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Research progress and prospects of urban resilience in the perspective of climate change

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The natural hazards caused by climate change have a significant impact on the production and life of urban residents, enhancing urban resilience is an important way to cope with climate disasters and ensure the safety of urban systems. Based on the “urban resilience” research relevant literature, the paper applies bibliometric analysis software to reveal the research hotspots and evolution trends of urban resilience in the perspective of climate change. The results indicate that the main research contents can be summarized into four aspects: i) influencing factors of urban resilience; ii) evaluation index and method of urban resilience; iii) the impact of climate change on urban resilience; iv) Enhancing urban resilience in response to climate change. Finally, potential directions for future research on urban resilience were proposed, multi-dimensional research on urban resilience should be carried out from aspects of theoretical development, urban planning based on resilience mechanisms should be carried out from the perspective of planning practice, and innovation and reform should be carried out in policy implementation and urban management. Accurately understanding the conceptual connotation and construction mechanism of urban resilience is a crucial premise for climate mitigation and adaptation. Relevant research conclusions can provide useful reference for theoretical research and spatial planning of resilient cities.

KEYWORDS

urban resilience, climate change, urban system, nature-based solutions, sustainable development

1 Introduction

The global urbanization rate has exceeded 50% on average, and the number and density of urban population are rising every day. Cities are the centers of economic activities and innovation, as well as the main sources of energy consumption and greenhouse gas emissions (Kennedy et al., 2014; Zhao et al., 2020). The changes in urban development around the world will have a huge impact on global sustainable development after the novel coronavirus pneumonia (COVID-19). With the continuous deepening of urbanization, more and more people gather in cities, and the economic and population agglomeration function of cities are more prominent. At the same

time, meteorological disasters caused by extreme climate have become the main types of disasters threatening the security of urban space. The impact of climate change on cities has become increasingly significant. On the one hand, urban areas consume more energy and emit more greenhouse gases, which is the main cause of climate change; On the other hand, densely populated urban areas are extremely vulnerable to climate change, especially for the region's "most disadvantaged populations" (Klein et al., 2003; Hunt and Watkiss, 2011). Climate change has exacerbated existing urban problems and made cities more vulnerable (Adger et al., 2003; Tyler and Moench, 2012). Under the background of global climate change, various uncertain risks such as extreme climate and natural disasters have posed an important obstacle on human living environments and urban sustainable development. How to enhance the resilience of urban system has become a new problem for cities. Therefore, it is necessary to explore how to build a future city that can effectively resist the crisis and be inclusive by enhancing urban resilience.

The increase of extreme weather disasters caused by climate change continues to threaten the safety of human settlements and ecological security. Floods and droughts, food and water shortages, and climate disaster events adversely affect future urban land structure, infrastructure construction, as well as the life, welfare, and property of residents (Abel et al., 2011). Enhancing urban resilience is an important initiative to effectively avoid the loss of life and property caused by climate risks and to improve the wellbeing of society. In recent years, "urban resilience" has received a lot of attention in the field of urban planning and social governance (Ribeiro and Goncalves, 2019; Tong, 2021). Urban resilience is a new approach to urban risk management, it focuses on improving the ability of self-organization, functional coordination, and adaptability to uncertainties of the urban system (Ahern, 2011; Shao and Xu, 2015), pays attention to the plasticity of changes in natural and human factors (Xu et al., 2018), and pursues the concept of sustainable development of human and environmental systems. It can be seen that how cities can operate normally and maintain resilience in the face of increasing risks and challenges (Cai et al., 2012), and building climate resilient city has become a new project that needs to be studied urgently.

Urban resilience has become a new analysis tool and research perspective in the field of urban sustainable development and global environmental change (Li and Zhang, 2011; Zheng et al., 2018). In order to effectively reduce the damage caused by climate disasters to human economy and society, urban resilience can contribute to ecosystem resilience and human wellbeing through ecosystem services (Demuzere et al., 2014), thus is considered a widely adopted and effective approach for climate change mitigation and adaptation, while driving economic development and improving social wellbeing. City is a complex and diverse system, vulnerable to the impact of natural disasters. The Intergovernmental Panel on Climate Change (IPCC) pointed out that global warming has made extreme weather more frequent in various regions, and "climate-resilient pathway" as an important development strategy for mitigating and adapting to climate crisis (Denton et al., 2014). In addition to coping with climate risks, urban resilience also focuses on strengthening the city's overall anti-risk capabilities. In the face of risks or disturbances, cities can adapt and recover to the original state, and they can also predict, anticipate and prevent the risks and disturbances of climate change in advance

(Moser and Boykoff, 2013; Maru et al., 2014; Meerow et al., 2016; Shaker et al., 2019), which emphasizes the initiative and learning capacity of urban systems. Scientific diagnosis of climate risks and design of urban system development path according to different types of risks and adaptation goals (Tyler and Moench, 2012), which is an important branch of urban resilience. On the basis of sustainable development of cities from the perspective of climate change, this paper summarizes the progress of urban resilience, systematically sorts out the basic concepts and main research topics of urban resilience, and proposes the future development direction according to the current research trends, so as to provide support for the comprehensive research of multi-factor, multi-level and multi-objective urban resilience in the future. It provides reference for improving the ability of cities to cope with uncertainty and urban sustainable development research.

2 Materials and methods

2.1 Definition and scope

Climate change refers to the change of climate state caused by natural internal processes or external forcing, as well as the continuous change of atmospheric composition or land use by human activities. Climate change brings various problems, such as sea level rise due to global warming, and changes in the climate environment that make extreme weather such as droughts, floods, hail, storms and high temperatures frequent, which have a significant impact on human survival and activities (Jabareen, 2013). Urban resilience reflects the ability of urban systems to adapt and recover from risks such as natural disasters and major social events. Coping with natural disasters caused by climate change is one of the most important directions for building resilient cities, focusing on the long-term impact of urban systems on climate change processes and the comprehensive response to extreme climate disasters (Barbarossa et al., 2018).

2.2 Data sources

In order to explore the research progress and hotspots of urban resilience, the relevant literature data in this paper are from the core databases of "Web of Science" (WoS) and "China National Knowledge Infrastructure" (CNKI). We searched the literature database for topics (including subject, title or keywords) with "Urban Resilience + Climate Change" or "Resilient City + Climate Change", and other keywords or concepts related to resilience, such as "green infrastructure", "Climate change and disasters", "climate change impact"; The time span of literature retrieval was set from 2003 to 2022 (the retrieval time was February 2023); According to the above retrieval conditions, the advanced search method of WoS and CNKI database was used to cover all the literature as far as possible, and a data set of 1635 literatures related to urban resilience from 2003 to 2022 was preliminarily obtained. Therefore, a document-screening task was carried out manually, by further reading the title and abstract of the literature, the irrelevant literature was eliminated, and 559 valid literatures were retained.

2.3 Research methodology

Based on the “urban resilience” research related documents collected in WoS and CNKI core database from 2003 to 2022, this paper uses CiteSpace and VOSviewer two kinds of bibliometric software to analysis and knowledge visualization of the above datasets. The analysis function of CiteSpace can process the literature data with keyword co-occurrence and literature co-citation. The literature with strong co-citation is clustered by different algorithms, combined with data information such as high-frequency keyword matrix and highly cited literature, and then the literature clusters are named with nominal terms extracted from titles, abstracts or keywords. Through the induction method of co-occurrence clustering and high-frequency words analysis of keywords in domestic and foreign literatures, the hot topics of urban resilience research were analyzed, and the research hotspots and frontier issues of urban resilience were grasped based on keyword frequency map. The visual bibliometric analysis of literature was conducted by VOSviewer software to reveal main content of the literature. With the help of qualitative bibliometric analysis, the research hotspots, evolution trends and characteristics of urban resilience research can be obtained. The distribution structure, quantity change and correlation of literatures were conducted on the existing literature dataset and co-occurrence network of keywords, for better grasping the main research content and evolutionary relationship in current research.

3 Results and evolution trends

3.1 Research hotspots

Keywords are the author’s concise summary of the main idea of the article, which can reflect the hot topics in the research field. The VOSviewer software was used to statistic high-frequency keywords in the literature, and the frontier hotspots of urban resilience research were analyzed by visual clustering map. According to the keyword clustering map, resilience, urban resilience, vulnerability, sustainability, adaptation, risk, systems, governance, ecosystem services, challenges, infrastructure and green infrastructure are the keywords most frequently used by scholars in the study area of urban resilience.

The hot topics in the research field of urban resilience were displayed by using the co-occurrence function of the visualization software VOSviewer. We searched all keywords in the literature, high-frequency keywords were screened out, and a co-word knowledge graph is generated according to the core keywords (Figure 1). Combined with relevant literatures, four hot topics in the current international research on urban resilience were summarized: ecosystem resilience, infrastructure resilience, governance resilience, and urban sustainable transformation. From the major clusters recognized by Citespace, five topics were identified after reviewing the highly co-cited document in the clustering diagram. These topics were named as “urban heatwave and high temperature,” “urban waterlogging and flood,” “sea-level rise,” “forest wildfire,” and “Nature-based Solutions (NbS),” respectively.

3.2 Evolution trends

The concept of resilience has experienced three stages of evolution from engineering resilience (Berkes and Folke, 1998), ecological resilience to more complex social-ecological resilience (Carpenter et al., 2001; Folke, 2006). According to the sequence change of high-frequency co-occurrence keywords (Figure 2), the study of urban resilience has undergone a transformation from large-scale space to small-scale space. From the resilience of social ecosystems to resilient cities and resilient infrastructure, the spatial scale of resilience has gradually focused on cities and their internal spaces. More resilience studies of different types of small-scale spaces will become a useful supplement to the macro-and meso-scale studies of regions and cities.

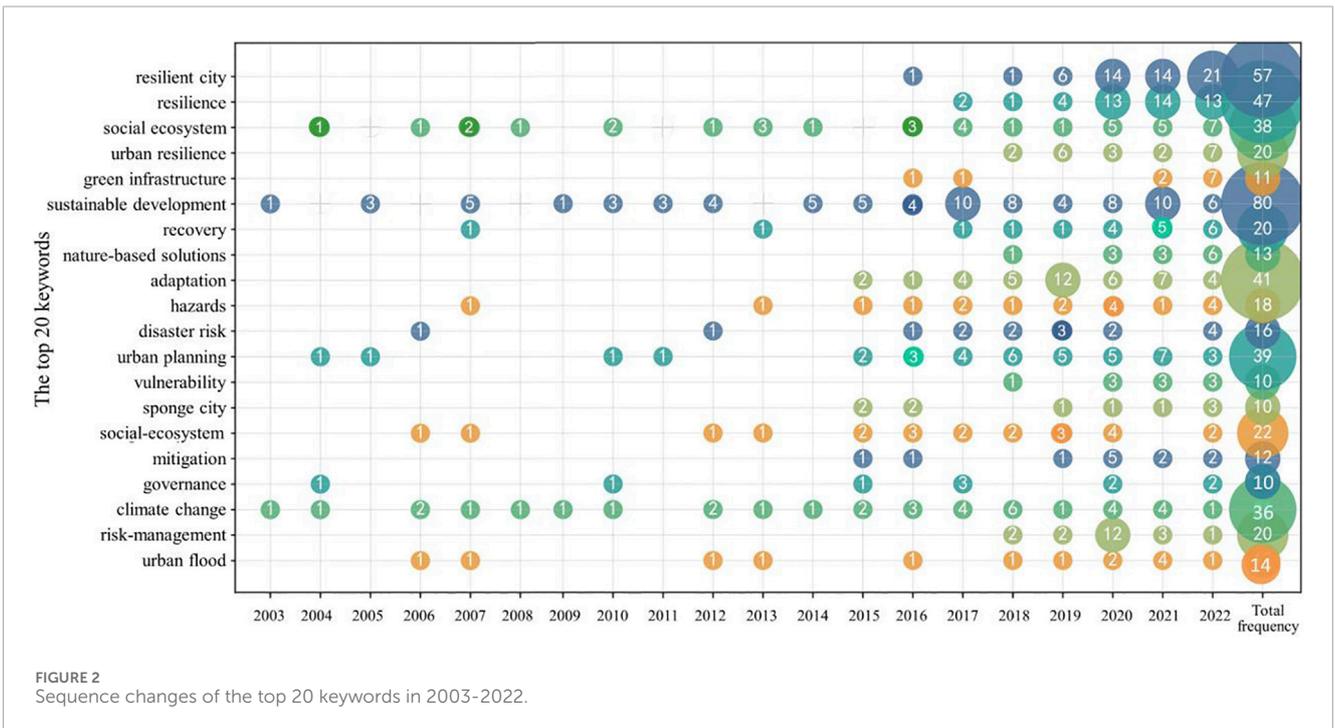
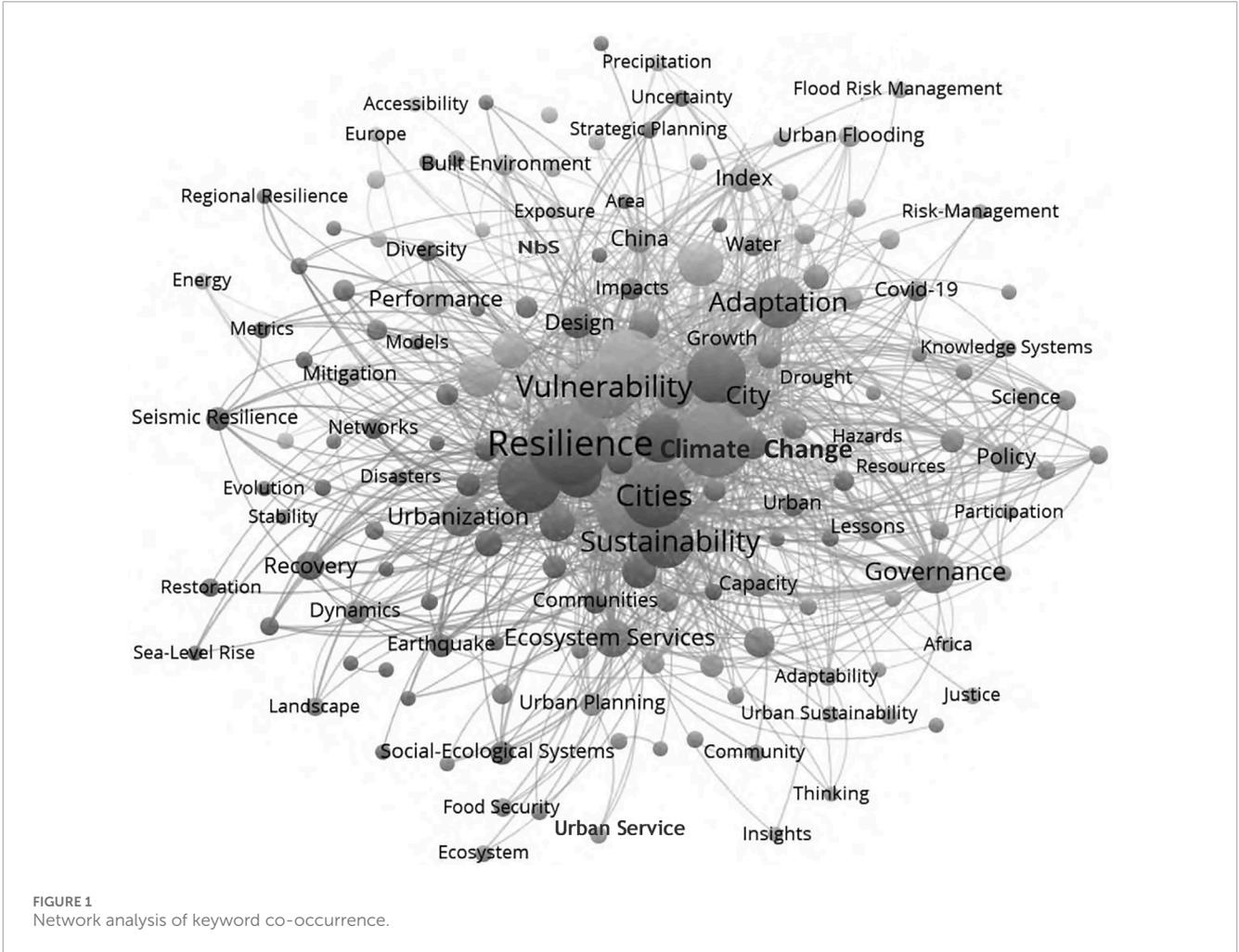
From the perspective of research fields and hotspots, the research on “urban resilience” has shown a trend towards a multidisciplinary field. The previous related papers mainly focused on the resilience and vulnerability of social ecosystems, including resilience to specific disasters, how to deal with urban risks has been a worldwide concern for a long time. The research direction has gradually expanded to resilient cities, sponge cities, green infrastructure, etc. It can be seen that the overall evolution trend of “urban resilience” research is its corresponding planning strategies, governance measures, evaluation methods and so on. In recent years, many studies have extensively explored the role of nature-based solutions in addressing climate change and natural disasters. Nature-based solutions enhance urban resilience in terms of both urban planning and infrastructure to address climate change mitigation and adaptation (He et al., 2023).

3.3 Main research content

In order to withstand the risks of climate change, urban systems need to have the ability to update, restructure and adapt. Enhancing urban resilience has become the best approach to urban sustainable development to effectively cope with various impacts or changes and reduce the vulnerability and uncertainty of the development process.

(1) Influencing factors of urban resilience

From the basic elements of urban composition, land use, economic development, housing, transportation, disaster and infrastructure plans affect the resilience of a city. Economic, social, and institutional factors influence urban resilience, and the level of urban economy determines the resilience of urban economic development and is the dominant factor affecting post-disaster economic resilience (Zhou et al., 2019). Climate change poses systemic and complex problems for urban planning and management at multiple levels and scales, which are difficult to be solved by traditional linear methods (Carter et al., 2015) and need to deal with problems at different levels from more dimensions. Policy intervention and institutional management play a lasting role in improving urban resilience and regional transformation (Dawley et al., 2010). Infrastructure plays an important role in ensuring sustainable urban development (Paul and Charles, 2012), reasonable urban spatial form can not only reduce the frequency and intensity of extreme climate disasters, but also enhance the



system resilience and adapt to climate change (Feng et al., 2020). Urban ecological environment aims to achieve specific goals such as maintaining biodiversity, reducing flood risk, alleviating heat island effect and safeguarding human settlement environment (Chad et al., 2018).

(2) Evaluation index and method of urban resilience

The main content of quantitative research on urban resilience is to construct an evaluation index system for resilience assessment, or to construct an economic or mathematical model (Sherrieb et al., 2010) for static resilience evaluation or analysis of influencing factors, in order to provide a basis for quantitative decision-making. Geographical location has an important effect on the distribution of spatial difference in urban disaster resilience, remote sensing models can assess the spatial heterogeneity and quantitative characterization of spatio-temporal evolution of urban resilience (Li and Zhai, 2017); Aiming at the goal of resilient community action, the evaluation index system of urban community resilience was preliminarily constructed from five dimensions of infrastructure, society, economy, institution and nature (Joerin et al., 2012); Assessing urban resilience through network resilience evaluation of network efficiency, diversity, and connectivity (Peng et al., 2018). Therefore, to better achieve urban resilience, the combined effects of physical, social, and natural factors need to be incorporated into the assessment of adaptive planning policies. However, how to evaluate the implementation effect of adaptive measures from multiple perspectives such as social, economic and ecological perspectives still needs more research and exploration (Han and Peng, 2019).

(3) The impact of climate change on urban resilience

Cities' response to climate risks depends on infrastructure standards, resource quality endowments and investment in environmental governance (Highfield et al., 2014; Han et al., 2021). Climate change is having a great impact on the space for human survival and activities, a series of natural disasters related to climate change have seriously threatened economic development, infrastructure operation, human health, and the safety of citizens' lives and property (Satterthwaite, 2013; Papa et al., 2015). This requires urban and regional development, especially in the layout of productive forces, urban and rural infrastructure construction and major project planning, to fully consider the requirements of adapting to climate change (Barbarossa et al., 2018). In the context of extreme weather occurs frequently, the risk uncertainty faced by cities has increased. Under the background of increasing uncertainty of disasters and risks, the concept of resilient city is further recognized and concerned by the academic community, and is considered as an important indicator and collaborative process of sustainable development (Magis, 2010; Ahern, 2011; Leichenko, 2011). Enhancing urban resilience is not only a strategic choice, but also a new paradigm of urban development in the context of climate change.

(4) Enhancing urban resilience in response to climate change

Numerous studies have presented strategies and practices to enhance urban resilience in various aspects from macroscopic urban morphological planning and microscopic spatial design (Wang and Zang, 2017), covering urban stormwater and water system resilience planning and design (Zhou and Li, 2017; Li et al., 2019; Zhang et al.,

2019), delta urban planning (Dai et al., 2017; Dai et al., 2019), and island planning and design (Wang et al., 2017; Bosselmann et al., 2019; Chen et al., 2019; Tu, 2019). Furthermore, the combination of grey and green infrastructures can reduce the reliance on the overall urban drainage system, urban woodland and sunken green spaces can effectively store and detain rainwater (Ahern, 2011; Casal-Campos et al., 2015; Meerow and Newell, 2017). Spatial planning has been widely accepted as an effective strategy responding to climate change and city safety problems caused by climate change and extreme weather events. Since spatial elements should be rationally distributed in land use and urban development regulations, to reduce the impact of climate disasters on cities, major infrastructure and important urban space needs to avoid climate-sensitive areas. In the process of building resilient cities to cope with climate change, the content of climate change adaptation should be incorporated into spatial planning, and a climate adaptation strategy featuring government-led and public participation should be formed in the planning system (Markolf et al., 2018).

4 Conclusion and future directions

Based on the perspective of climate change, this study tries to analyze the research hotspot, main research content, and the future directions of urban resilience. The high-frequency co-occurring words with urban resilience involve resilient city, vulnerability, sustainability, risk adaptation, system governance, ecosystem services, challenges, infrastructure construction, green infrastructure, reflecting the research hotspot in different stages. According to the existing literature, urban resilience construction is a comprehensive improvement of society, economy, ecology, infrastructure, and governance level. Urban resilience is enhanced through multiple means such as urban planning, infrastructure construction and maintenance, and institutional mechanism optimization, so that cities can integrating nature-based solutions for urban resilience to cope with extreme weather, and improve the resilience of cities to climate change.

The trend of climate change is inevitable, and urban resilience research has weaknesses in disaster prevention planning, resilience and spatial integration, and regional linkage. Adaptive measures should be taken as early as possible to reduce disaster risk and promote sustainable urban development. The current research progress mainly focuses on the mitigation and adaptation of urban resilience to climate change, as well as nature-based solutions to enhance urban resilience to reduce disaster risk. With the intensification of climate change, the frequency and intensity of extreme weather and climate events such as floods, droughts and high temperatures will also increase. It is particularly important to understand the sensitivity and vulnerability of urban systems to these changes. On this basis, a flexible and effective urban resilience planning program can be developed, taking into account social, economic and environmental interests.

Climate change brings various negative effects to human daily life and production, and thus poses a threat to sustainable urban development. Urban resilience is a hot topic on how urban space responds to natural disasters caused by climate change. The United Nations Human Settlements Programme (UN-Habitat) identified urban disaster risk management, urban economy and

society, resilient infrastructure and basic services, urban planning and environment, and urban governance as five pillars of urban resilience. Based on the analysis of the current research progress and predicament of urban resilience, the authors assume that more attention should be given to the following aspects:

- 1) Conduct multi-perspective systematic study on urban resilience. Faced with complex urban systems, future research on urban resilience needs to conduct a holistic evaluation of the interaction between urban systems and climate change. New technologies such as big data crawlers, sensor technology, digital image recognition, and interdisciplinary modeling methods can support resilience planning. Strengthen dynamic observation and research on human, logistics and information flows by means of emerging technologies, so as to improve the city's prediction and preparation for unknown risks. Planning for the construction of resilient urban infrastructure often includes nature-based solutions that can have a positive impact on the social and natural environment. Nature-based solutions for urban resilience are means of sustainable development with social, economic, and environmental benefits.
- 2) Planning and design city based on resilience mechanism. With the aggravation of climate change, it is urgent to improve the adaptability of cities in spatial planning system regarding resilience planning and risk reduction. The urban resilience mechanism covers the development process of the urban system and the whole life cycle. It emphasizes the systematic construction of planning techniques, construction standards, social governance and public participation to comprehensively enhance the structural adaptability of urban system, so as to enhance the overall resilience of the city. In planning and design practice, the resilience planning strategy of climate mitigation and adaptation is incorporated into the planning system, so as to promote achievement the goal of urban resilience to climate change.
- 3) Innovation and reform of urban governance and management system. In order to form a virtuous cycle of resilient urban construction, the institutional method of feedback mechanism is established from the effects and influencing factors of urban resilience practice. Explore the establishment of a resilience infrastructure project library and encourage the application of science and technology to promote the development and pilot of resilience projects. Innovate financing channels and public-private partnership models, increase investment in

urban resilience construction, and guide more social capital to invest in resilient infrastructure. Governments and financial institutions can further explore the ecological paths of urban resilience construction that combines resilient infrastructure with nature-based solutions.

Author contributions

WW and HW were in charge of designing the experiments and writing the manuscript. HW, XH, and HH were in charge of revising the manuscript. HW was in charge of project administration. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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