稳步发展；相关部门逐步意识到增强城市空间气候适应性的重要性，并在城市建设的各方面采取了积极的应对措施，对生态环境治理的投入也有所增加。相应地，研究区域城市空间的3项气候适应性能力和综合气候适应性能力基本呈现上升的趋势。然而，研究年份内，研究区域的交通出行及工业企业建筑能源消耗量大、城市空间形态不紧凑、绿地碳汇系统薄弱等问题均较为突出[68]，三项气候适应性能力和综合气候适应性能力的分值都较低。与此同时，综合气候适应性能力的得分也呈现出较大波动，且直至2017年才由负转正。

研究区域城市空间的保护修复能力最初表现平稳，自2011年起逐渐上升。在主因子方面，经比较发现，研究区域的室内步行系统覆盖率与部分发达国家寒地城市差距较大[69]。尽管2008年哈尔滨市政府拟改造建设南岗区秋林大商圈的空中暖廊，但这一项目最终因安全管理因素、影响已有商业运行等问题未能实施。室内步行系统建设不足导致研究区域城市空间缺乏有效的冬季恶劣气候防护，或为制约保护修复能力提升的主要原因之一。2016年哈尔滨市政府发布《哈尔滨市大气污染防治专项行动方案（2016—2018年）》[70]，计划全面改造冬季供暖褐煤锅炉；2019年起推行的《哈尔滨市清洁取暖实施方案（2019—2021）》[71]和2022年公布的《哈尔滨市生态环境保护“十四五”规划（征求意见稿）》[72]都主张推动清洁能源发展，主因子建筑清洁取暖率有望在政策支持下继续提升，有助于增强研究区域城市空间的气候适应能力。

相较于其他两项能力，研究区域城市空间的适应性调节能力得分最低——这也是导致综合气候适应性得分较低的主要原因——但总体仍呈现上升趋势。在主因子方面，自2013年起，哈尔滨陆续将三条地铁线路投入运营，轨道交通出行比例随之逐步上升，在一定程度上提升了城市空间的气候适应性。本研究采用高德地图对哈尔滨市交通状况的统计结果，来近似衡量研究区域的冬季城市交通运行指数。鉴于2016、2017年度哈尔滨一季度的交通拥堵程度排名分别位列全国第一与第二，高峰拥堵延时指数达1.9以上[73]，通过提升哈尔滨冬季的交通运行指数（如提升冬季运行效率、减少早晚高峰拥堵时长等）来增强研究区域城市空间的适应性调节能力的潜力较大。此外，研究区域内用地兼容性的情况虽然随着历年来城市混合型用地功能布局模式的发展有了一定程度的改善，但对于适应性调节能力的提升效用不甚明显。绿化覆盖率虽然在10年间整体呈现上升趋势，且在2015年后初步达到国家园林城市的标准（不低于36%），但与国家生态园林城市标准（不低于45%）仍存在较大差距；加之冬季严寒气候影响，研究区域内城市绿化的适应性调节能力仍显不足。近年来，城市通风廊道建设水平逐渐引起相关部门的重视，2018年4月发布的《哈尔滨市城市通风廊道规划》[74]对划入通风廊道的区域严格进行建设规模和密度控制，并要求在有条件的情况下打通阻碍廊道连通的关键节点，但完成城市通风廊道系统构建、进而全面改善研究区域城市空间的适应性调节能力尚需一定的时间。

研究区域城市空间的计划性撤退能力的提升趋势不甚明显，除2014年及2017年外，其余年份的得分均位于−0.2～0分之间，推测可能源于长期以来相关部门对计划性撤退能力所对应指标的关注度有限。在主因子方面，城市应急通道网络建设覆盖率在近几年才逐步引起重视，政府部门于2022年印发《哈尔滨市突发公共事件总体应急预案（试行）》[75]，其中详细说明了灾害发生时的应急处置及应急保障措施，但未从城市空间层面提及具体的城市应急通道路径及场所。哈尔滨中心城区长期评分为负值的计划性撤退能力亟需增强。

4.3.2 气候适应性的空间分布特征

本研究将研究区域以主干路、快速路及镇域边界等为界，划分为48个片区单元，依据2017年（研究年份的最后一年）各项指标的数据值，为各单元气候适应性评价指标赋值用于开展空间分析。由于气候适应性的空间分布不会严格按照所选的道路及河流边界整齐分布，而插值分析可以对未采样的区域化变量取值进行最优估算，且计算的准确性及精度

较高[76]，因此本研究在ArcGIS10.3软件中采用Kriging插值势能分析[77]绘制了研究区域气候适应性的空间分布地图。此后，本研究借助ArcGIS10.3软件中常用的自然断点分级法[78][79]将评价结果划分为7级，进而对划分结果数值进行近似取整处理，以更清晰地反映研究区域气候适应性的空间分布特征（图3）。

哈尔滨中心城区城市空间的综合气候适应性评分较低，得分为正值的用地面积不足总面积的1%。得分低于−0.4分的区域占总研究区域用地面积的70%以上。同时，各市辖区的气候适应性存在较为显著的空间差异和要素发展不均衡现象，研究区域北部的气候适应性普遍优于南部，主城区的气候适应性性优于其他区域，总体呈现由城市中心向外放射的空间分布格局。

综合气候适应性能力得分相对较低（−0.7，−0.4］的区域分布较为集中，位于研究区域南部，区域内土地利用性质单一化的问题十分突出——包含众多工业企业，如重型机器制造厂、制药公司及工业物流园区等，加之能源消耗严重、长期职住分离，导致此区域保护修复能力得分较低。同时，研究年份内，分别位于中心城区东南部与西南部的阿城区与双城区陆续撤县设区，受此影响，部分土地利用结构发生变化，破坏了区域生态环境。以阿城区为例，耕地面积由2006年的9.34万公顷减少到2018年的7.25万公顷，这一变化对该区域的适应性调节能力造成了较大影响。

综合气候适应性能力得分中等（−0.4，0］的区域主要位于研究区域北部、中部偏南与东部区域。这部分区域大部分为哈尔滨的老旧中心城区，主要存在人口密度大、基础设施建设薄弱、建筑能源消耗较大、道路交通建设水平较低等问题，导致其适应性调节能力与计划性撤退能力均处于较低水平。此外，哈尔滨主城区道路网密集，应急通道数量不足且缺乏大型的应急疏散场所，导致该区域内部计划性撤退能力也相对较弱。

综合气候适应性能力相对较高（得分高于0）的区域全部位于研究区域内的沿江部分，区域内大多为哈尔滨近15年来新开发的地区，且部分片区属于哈尔滨新区重点建设区域，基础设施相对完善、绿化水平相对较高。此外，此区域受工业企业的污染影响较小，并有沿江、沿河通风廊道及城市绿地广场等冷岛要素，适应性调节能力相对较高。

5 哈尔滨中心城区城市空间的气候适应性提升策略应对

评价结果显示，哈尔滨中心城区城市空间的气候适应性呈现时空差异。在研究年份内，研究区域城市空间的气候适应性虽已逐步提升，但总体仍处于较低水平。同时，虽然大部分城市空间均存在交通出行及工业企业建筑能源消耗量大、城市空间形态不紧凑、绿地碳汇系统薄弱等共性问题[68]，但可以划分气候适应性城市空间分区以发现局地亟待解决的最主要矛盾。未来应依据气候适应性评价结果，提出相应的规划设计对策，以辅助中国严寒地区开展城市气候适应性规划行动、制定气候适应性决策。

5.1 将气候适应理念纳入国土空间规划编制过程

近年来，中国部分城市的规划编制体系已纳入对气候适应性的考虑，但相关内容仍以宏观、原则性的指导建议为主，导致规划成果在适应气候方面考虑不足。本研究以上述城市空间气候适应性评价指标体系中的主因子为例，依托《自然资源部关于全面开展国土空间规划工作的通知》[80]中市级国土空间总体规划的报批审查要点，借鉴相关文献中对各层次城市规划编制应对气候变化的主要内容[81][82]，试将气候适应理念纳入国土规划编制的过程，以期对哈尔滨国土空间总体规划气候适应性相关内容进行补充（表4）。

提升保护修复能力的主要途径包括建设城市地下空间或室内步行系统，以为城市居民提供冬季的气候防护；控制用地兼容性以提高土地和空间的利用效率；积极通过新型能源技术的应用增加城市冬季建筑清洁取暖比例。提升适应性调节能力的主要途径包括逐步完善城市轨道交通建设、优先保障城市冬季的交通运行效率；基于生态环保的顶层设计确定适应严寒气候特征的城市绿地空间布局方式及种植结构，进而提升城市整体的绿化覆盖率，在现有城市水系、沿江防护林带基础上划定城市通风廊道。提升计划性撤退能力的主要途径包括建立气候灾害的紧急预警体系、构建城市应急通道网络，为城市居民提供切实可行的措施以转移或分散风险。

5.2 制定气候适应性的城市分区管控措施

依据气候适应性评价结果，可针对性地提出分区管控措施，同时发挥各分区在气候适应上的协同效应，实现哈尔滨中心城区城市空间整体气候适应性的提升。南岗区中部、道里区北部等应主要以优化城市功能布局、调节人口密度等措施降低地域气候环境带来的不利影响；松北区、道外区东部等主要以加强土地功能混合与集约高效利用等措施增强气候适应性；双城区及阿城区外围面积较大的耕地破坏区域，应按照耕地面积不减少、质量不降低的要求维护气候安全；平房区与香坊区等应重点应对能源消耗严重问题，以提升气候适应性能力。

6 结论及展望

严寒地区气候条件复杂、易受气候变化影响。本研究立足于严寒地区的气候问题特征，综合考虑适应严寒地域气候与气候变化两方面气候问题，依据保护修复、适应性调节、计划性撤退三类策略构建中国严寒地区城市空间的气候适应性评价指标体系，以典型严寒地区城市哈尔滨的中心城区为研究对象展开评价，并基于结果分析提出相关规划设计

表 4：哈尔滨国土空间总体规划气候适应性内容补充要点

报批审查要点	气候适应性主因子	补充细节内容	气候适应性途径
城乡公共服务设施布局	室内步行系统覆盖率	确定室内步行系统的重点分布区域及建造形式，并积极拓展其他气候防护措施类型	保护修复
中心城区城市功能布局	用地兼容性	确定土地多功能混合的重点区域及土地相互兼容方式	
重要线性工程网络	建筑清洁取暖率	确定利用清洁能源进行建筑冬季取暖的比例，制定清洁能源消费目标	
	轨道交通运行比例	增加城市轨道交通覆盖面积，对轨道交通设施进行气候防护	适应性调节
	冬季交通运行指数	提升公共交通可达性，重点保障冬季交通运行效率	
城市结构性绿地的控制范围和均衡分布要求	绿化覆盖率	在提升城市绿化覆盖率的基础上，确定绿化覆盖面积中乔木种植比例及种植重点区域	
通风廊道的格局和控制要求	城市通风廊道建设覆盖率	确定以松花江、马家沟河两侧为主要生态屏障的城市通风廊道系统，构建层次分明、相互连通的生态空间体系	
城市安全与综合防灾体系	城市应急通道网络覆盖率	根据城市主干路、绿地及开放空间等确定应急疏散方向及主要场所	计划性撤退

对策。研究区域城市空间的气候适应性分布不均衡及协同不足问题，在中国严寒地区其他城市也有体现。本研究的城市空间气候适应性评价工作所依托的数据为2008～2017年，随着国家及地方政策的不断出台，近年部分评价指标（如建筑清洁取暖率、轨道交通出行比例）已有大幅提升，城市空间的气候适应性能力得到一定程度提升。未来，应进一步完善城市轨道交通建设、优先保障城市冬季交通运行效率、构建城市通风廊道等措施，逐步提升城市空间的气候适应性。由此，将气候适应理念纳入国土空间规划编制过程，并制定具有前瞻性的气候适应规划和协同政策设计，是提升中国严寒地区城市空间气候适应性的关键。本研究团队也将在后续研究中持续关注相关政策与城市空间建设发展进程。

由于城市系统自身的复杂性，不同规模的城市面对的气候适应性问题差异很大。本研究旨在探索中国严寒地区城市空间的气候适应性评价指标体系构建与应用，在指标体系的设计及运算方法方面还存在改进的空间。例如，未来应当结合特定的气候风险提出更具针对性的评价指标[83]，探讨除线性加权和法以外更为科学的指标运算方法，并在中国其他严寒地区城市进行评价验证、展开气候适应性的对比研究等。

本研究将为未来中国开展严寒地域气候背景下的国土空间规划体系编制、气候适应性专项规划研究等提供一定的参考，进而推动中国严寒地区城市的气候适应性建设，也对中国正在开展的气候适应型城市建设试点工作具有积极的借鉴意义。

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图 1. 严寒地区城市空间的气候问题特征、城市空间要素与气候适应性途径的相互作用关系
图 2. 哈尔滨中心城区城市空间的气候适应性动态变化图
图 3. 哈尔滨中心城区气候适应性空间分布特征：保护修复能力空间分布（图 3-1）；适应性调节能力空间分布（图 3-2）；计划性撤退能力空间分布（图 3-3）；综合气候适应性能力空间分布（图 3-4）