The application of resilience theory in urban development: a literature review

Li Kong1 · Xianzhong Mu1 · Guangwen Hu1 · Zheng Zhang1

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Abstract
In the complex context of urbanization and climate change, how to improve the resilience of cities to deal with various uncertain and unpredictable threats is a new topic with both theoretical and practical challenges. In this paper, the researches on urban resilience are summarized using the bibliometric analysis combined with the visualization analysis. We provide a systematic and objective review of resilience applied to urban development focusing on its conceptual frameworks, research tendencies, and assessment methods. The analysis results demonstrate that an increasing attention has been given to urban resilience, especially in the field of climate change. The degree of research varies significantly in different countries, with the USA dominating in the number of publications, followed by the UK and China. Scholars’ attention to urban resilience in different periods is closely related to the development background and disasters experienced by their countries, but there are also some commonalities. Meanwhile, the multi-dimensional research on urban resilience has been recognized by many scholars. Quantitative assessment tools such as simulation model and optimization model have been widely used to assess the level of urban resilience. Based on this, we put forward the future research trends in this field and provide a potential guide for future application of urban resilience.

Keywords Resilience · Urban development · Sustainable development · Bibliometric analysis · Visualization analysis · Development tendency

Introduction
The city is a highly concentrated area of population, industry, and wealth, and it is an important place for people to live and work (Bloom et al. 2008). Although cities account for only 2% of the earth’s surface, they consume 75% of the world’s resources (Madlener and Sunak 2011). Urbanization is an important phenomenon of urban development, which is related to the concentration of urban population, economic activities, and resource consumption. Given the continuous expansion in size and ongoing increase in complexity of cities, a proportionate increase in the vulnerability of cities to extreme events and disasters can be observed (Ribeiro and Pena Jardim Gonçalves 2019). Moreover, public health events could also have a great impact on cities, with the COVID-19 a clear example that trigger health, social, and economic consequences for cities (Wister and Speechley 2020). Surveys show that 95% of COVID-19 cases occur in urban settlements, affecting more than 1500 cities around the world (Zhu et al. 2020; Acuto et al. 2020).

Based on this premise, how to resist these potential hazards is a hot topic in the field of urban planning.

With the acceleration of urbanization, resilience, as an important frontier theory in the field of public security, provides a systematic framework for solving urban security risks and enhancing urban disaster resistance. Therefore, enhancing urban resilience has become a key link to achieve sustainable development under the increasing urban
pressure, and resilience theory has been gradually applied in urban management. As a new research perspective, resilience has become an important field of urban research and a priority goal of urban construction.

In the 1990s, the concept of resilience was first introduced into the field of urban management (Tobin 1999). In 2002, the International Council for Local Environmental Initiatives (ICLEI) proposed the topic of “resilient cities,” which was introduced into urban and disaster prevention research, setting off a wave of research on urban resilience (Motesharre et al. 2016). In 2013, the Rockefeller Foundation initiated the 100 Resilient Cities Program, with the goal of assisting cities around the world in becoming more resilient to the social, physical, and economic threats that increasingly affect the twenty-first century (Spaans and Waterhout 2017). Subsequently, the construction of resilient cities has been widely discussed and concerned in various cities. In London, The Risk Management and Resilience Program was published in 2011 to improve its ability to respond to extreme weather events and improve the living quality of citizens; New York introduced A Stronger, More Resilient New York plan in 2013, which laid out initiatives to build resilient cities; Tokyo put forward the Regional Plan of Metropolitan Territorial Strength and Resilience in 2016 (Guan and Gao 2021); and in China, academics and policymakers have an increasingly profound understanding of the role of resilience in the development and construction of cities, such as the proposal of “Sponge City” and “Park City.” In recent years, the urban master plans of Beijing, Shanghai, and other cities have emphasized “strengthening the ability of cities to cope with disasters and improving the resilience of cities” (Zheng and Lin 2017). On the whole, resilience theory expands the connotation and application of urban public safety management system (Shang and Huang 2020).

At present, how to effectively enhance urban resilience has emerged as an important research topic. In view of the urgent policy and practice needs of countries, this paper reviews literatures on urban resilience from three aspects: conceptual frameworks, research tendencies, and assessment methods, and summarizes the application of resilience theory in urban development. On the basis of reviewing and analyzing about the urban resilience literature, we put forward views on current trends and propose future research space.

Conceptual framework

Resilience

Resilience originally meant “bounce back” or “recover and return to the original state,” and the concept was first used in engineering and psychology (Klein et al. 2003). Most scholars take Holling’s research (Holling 1973) for the beginning of the modern resilience theory. He pointed out the multi-steady-state characteristics of ecosystems and used the concept of resilience to study system problems for the first time (Holling 1996). Then, the study of resilience further evolved from an early urban ecosystem to social-ecological systems that integrated social dimension (Folke 2006). In the context of social-ecological systems, resilience is related to the system’s ability to self-organize, learn, and adapt (Cumming and Peterson 2017; Sterk et al. 2017). Since then, resilience has been widely used in scientific fields.

The concept of resilience has developed in three main stages (Li et al. 2019): engineering resilience, ecological resilience, and evolutionary resilience. Engineering resilience assumes that the system exists in a single equilibrium state and focuses on the system’s resistance to impact and the speed of recovery to equilibrium state (Pendall et al. 2009), which is suitable for the study of physical systems; ecological resilience emphasizes that systems have multiple equilibrium states and reflects the ability of the system to absorb maximum impact before changing its structure and function to another equilibrium state (Reggiani 2013), which is mainly applied to the study of ecosystem; and evolutionary resilience is a long-term dynamic process (Hudson 2010) and it emphasizes the ability of a system to achieve long-term development by constantly adjusting its economic, social, and political structure to adapt to frequent disturbances, which is applicable to the study of economic systems. Evolutionary resilience concerns the dynamic disequilibrium evolution of the system and emphasizes the adaptability cycle of innovation and learning. Therefore, it is widely recognized and provides a profound theoretical foundation for the application and practice of resilience theory.

With the further expansion of research range, scholars and policymakers have paid more attention to the concept of resilience and put forward some general definitions. For example, Haines (2009) pointed out “resilience refers to the ability of a system to withstand significant damage under unacceptable degradation parameters and recover at an appropriate time and reasonable costs and risks.” The Intergovernmental Panel on Climate Change (IPCC) described the resilience as “a system’s ability to anticipate, absorb, accommodate, or recover from the impact of a hazardous event” (Rana 2020). Cinner and Barnes (2019) pointed out “resilience is commonly defined as the ability to cope with changing social or environmental conditions while maintaining main structural, functional, and identity elements.” Convertino and Valverde (2019) put forward “resilience can be seen as the response of a system to the observations or predictions of one or more definable risks.”

Bruce et al. (2020) defined resilience as “the ability of a system to persist, adapt and transform when conditions require it.” In addition, some scholars argued that...
“as a concept, resilience is both appealing and intimidating because it necessitates a coherent and multidisciplinary explanation” (Barrett et al. 2021). Although there is no consensus on defining resilience, some similarities can be observed in these definitions, which are based on the accepted characteristics of resilience: robustness, recoverability, redundancy, intelligence and adaptability etc.

In recent years, resilience has become a visible term and has been used to different fields of knowledge. Many other disciplines have started using the terminology, such as agriculture (Bahta and Myeki 2021; Córdoba Vargas et al. 2020), environment (Manyena et al. 2019), energy (He et al. 2017; Maryono et al. 2016), climate change (Heinzlef et al. 2020; Keshavarz and Moqadas 2021) and transportation (Leobons et al. 2019; Wang et al. 2020) etc. For the sake of study, the performance of resilience has aroused scholars’ discussion. Some scholars believe that resilience is reflected as a process of the system (Sherrieb et al. 2010), while others believe that it is a result and state that reflects the system capability (Kahan et al. 2009). Furthermore, some scholars believe that, ideally, resilience should be a combination of process and outcome states (Cox and Hamlen 2015; Cutter et al. 2008). The performance of resilience varies in different research fields slightly. Specifically, it is mainly manifested as resist, coping force, recover, and adapt in the field of infrastructure (Hosseini et al. 2016; Wu and Chen 2021); as the availability, accessibility, affordability, and acceptability of energy supply, transportation, and distribution in the field of energy (Sharifi and Yamagata 2016); and as community’s resources, ability to adapt and absorb disturbances in the field of society (Rapaport et al. 2018).

Urban resilience

The expansion of large cities and the increase of urban diseases are the problems facing the society today. In response to threats to urban survival and sustainable development, urban resilience has emerged. Compared with previous studies on urban risk, urban disaster, and urban vulnerability, urban resilience tends to mean how much risk a city can withstand and how long it can recover after a disaster. It is a comprehensive performance of improving urban risk resistance ability, reducing urban vulnerability, and reducing urban loss after disaster. By contrast, urban resilience is more strategic, global, and perspective (Zheng et al. 2018). A diagram of the related concepts is shown in Fig. 1. Since 2019, the impact of COVID-19 on urban areas has increased the focus on urban resilience (Kapucu et al. 2021).

The urban system consists of many interdependent and interactive networks containing different physical and social elements. The vulnerability of cities exists everywhere, from infrastructure to transport, energy and resource supply etc. Godschalk (2003) proposed that resilient cities are sustainable networks of physical system and human community which can manage extreme events and it must be able to survive and operate in the face of disaster. That is, urban resilience is a comprehensive concept that includes both “hard indicators” (infrastructure, transportation, etc.) and “soft indicators” (economic, social, etc.). Therefore, in the early years, urban resilience theory was applied in physical and socio-economic fields. Where, physical resilience mainly refers to the resilience of infrastructure (Dhar and Khirfan 2017; Spaans and Waterhout 2017), economic resilience mainly involves the healthy level of economic development (Klein et al. 2017), and social resilience refers to the recovery capacity of communities and people (Friend and Moench 2013).

With the emergence and prominence of many urban problems, the main concern of urban resilience research is to improve the capacity of cities to cope with various natural disasters and socio-economic risks under the background of climate change, globalization, and urbanization. These capabilities include the ability of cities to take measures before, during, and after destructive events to limit their negative impacts (Heinzlef et al. 2020) and also include the ability of cities to keep or restore to their intended functions in the face of disturbance on temporal and spatial scale (Meerow et al. 2016). Overall, urban resilience appears to be an appropriate response to the increased risk in urban areas.

The concept of “urban resilience” has developed from the technological sciences (Pimm 1988; Hollnagel and Woods 2006) and environmental and biosciences (Holling 1973, 1996; Adger et al. 2011). With the deepening of scholars’ understanding, resilience theory has been widely used in many fields of urban development. In different research fields, researchers have different priorities on urban resilience and have proposed different definitions, as shown in Table 1.
Combined with the literature review and Table 1, we can see that the definition of urban resilience is mainly proposed from two perspectives essentially. On the one hand, it is proposed in the wake of threats to the city, and on the other hand, it is proposed under the requirements of urban sustainability, aiming to improve the capacity of system services. Therefore, although there is some heterogeneity in definitions, there are correlations and similarities between them, and they are generally dynamic, malleable, and unbalanced (Li et al. 2021). However, it is worth noting that the dynamic and fuzzy definition of urban resilience also challenges the transformation of resilience from a theoretical concept into practical urban intervention measures (Brand and Jax 2007; Wardekker et al. 2020), which determines the difficulty of applying resilience into practice to some extent.

**Visualized analysis on urban resilience**

This paper analyzes the trends and characteristics of the research on urban resilience through bibliometric analysis combined with visualization analysis. The research tool in this part is Citeseer software, which is one of the most popular knowledge mapping tools created by Chen in 2004 (Chen 2004; Ji and Pei 2019). Specifically, in the retrieval process, “urban resilience” or “the resilience of city” or “resilient city” or “urban risk and recovery capability” or “urban disaster and recovery capability” are selected as the searching keywords from “Web of Science” and “Scopus” databases. Then, subjects with more than 100 literatures are selected as the search scope, then the first 3000 literatures in the two databases are selected according to the correlation

| Research fields | Definitions |
|-----------------|-------------|
| Environment     | (1) The responses of anthropogenic disturbance events to air quality under different macroeconomic backgrounds (Feng et al. 2022)  
(2) The ability to adapt against disturbances and maintain equilibrium by interconnections in human–environment systems (Li et al. 2018a)  
(3) The ability of a country or region’s economy to adapt to external shocks (Wang et al. 2021a) |
| Economy         | (1) The ability of the economic system to cope with external shocks and promote sustainable development (Zeng 2020)  
(2) The ability of an urban system to cope with external shocks and prevent potential losses at multiple levels of firm, family, market, and macro economy (Rose 2004)  
(3) The dynamic ability of a country or region’s economy to adapt to external shocks (Wang et al. 2021a) |
| Society         | (1) The ability of a city to respond to disturbance while remaining its function and structure (Lu and Stead 2013)  
(2) Community members perceive changes in the social environment and modify their behavior based on existing knowledge and learning (Aoki 2016)  
(3) The ability of social entities and mechanisms to take measures for predicting, absorbing, and adapting disasters, as well as to engage in recovery activities to reduce future damages and their effects (Saja et al. 2018)  
(4) The ability of physical systems to integrate with human communities in urban development (González et al. 2018) |
| Ecology         | (1) The core of ecological resilience is the connection between structure and function or process (Pickett et al. 2004)  
(2) The system can reach a new equilibrium through a series of processes such as resistance, absorption, repair, promotion, and learning in disturbance, emphasizing the ability of sustainable development of the system (Zang and Wang 2019)  
(3) The ability of an ecosystem to self-organize, and in the same conditions, the maximum amount of disturbance that the system can withstand (Zhang et al. 2020a)  
(4) The ability of ecological environment to bear the disturbance of external factors (Xiao et al. 2020) |
| Resource        | (1) The ability to deal with water related chronic stresses or sudden shock, including persistence, adaptability, and transformability (Arup 2019)  
(2) The ability of different energy systems withstands risk shocks and what factors determine the speed at which energy systems can recover from damage (Chen et al. 2020)  
(3) The capacity of energy systems to overcome disruptions caused by economic, social, environmental, and institutional shocks (Gatto and Drago 2020) |
| Transportation  | (1) An integrated, high level, all hazard, national incident management system (Reggiani 2013)  
(2) The ability of people, goods, repair, rescue, and disaster response teams to operate effectively (Serdar et al. 2022)  
(3) The ability of the transportation system to keep functionality in the face of perturbances, as well as the efficiency of restoring performance after disturbances (Chen et al. 2021) |
| Climate change  | (1) The degree of urban adaptation to climate-related disasters (Tong 2021)  
(2) The ability to reduce the vulnerability of cities’ natural resources and social economies to respond to climate risks (Zheng et al. 2018)  
(3) The ability of cities to cope with the shocks and stresses caused by climate change, as well as keep their function by adapting, recombination, and evolving to a desired and improved state (Folke 2006) |
| Planning        | (1) The ability to satisfy the needs and aspirations of residents and enable their innovation ability to be realized on the premise of ensuring the functional integrity of the city (Lwasa and Njenga 2012)  
(2) The ability to manage the environmental threats of adjusting social and institutional frameworks, mainly focus on improving physical and infrastructure to prevent interference (Lu and Stead 2013) |
ranking. On this basis, we use the “Remove Duplicates” function in Citespace to remove duplicate documents from the two databases, and use the remaining documents as samples for bibliometric analysis in our research. This section is carried out mainly from two aspects: publication outputs analysis and research countries analysis, so as to clarify the research status and main research topics of urban resilience deeply.

Analysis of publication outputs

Quantitative analysis of the publications

With the development of urban resilience theory, a substantial body of research has been published on urban resilience. In order to intuitively analyze the publication quantity of urban resilience in different periods, we display the annual publication trend of sample literatures in Fig. 2.

As illustrated in Fig. 2, the number of urban resilience publications increased in most years. In the last decade, the academic research on urban resilience had exploded, which is related to the accelerated development of urbanization (Wang and Xue 2019). On the whole, the research progress of urban resilience can be divided into three phases. The first phase is from 1990 to 2002, and the research on urban resilience is in the preliminary exploratory stage. In this period, the number of annual publications was almost constant, accounting for only 1.1% of the total output. The second phase is from 2003 to 2013. In this period, with the proposal of “Resilient City” in 2002, scholars began to pay attention to urban resilience and the number of published papers increased to a certain extent, accounting for 14.5% of the total output. The third phase is from 2014 to 2020. With the launch of the Global 100 Resilient Cities program, the number of publications has increased significantly, accounting for 84.4% of the total output. In general, there is an increasing trend in urban resilience field between 1990 and 2021, which indicates that more and more scholars have paid attention to the research on urban resilience.

Research topics analysis

Based on an overview of the definitions and theories of urban resilience, we find that the research on urban resilience is not limited to the original ecosystem, but across many fields, to the environment, resources, engineering, economy, management, and others. Therefore, in order to clear the main research topics and research tendency of scholars in the field of urban resilience, we made statistics on sample literatures based on keywords and selected the keywords with more than 10 occurrences for statistical analysis. The result is shown in Fig. 3.
In Fig. 3, each node represents a keyword and the node size indicates the number of occurrences of the corresponding keyword, connecting line between the nodes indicates that the linked keywords appear in the same literature, and the color of nodes and lines represents the year of research.

We can see from Fig. 3 that studies on urban resilience mainly focus on risk and disaster control in the fields of climate change, resource management, economic and social growth, environmental management, transport policy, infrastructure construction, urban planning, etc. Meanwhile, similar to the increase trend of publications in the “Quantitative analysis of the publications” section, the use of most keywords has increased significantly over the past decade.

Among the main fields, there are many studies on urban resilience taking climate change into account, and the related research appears earlier. Over the last decade, the extreme events associated with climate change have increased in frequency and intensity. Cities are important areas for population aggregation and industrial development, and they are greatly affected by extreme high temperature. Meanwhile, urbanization itself will cause “urban heat island” effect, so the influence of climate change on cities has always been a focus of attention. Therefore, more and more cities are adapting to climate risks, and building resilience is considered a critical response to climate change (Jacobson 2020; Adger 2000; Leykin et al. 2016). Subsequently, the study of urban climate change resilience has become a hot topic.

Scholars have studied how to improve urban climate resilience from many aspects. For example, secure and efficient storm water drainage is a significant challenge for cities in the context of climate change (Jiang et al. 2018; Kammen and Sunter 2016). Some scholars have applied the concept of resilience to the management of urban flooding in response to the vulnerability of society to flooding and climate change (de Koning et al. 2019; Djordjević et al. 2011; Wang et al. 2019). In addition, peri-urban areas are also typically very susceptible to climate impacts, resulting in vulnerable socio-ecological conditions that pose challenges to public health (Heyd 2021; Horton and Horton 2020). Some scholars have proposed the importance of improving urban climate resilience from the perspective of infectious diseases (Matthew et al. 2022; Semenza 2021). A review of relevant literature shows that the growth of cities and their surrounding areas is not only a result of climate change, but also a cause of climate change. At present, carbon neutrality is raising profound technical and economic transition globally. Hence, under the goal of achieving carbon neutrality, improving urban climate resilience is still one of the key directions of future research.

At the same time, some other fields have also attracted the attention of scholars. As for urban social resilience, since the vulnerability and risk diversity of urban society is obvious and worthy of attention (de Ruiter et al. 2020; Tilloy et al. 2019), the number of publications is also at a high level. In specific studies, it is critical to understand what kinds of civic organizations and activities can improve social resilience (Cutter 2015). Bixler et al. (2021) put forward that when city program staff and nonprofits join together, they gain a more holistic perspective on understanding vulnerability and strategies to enhance community resilience; as for urban infrastructure resilience, the concept of resilience has been applied to infrastructure systems widely. At present, green infrastructure is widely recognized as an important strategy for sustainable urban management, which aims to reduce flooding risk, improve water quality, and harvest
rainwater (Meerow and Newell 2017; Simić et al. 2017; Fu et al. 2021). Relevant studies mainly include the contribution evaluation of green infrastructure (Zuniga-Teran et al. 2020) and its function improvement strategies (Zhang et al. 2020b); as for urban economic resilience, the spread of the COVID-19 had a dramatic impact on the global economy, which highlighted the importance of improving economic resilience in the face of major shocks. Scholars mainly focused on the study of influencing factors (Tan et al. 2020) and promotion mechanism (Li and Zhang 2020; Wang et al. 2021a) of urban economic resilience; as for urban resource resilience, it is an emerging topic and existing researches focus on water management (Bruce et al. 2020; Boltz et al. 2019), energy policy (Maryono et al. 2016; Charani Shandiz et al. 2020), and land management (Du et al. 2020). Scholars have thoroughly investigated the features of human, society, and governance capacity required for urban resource resilience (Bruce et al. 2020; Esfandi et al. 2022; Sharifi and Yamagata 2016), which can promote the research in the later period; as for urban transportation resilience, the resilience evaluation of urban rail transit networks has become more and more popular in the past decades (Jin et al. 2014; Lu 2018; Zhang et al. 2018). Transportation infrastructure is critical in emergency management when disasters occur. Meanwhile, the resilience of the transportation system will have a key impact on the resilience of other urban systems and leads to changes in the overall resilience and stability of the city (Serdar et al. 2022). Therefore, improving transportation resilience plays an important role in achieving healthy urban development; Finally, resilience is considered the key to maintaining the sustainability of an ecosystem and urban ecological resilience is an important research field of early resilience theory (Colding 2007). With the deepening of research, the study of urban ecological resilience is not limited to a single field, but focuses on the combination of other fields. For example, some scholars have developed studies on the resilience of social-ecological systems (SES) (Botequilha-Leitão and Díaz-Varela 2020; Folke 2006; Sterk et al. 2017) and social-economic-ecological systems (SEES) (Wang et al. 2018).

Analysis of countries

Quantitative comparison of publications in different countries

The research of urban resilience in various countries is depicted based on Citespace software, as shown in Fig. 4. In Fig. 4, each node represents a country and the node size indicates the quantity of published papers from that country, connecting line between the nodes indicates that there is cooperation between connected countries, and the color of nodes and lines represents the year of research. Among them, the node with purple circle outside means its betweenness centrality is not less than 0.1, which is a key node in the network and represents that such countries are acting as a junction. The wider the purple circle, the greater the centralities of the country.

It can be seen that previous researches mainly focus on the Americas, Europe, Asia, and Oceania, among which the USA dominate the number of publications (535 publications), followed by UK (285 publications) and China (278 publications). The top 10 countries contribute to 62.3% of the total number of publications, and the degree of research varies significantly in different countries. Furthermore, the center color of the node where the USA is located is darker, indicating that the study of urban resilience in this country started earlier. Subsequently, the UK, Germany, and other
European countries also gradually began related research. It is worth mentioning that the research of Chinese scholars on urban resilience started relatively late, but ranked third in total publications, indicating that China is developing rapidly in this field.

Further, we can see that there has been extensive collaborative relationships between countries, especially the France, Sweden, USA, Germany, and Italy, which act as a junction. As more attention to urban resilience and increasing awareness of building resilient cities around the world, scholars from all over the world have carried out different degrees of cooperation. But, measures to improve resilience are different for particular countries facing different institutional environments and emergent risks (Coaffee 2013). Therefore, it is necessary for countries to mutually promote and learn among countries; at the same time, appropriate resilience indicators and coping strategies also should be developed for the specific conditions of different cities and regions to adapt to their long-term development.

**Evolution analysis of research topics in different countries**

In order to better understand the evolution trend of urban resilience and compare the differences among countries, considering that the use of keywords is closely related to the development of academic fields, we selected the countries with the top three publications (USA, UK, and China) and calculated the data of keywords with more than 10 occurrences into the timezone view. The results are shown in Fig. 5.

In Fig. 5, the meanings of node and connection lines are the same as in Fig. 3, and the year on the horizontal axis corresponding to each keyword node represents the year in which the keyword first appeared in sample literatures. In general, among the three countries, the USA started the research on urban resilience earliest, and China started the research last, which is consistent with the results in Fig. 4. Then, we analyze the evolution of research topics deeply in the three countries based on their policy and development background.

First, American scholars had conducted studies on urban resilience before 1990. During the sample period, researches with “human” as the keyword appeared earlier and were widely studied. Early studies mainly focused on the mental resilience of urban children (Parker et al. 1990; Wyman et al. 1991), adolescents (Luthar 1991; Luthar et al. 1993; Reynolds 1998), and some disease survivors (Rabkin et al. 1993; Siegel and Meyer 1999) in the face of different pressures. After 2000, the research on urban resilience gradually increased, and the growth tendency became more obvious after 2010. During this period, due to the adverse impact of climate change and some natural disasters, such as Hurricane Sandy, the USA began to consider disaster management and long-term response in the context of climate change risk from mechanism design. Then, many cities responded accordingly. In 2008, Chicago launched the Chicago Climate Action Plan to mitigate and adapt to the impacts of climate change; in 2013, New York introduced A Stronger, More Resilient New York plan, which directed scholars to study the recovery from Hurricane Sandy (Rosenzweig and Solecki 2014; Graham et al. 2016). Meanwhile, under the guidance of relevant policies, American scholars have conducted more extensive research on urban resilience, involving urban disasters such as hurricane and flood (Vugrin et al. 2011; Cutter 2015; Khazai et al. 2018; Deatrick 2015), urban resources such as water and energy (Milman and Short 2008; McPhearson et al. 2015; Raub et al. 2021; Buckley et al. 2021), urban ecology (Pickett et al. 2004; Menconi et al. 2020), urban society (McMillen et al. 2016), etc. Recently, the research on urban resilience in the context of COVID-19 also has attracted the attention of scholars (Schenk et al. 2021; Pietrzak et al. 2021). It is worth mentioning that the concern about climate change is obvious in various fields, and improving climate resilience has become a consensus among American scholars.

Second, British scholars began to carry out systematic research on urban resilience around 1998, but there were few studies before the twenty-first century. The fourth Assessment Report of IPCC, published in 2007, marked that the theme of “resilience” has become one of the core elements of urban planning in UK. Subsequently, researchers also recognized the importance of building resilience in urban development (Crichton 2007; Coaffee 2008). In earlier studies, the resilience theory was applied in urban flood management (McFadden et al. 2009; Djordjević et al. 2011), environmental management (Coaffee 2008), and water management (Brown et al. 2011; Yazdani et al. 2011) to some extent. At the same time, considerations of climate change were also beginning to appear in research (Charlesworth 2010; Djordjević et al. 2011). After 2012, the research of British scholars on urban resilience increased and the research field became more extensive, including the research on resilience in infrastructure (Blockley et al. 2012; Rogers et al. 2012), transport (Pregnolato et al. 2017) and ecology (Cavallaro et al. 2014; Dennis and James 2016), etc. Further, researches on urban resilience in the context of COVID-19 also have received attention from British academics after 2019 (Pelling et al. 2021; De Kock et al. 2021).

Third, Chinese scholars began to carry out systematic research on urban resilience around 2005. Similar to the USA and UK, the researches with “human” as the keyword appeared earlier and were widely studied during the sample period, among which the research on psychology was more prominent. More often than not, the outbreak of some disasters has intensified scholars’ concern on the resilience of human psychology. For example, Chen et al.
(2008) conducted a preliminary study on the psychological resilience of survivors after catastrophe; Bonanno et al. (2008) studied the mental resilience and dysfunction of SARS survivors in Hong Kong; and Hou et al. (2021) used a population-based study to research the probable anxiety and components of psychological resilience amid COVID-19. Otherwise, continuous industrialization and rapid urbanization have led to the rapid development of Chinese cities, but they are also facing the chronic pressure from “big-city diseases” such as resource shortage, environment deterioration, and traffic congestion. The Chinese government has proposed measures such as pilot projects to build “Sponge City” and “Park City” to improve urban resilience. Accordingly, researches on urban resilience of Chinese scholars have increased significantly, extending to many fields such as economy, ecology, and environment, among
which climate change has attracted more attention. Relevant researches have involved many cities such as Beijing (Yan and Xu 2010; Li et al. 2020), Nanjing (Wang et al. 2021b), Kunming (Wang et al. 2021a), etc.

On the whole, based on different national development backgrounds, scholars of the three countries attach great importance to the research of urban resilience and consider how to improve it to better cope with emergencies. Studies with “human” as the keyword appeared earlier in the three countries and there were many studies in the later period, which illustrated the important position of population factors in urban security. After 2012, with the rise of the topic of “resilient cities,” the research on urban resilience in all three countries has increased significantly in both the research field and research quantity, especially in the urban drainage system renovation, ecological environment management and water resource security, etc. At the same time, in the process of globalization and urbanization, researches on building resilient city to cope with climate change and achieve sustainable development have received increasing attention from the academic community. In addition, since 2019, with the outbreak of COVID-19, scholars from all three countries have applied the resilience theory to urban design and planning in the context of COVID-19.

**Urban resilience assessment**

Urban resilience assessment is the foundation of systematically understanding the concept of resilience and effectively promoting harmonization between theory and practice (Brown et al. 2018; Sun et al. 2021). The main step in improving urban resilience is to assess the current level of resilience. At present, since the vagueness and openness of the concept of urban resilience, the evaluation of urban resilience is still under development. This paper analyzes the situation of urban resilience assessment from three aspects of assessment dimensions, assessment indicators, and assessment methods.

**Assessment dimensions**

Before evaluating the resilience of a city, it is necessary to clarify the dimensions of assessment.

The research dimensions of urban resilience can be divided into single-dimension and multi-dimension. Due to the complexity of urban system, multi-dimensional evaluation system has been recognized by many scholars. UN Office for Disaster Risk Reduction (UNDRR) put forward two dimensions to build urban resilience: physical and environmental side and institutional side. Rockefeller Foundation proposed that the resilient city includes four dimensions: economy and society, health and well-being, infrastructure and eco-systems, and leadership and strategy (McGill 2020). In the study of urban resilience, scholars choose the research dimensions based on their own research objectives and emphases, which are summarized in Table 2.

As we can see from Table 2, scholars mainly choose various subsystems within urban system as the main dimension of resilience research and establish a multidimensional evaluation framework, in which social, economic, ecological, and environmental dimensions account for the majority. Future studies on urban resilience should still be guided by systematic principles and appropriate dimensions should be selected according to the purpose of evaluation.

**Assessment indicators**

In order to turn the resilient city, an abstract and complex system, into a measurable term, scholars attempt to develop resilience indicators. Before the selection of indicators, it is crucial to determine the evaluation criteria of urban resilience. Which can provide a yardstick to judge whether a city is resilient. Previously, some scholars put forward some evaluation criteria for urban resilience. Ahern (2011) proposed five urban planning and design strategies for building urban resilience, including multifunctionality, redundancy and modularization, (bio and social) diversity, multi-scale networks and connectivity, and adaptive planning and design; Carlos and Eduarda (2013) found that urban system resilience needs to be assessed against the criteria of multifunctionality, self-sufficiency, modularity, diversity, and flexibility related to learning and adaptability (past and present); Suárez et al. (2016) put forward the key factors for maintaining resilience in urban systems, including diversity, modularity, tightness of feedbacks, social cohesion, and innovation; and Zhang et al. (2020a) selected the assessment indicators of urban ecological resilience based on the resilience principles of diversity, slow variables, openness, social capital, and ecosystem services.

This paper mainly selects the general criteria of diversity, flexibility, modularity and redundancy, robustness, tight feedbacks, and innovation, and then summarizes their descriptive indicators. The results are shown in Table 3.

As can be seen from Table 3, scholars have proposed multiple indicators under different evaluation criteria and these indicators involve a wide range of issues. Evaluating the urban resilience through these indicators qualitatively or quantitatively would assist planners and policymakers in making an informed judgment about the current state of the city. The induction of the above indicators in this paper is of guiding significance to the establishment of the comprehensive evaluation framework of urban resilience.

In the process of study, it is critical to clear how each indicator promotes or hinders urban resilience. Meanwhile, it is worth noting that these indicators do not exist in
isolation; thus, their interconnections and how they reinforce one another should also be investigated. Based on different research needs, the importance of each indicator is different. In many researches, a methodology is usually chosen to quantify the relative weightings of indicators which include subjective and objective methods. The methods mainly focus on Delphi method, literature review, interview, analytic hierarchy process (AHP) and entropy method etc. Chen et al. (2016) constructed the evaluation index system of urban resilience using Delphi and AHP methods. Huang et al. (2021) used the literature review and Delphi method to identify the main influencing factors of urban resilience. Wang et al. (2021a) and Osman (2021) combined the literature research with interviews to determine the major indicators of urban resilience. Leobons et al. (2019) conducted a systematic literature review to identify the major indicators of resilience in transportation. Bai et al. (2019) established the comprehensive evaluation index system of urban resilience using entropy method. Moghadas et al. (2019) used a combination of the AHP and TOPSIS to get 15 Tehran’s urban districts ranked according to their resilience levels. Zhu et al. (2021) proposed a comprehensive evaluation framework of urban flood resilience by using VIKOR and gray relational analysis.

**Assessment methods**

Various mature methods for assessing urban resilience have appeared in different fields (Quinlan et al. 2016). The majority of evaluations of urban resilience are conducted from qualitative and quantitative aspects, including the assessment in a single field and the city as a whole.

**Qualitative resilience assessment**

In view of the openness and complexity of the concept of urban resilience, some scholars have adopted qualitative research. Hockings et al. (2009) proposed that qualitative assessments are appropriate when available data, resources, scope, scale, and time are limited and risks associated with follow-up activities are low. Generally, the level of veracity of qualitative assessments is considered sufficient for decision-making (Jacobson et al. 2011).

On the one hand, some qualitative assessments are adopted for feature analysis to explore the elements constituting urban resilience through questionnaires and interviews and assess the level of resilience development. Jozaei and Mitchell (2018) assessed the resilience of Tasmanian coastal governance through expert judgment on the important attributes identified in an online survey. Ling and Chiang (2018) assessed the main capabilities gained from climate change scenarios and flooding through the semi-structured interviews with 15 key retailers, focusing on the driver, pressure, state, impact, and response framework. Grefalda et al. (2020) evaluated the institutional resilience of local government units in Aurora in climate and disaster management based on a survey to 87 members of
the technical working group from eight municipalities and provincial government.

On the other hand, some qualitative assessments are used by designing an acceptable assessment framework to evaluate urban resilience. Saja et al. (2018) proposed the “5S” model of social resilience which is a development of existing framework of social resilience in previous literature. Scholars can use the framework to measure social resilience by selecting relevant characteristics. Wardekker et al. (2020) described a diagnostic tool, a three-step approach, which was intended specifically to support the process that policymakers and operators go through while assessing the resilience of their particular case. Roach and Al-Saidi (2021) used a holistic assessment framework of micro-level vulnerability and macro-level resilience to highlight main areas for improving resilience in urban water and energy supply conflicts in the Middle East and South Sudan.

In general, the advantage of qualitative methods is to make use of expert knowledge to the utmost extent, which can provide a comprehensive and systemic understanding of urban resilience. However, relying more on personal subjective information and judgment may also be the weakness of qualitative research.

**Quantitative resilience assessment**

Quantitative assessment is a numerical measure of the level of resilience. In the early years, some scholars used a definition-driven approach (Bruneau et al. 2003; Chang et al. 2004; Henry and Emmanuel Ramirez-Marquez 2012; Mugume et al. 2015) to the assessment of urban resilience when the theoretical system and conceptual framework of resilience were initially mature. Later, with the diversification of research fields, the assessment methods of urban resilience gradually diversified, including simulation model, optimization model, network analysis and spatial analysis, etc.

System dynamics (SD) is a kind of simulation model that can reveal the complex system’s internal motivation and structure, which has been applied in many research fields (Forrester 1987). In the field of resilience, SD model is used in the quantitative evaluation of urban resilience because it can clarify the causal relationships within urban system (Li et al. 2020). Datola et al. (2019) used the SD model to assess the impact of different resilience scenarios on urban systems. Li et al. (2020) established a SD model to clear the causal feedback and interaction mechanism among various components of urban resilience, and conducted an empirical study in Beijing. Li et al. (2021) developed a SD model of urban resilience that pay more attention to the multidimensional and evolutionary characteristics, which provided a supplement for the quantitative assessment of urban resilience. Mou et al. (2021) used the SD model to explore the
In some simulation processes, many scholars evaluate urban resilience by designing different scenarios. Scenario simulation plays an important role in the path selection of improving urban resilience. Dong et al. (2017) defined a new formula for system behavior simulation to assess the resilience of green and gray infrastructure to future changes under baseline scenario and future scenarios and in each future scenario, green and gray infrastructures with different scales were set up for simulation. Fu and Wang (2018) developed an integrative urban resilience capacity index (IURCI) to evaluate urban resilience and compared the IURCI values under different scenarios to get a preferred scenario. Chen et al. (2020) proposed a new model that can simulate the urban resilience under different disaster scenarios and then analyzed the key parameters of the model. Fu et al. (2021) developed a novel GIUR-PSS (green infrastructure in urban resilience planning support system) framework and designed five scenarios to assess the performance of green infrastructure in building urban resilience.

Optimization models are also a common method in urban resilience assessment. Promoting urban resilience necessitates a multi-criteria approach to achieve optimal solutions that solve the attention of all stakeholders and facilitate decision-making effectively. Therefore, multi-objective optimization model has been recognized by some scholars. As for the resilience evaluation of urban water system, Behzadian et al. (2014) set three objectives: resilience, reliability, and total cost, and determined optimal solutions by using multi-objective evolutionary algorithm. McClymont et al. (2020) established a resilience-driven optimization model, taking water quality and quantity as optimization objectives and their spatial distribution level as decision variables to conduct a multi-objective optimization and determine the suitable scheme. Liao et al. (2018) proposed an optimization model with dual constraints of budget and traverse time to assess and optimize transportation resilience under disaster risk. Bixler et al. (2021) put forward an approach for assessing multi-hazard risk that took into account exposure to multiple natural hazards as well as social vulnerability based on research and practice in Austin.

In addition, social network analysis (SNA) is a research method based on graph theory, probability theory, and geometry (Zaw and Lim 2017), which emplaces stakeholders in a social network composed of formal or informal relationships. This approach can provide communities with a clear roadmap to describe the characteristics and interrelationships of stakeholders in disaster management activities. Some scholars have applied this method to the resilience research of urban communities and organizations. Therrien et al. (2019) conducted a social network analysis of organizations working on climate change adaptation and resilience in the Montreal area to provide insights into policy implementation in these areas; Guarnacci (2016) applied SNA to disaster research and investigated community resilience following the December 2004 tsunami and the March 2005 earthquakes in Nias and Aceh, Indonesia; and Cui and Li (2020) calculated social capital of communities before, during, and after disasters according to SNA to evaluate the level of community resilience in Nanjing, China.

Recently, using spatial data to assess urban resilience is becoming more popular. As we all known, the geographic information system (GIS) enables data recording, analysis, and summarization at various spatial and temporal resolutions, as well as visualization through thematic maps and graphics that can improve policy-making (Małczewski 2006; Alberico et al. 2020). It mainly applied in the fields of urban planning and infrastructure design. On this basis, it is feasible and meaningful to analyze the spatial composition of risk using GIS. Lhomme et al. (2013) developed a Web-GIS for exploring the resistance, absorption, and recovery capacities of various technical networks. Li et al. (2014) assessed the spatial resilience by using an indicator-based system, a multi-criteria evaluation method, and spatial visualization based on GIS. Meerow and Newell (2017) applied the GISP model to obtain the degree of green infrastructure intervention required in different areas of Detroit.

Moreover, several other assessment methods are applied in various fields of urban resilience, for example, the CGE model for assessing economic resilience (Rose 2004), the network model for assessing transportation resilience (Chen et al. 2021; Tang et al. 2020), and the life cycle model for assessing infrastructure resilience (Liu et al. 2020).

At the same time, the mixed assessment combining qualitative and quantitative methods is also been applied by scholars. Zheng et al. (2018) explored the relationship between resilience and development by combining expert consultation and exploratory factor analysis; Bixler et al. (2020) linked the metropolitan networks to resilience planning and implementation by combining interviews and social network analysis; and considering that resilience reflects the system’s ability to adapt to the catastrophic shifts or the transitions between equilibrium states, Li et al. (2018b) proposed a new multi-stage framework to evaluate the abrupt change in state of resilience in urban socio-environmental systems based on the calculation of resilience values. Combined with an analysis of the tipping points, this multi-index evaluation method can be used to determine the early warning signal of socio-environmental systems; Sweetapple et al. (2019) captured a wide range of potential futures and identified of tipping points while illustrating the impact of increased resilience on sustainability in the design and operation of sewage systems.

Through the above review of methods, it can be seen that the assessment methods of urban resilience are mostly focused on a single field. This is because the single disasters
or specific field of urban resilience easier to exploit the causal mechanism and put forward the quantitative index. In comparison, the comprehensive resilience involves a wide range and has complex causal chains, making it difficult to conduct quantitative assessment. However, as a complex coupling system, the coordinated development among subsystems is a guarantee of the healthy and sustainable development of the city; thus, the comprehensive evaluation of urban resilience should be strengthened.

Conclusions

This paper conducts a comprehensive and objective review of urban resilience through bibliometric analysis combined with visualization analysis, highlighting its conceptual frameworks, research tendencies, and assessment methods. Some enlightening conclusions for urban resilience development can serve to provide in-depth understanding of the field as follows.

First, with the 100 Resilient Cities Program proposed in 2013, the research of urban resilience has increased significantly in both the research field and research quantity. Relevant research mainly focuses on risk and disaster control in the fields of climate change, resource management, economic and social growth, environmental management, transport policy, infrastructure construction, urban planning, etc. Thereinto, as a means to reduce the adverse effects caused by climate change, climatologists, especially those focusing on urban areas, are increasingly focusing on the study of urban climate resilience. They are trying to make cities more resilient to the shocks and stresses of climate change or other complex challenges.

Second, the degree of research varies significantly in different countries, with the USA dominating in the number of publications, followed by the UK and China. In addition, the research on urban resilience started early in the USA, followed by the UK, Germany, and other European countries. The research from Chinese scholars started late, but developed rapidly by comparison. Meanwhile, extensive cooperation has been carried out among countries on the study of urban resilience and a systematic research system has been established. In terms of the evolution of research topics, scholars’ attention to urban resilience in different periods is closely related to the development background and disasters experienced by their countries, but there are also some commonalities. Studies in three major countries all reflect that the important position of population factors and climate change in urban security. Moreover, since 2019, scholars have applied the resilience theory to urban design and planning in the context of COVID-19.

Third, according to the literature, there is heterogeneity in characteristics and definitions of urban resilience in academic views, but consensus has been basically reached. The depth and breadth of specific research has been expanded and the study of urban resilience has gradually shifted from theoretical exploration to practical application. Specifically, the multi-dimensional study of urban resilience has been recognized by many scholars, and according to different evaluation criteria, indicators covering a wide variety of issues have been proposed. Meanwhile, quantitative assessment tools such as simulation model, optimization model, network analysis, and spatial analysis have been widely used to evaluate the urban resilience.

It is possible to identify future development tendency of urban resilience by analyzing the main strengths and weaknesses of related research. Findings in this study specify the following research trends.

First, with the proposed goal of carbon neutrality, in the future, the study of urban climate resilience will continue to occupy an important place in the field of resilience. In the process of specific study, a standardized evaluation system of urban climate resilience should be developed based on urban risks brought by climate change, such as extreme weather and disease transmission. Meanwhile, the potential impact of climate change on various fields of the city should be considered to make the evaluation system more systematic and comprehensive. In the comprehensive evaluation of urban resilience, the importance of climate factors can be reflected by index weight.

Second, although it is necessary to establish a comprehensive evaluation system of urban resilience, it is difficult due to the complexity and dynamics of urban system and the wide range and complex causal chain of indicators. In future studies, there is a need to integrate knowledge from different fields to produce a clear operational definition and assessment criterion for urban resilience.

Furthermore, subsystems with close causal relationship and mechanism can be incorporated into the same framework, such as the socio-ecological system that have been studied. Then considering the coupling relationship and coordination mechanism among related subsystems of cities, the systematic research on urban resilience can be gradually promoted.

Third, the assessment of urban resilience has been widely discussed and concerned by scholars, which is also the basis for improving urban resilience. In future studies, the effectiveness and efficiency of different resilience enhancement ways can be compared by setting up different resilience improving scenarios, so as to determine the key measures suitable for various types of risks. Meanwhile, considering the dynamic nature of urban development, it is necessary to conduct the dynamic research on urban resilience and monitor the implementation effect of measures in different periods.
Overall, urban resilience has great research value in the present stage and resilience theory also has high application value in urban development. It is of great significance to promote urban sustainable development and improve urban functions and structure. This work will provide a potential guide for future research and application of urban resilience.

Author contribution Li Kong: literature search and data analysis; conceptualization; formal analysis; investigation; methodology; software; visualization; roles/writing—original draft.
Xianzhong Mu: project administration; supervision; funding acquisition.
Guangwen Hu: resources; investigation; writing—reviewing and editing.
Zheng Zhang: methodology; software; visualization.

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Declarations

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