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Spatiotemporal Dynamics and Mainstreaming Strategies of Ecosystem-Based Adaptation to Urban Climate Change

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Abstract: Cities worldwide are facing varying degrees of ongoing threats closely tied to climate change. Research is emerging that addresses climate risks as a pressing issue, especially for vulnerable cities in the Global South; however, there is a significant lack of systematic and application-oriented research on ecosystem-based adaptation to urban climate change. This study uses Shenyang in Northeast China as a case study, employing multisource data and integrated methods to examine and depict the dynamics of urban ecosystem-based adaptation to climate change amid rapid urbanization. The results indicate a decline in capacity for climate change adaptation during the study period. A framework for mainstreaming ecosystem-based adaptation is proposed, identifying specific strategies for climate change mitigation and adaptation in urban policy and planning processes in Shenyang. It also has significance for other cities to draw lessons from. By linking urban ecosystem dynamics, the capacity for urban climate adaptation, and sustainable urban governance, this study bridges the gap between research and practice in urban climate change adaptation, and expands the contribution of geography-based interdisciplinary integration to urban resilience. More practically, it provides references for Shenyang in adapting to climate change and transitioning to sustainable development.

Keywords: climate risk; ecosystem services; temperature regulation; urban adaptation strategy; Shenyang

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1. Introduction

Climate-related risks have emerged as a significant threat in the Anthropocene era [1,2]. The summer of 2023 saw severe heatwaves in Europe, India, and the United States. China experienced challenges not only with extreme heat but also with catastrophic flooding, while the Horn of Africa struggled with a persistent drought, considered to be the most severe in the last four decades [3]. Cities, as hubs of human activity, typically serve as major contributors to, and primary recipients of, these challenges. The interaction between the impacts of climate change and complex human activities has exacerbated the challenges faced by modern cities, subjecting them to unprecedented tests in terms of resilience, livability, and sustainable development [4]. Due to the high concentration and interconnectedness of valuable assets, urban areas, megacities in particular are prone to incurring incalculable losses in social, economic, and environmental domains when disasters strike [5].

The ability of cities to mitigate and adapt to disaster risks is becoming increasingly crucial due to the growing complexity of the risks facing them [6]; however, current approaches to disaster risk reduction focus excessively on strengthening the resistance capacity and standards of infrastructure facilities, which are evidently passive and unsustainable, and may exacerbate the sensitivity and vulnerability of urban systems [7]. This stems from the fact that these approaches typically adhere to an engineering mindset, relying heavily on reinforcement and reconstruction to enhance resilience [8]. While beneficial for enhancing robustness and durability, these approaches will inevitably compromise the long-term flexibility and adaptability of urban systems [9]. As emerging hazards are likely to surpass human knowledge and experience, passive endeavors like these are increasingly inadequate for timely and effective adaptation, reduction, and mitigation.

The adoption of an ecosystem-based approach to absorb risks and enhance resilience is gradually gaining acceptance in cities worldwide [10]. Specifically, when cities are considered socio-ecological systems, they are not isolated combinations of natural and human elements but, rather, interconnected, interdependent entities. The sustainable development of this integrated system does not aim solely for an optimal form but, rather, relies on the coordination and mutual promotion of internal components [11]. Since the framework of socio-ecological systems acknowledges the substantial impact and strong interdependence of social factors on ecological conditions (as well as advocating for the crucial role of ecological factors), the ecosystem-based approach is indispensable for the resilience and sustainability of urban systems, providing significant insights for addressing current environmental crises [12].

Ecosystem-based Adaptation (EbA) was officially proposed in 2009 by the United Nations Convention on Biological Diversity (CBD) and subsequently included in policies enacted by the European Commission [13–15]. EbA emphasizes the utilization of nature's potential, including biodiversity and ecosystem services, in adapting to the adverse effects of climate change and driving sustainability transitions, offering a cost-effective, multifunctional approach to achieving both environmental and social objectives [16,17]. As a relatively novel approach to addressing climate change challenges amid rapid urbanization, EbA aims to reconnect urban areas and degraded ecosystems to natural systems, leveraging nature's inherent power to respond to long-term environmental changes, which can also be seen as a consequence of the ecosystem services concept [18,19]. It is generally recognized that EbA is a subset of Nature-based Solutions (NbS), which is an umbrella term for ecosystem-based solutions and includes various approaches such as Ecosystem-based Adaptation (EbA), Ecosystem-based Disaster Risk Reduction (DRR), and Ecosystem-based Mitigation [20]. Another study also suggests that EbA and NbS have similar meanings, both referring to a nature-based approach in the context of climate change adaptation [21]. Overall, EbA is beneficial for improving the strained relationship between humans and the environment in cities, enhancing the resilience of urban social-ecological systems, especially against climate risks [22].

Although EbA is crucial for sustainability in most cities, research on EbA or NbS remains insufficient despite considerable progress. There is a notable absence of clearly articulated research on the effectiveness of the ecosystem-based approach for mitigating and adapting to climate change impacts [23]. Moreover, while there is academic and governmental consensus on improving and transforming current approaches to responding to the dynamics of climate change impacts, barriers and inertia hinder practical implementation [24]. This disparity indicates that the adaptation solution, from a social-ecological perspective, has not yet been mainstreamed and does not currently play a large role in wide adaptation practices, highlighting the need for further strengthening [25]. With a deeper understanding of the value of nature and its benefits to society, EbA for urban climate change should strive to address climate change risks by harnessing the potential of nature to generate ecosystem services, ultimately contributing significantly to enhancing climate resilience and urban sustainability.

The rapid pace of urbanization, coupled with the effect of urbanization on global climate change, has triggered profound changes in urban ecosystems, resulting in a significant decline in the provision of ecosystem services and an increased exposure to risks [26]. This greatly increases the probability of intense disasters and damages. Chinese cities have frequently experienced extreme high temperatures and heavy rainfall over the past decade, resulting in significant impacts on the urban economy and society. Although China has implemented a series of strategies and actions to address climate change, especially since joining the Paris Agreement, and is actively participating in global climate governance, it is faced with intertwined, complex risks in terms of its urbanization, which is still rapidly developing. The rapid urbanization process is expected to further exacerbate resource and environment conflicts, leading to irreversible changes in human–geographical relationships and intensifying the challenges of uncertainty faced by cities.

Evidence shows that the number of cities in China affected by floods has been increasing, with about two-thirds experiencing waterlogging, with 25% of those submerged for over 12 h during the worst serious floods [27]. Particularly in megacities like Shenyang, due to continuous heavy rainfall exceeding drainage capacity, the phenomenon of "seeing the sea from a city" has become common in recent years [28]. Flooding becomes one of the main challenges to cities during summer. In addition, secondary disasters caused by heavy rain and floods can also threaten multiple sectors in cities, such as industrial and agricultural production, transportation, and electricity, severely affecting the normal life, production, and travel of urban residents, and even causing permanent damage or destruction. Therefore, this research focuses on the evolutionary dynamics of EbA to climate change in Shenyang, which is important and urgent, and it will contribute to informed decision making in urban climate change adaptation governance.

Although ecosystem-based approaches are receiving increasing attention from the fields of science, policy, and practice, they have seldom been concretely discussed in terms of their mechanisms, practical applications to urban climate change adaptation, and their wide range of sustainable development co-benefits. Existing research indicates that urban development plans significantly influence the advancement of EbA and the provision of ecosystem services [29]. However, some scholars point out that, while ecosystem services are recognized for their vital role in urban resilience and sustainable transformation, there remain many gray areas in both the theory and application of ecosystem services [30]. Most notably, this concept has not been adequately valued in research related to the specific principle of urban resilience, nor has it been fully and time-effectively integrated into urban development practices [31]. Therefore, it becomes imperative to focus on strengthening and mainstreaming EbA, and incorporating the use of ecosystem services in urban development planning and decision-making processes. Introducing EbA into climate change adaptation in Shenyang city establishes a bridge between the dynamics of urban ecosystems, climate adaptation capacity, and urban development and governance practices, narrowing the gap between theoretical knowledge and practical application.

The following sections are organized as follows: Section 2 examines the relationship between urban ecosystems, ecosystem services, and climate change adaptation, elucidating the mechanisms of EbA following Section 1. Subsequently, Section 3 introduces the study area and data sources and processing, as well as the main research methods. Then, Section 4 presents the temporal and spatial patterns and evolutionary characteristics of EbA in Shenyang. Then, Section 5 puts forth a framework and operationalized strategies for enabling EbA mainstreaming in urban development processes. Section 6 mainly focuses on the effectiveness of EbA, progress of EbA, and the contribution of this research. Finally, Section 7 summarizes the main findings of the paper.

2. Literature Review

2.1. Urban Ecosystem, Ecosystem Services, and Climate Change Adaptation

Traditional approaches to addressing climate-related risks in urban areas have relied heavily on engineering techniques, posing challenges in effectively tackling the unprecedented complexity and uncertain impacts of climate change. There is a growing shift towards developing ecosystem-based solutions for climate change mitigation and adaptation, particularly in light of increasing global climate risks, notably in European countries. The crux of this solution lies in harnessing the full benefits that urban ecosystems provide to humans; these are known as ecosystem services (ES). The concept of ES, initially proposed by Ehrlich and Ehrlich in the early 1980s, has gained prominence and become a central focus in urban climate change adaptation due to its insurance and option values [32]. The insurance value ensures a continuous supply of essential natural benefits to combat climate challenges, while the option value involves maintaining these benefits for various purposes and making reversible decisions in response to different climate risks and disasters [33]. Urban adaptation, especially amid rapid urbanization and escalating climate risks, relies on the strategic delivery of diverse ES; for example, wetlands help mitigate storm surges, urban forests contribute to alleviating heatwaves, and urban parks serve as sites for nucleic acid detection amid the COVID-19 pandemic. Urban adaptation requires not only a variety of ES but their resilient provision as well [34]. This necessitates urban ecosystems to maintain biodiversity and ensure spatial and temporal alignment in the supply and demand of ES.

2.2. Mechanisms and Measuremens of EbA

Urban ecosystems play crucial roles in mitigating and adapting to climate change through mechanisms such as climate regulation, temperature regulation, air quality improvement, and stormwater management, supported by the resilient production and provision of ecosystem services (ES).

2.2.1. Climate Regulation

The rise in greenhouse gas concentrations in the atmosphere, driven by natural and anthropogenic factors, significantly contributes to global warming [35]. Ecosystems play a crucial role in reducing greenhouse gas concentrations, such as carbon dioxide, through carbon sequestration from various natural sources like forests, wetlands, microorganisms, soils, water bodies, and animals, primarily supported by biodiversity. This process mitigates the impacts and challenges posed by escalating global warming [36]. It is estimated that terrestrial ecosystems annually absorb approximately 3 billion tons of carbon dioxide from the atmosphere through photosynthesis, which is roughly equivalent to 30% of human-generated carbon dioxide emissions [37,38]. Additionally, different ecosystem types exhibit varying capacities for carbon storage, based on their biological and non-biological characteristics (see Table 1). The human-induced degradation of ecological components and structures significantly diminishes the carbon storage capacity of ecosystems [39]. Therefore, safeguarding urban ecosystems from destruction enhances their capacity for carbon sequestration, thereby reducing greenhouse gas concentrations in the atmosphere and mitigating the challenges associated with global warming.

Table 1. Estimation of Terrestrial Ecosystem Carbon Sequestration (Pg).

Component	**Carbon Sequestration**	**Component**	**Carbon Sequestration**
Plants	650	Soil inorganic carbon	1700
Plant roots	280	Frozen soil	1700
Soil microorganisms	110	Peatlands	600
Soil organic carbon	1600~2300		

Note: 1 Pg = (1 Pg = 1015 g). Source: Reference [24].

2.2.2. Temperature Regulation

Against the backdrop of global warming, heatwaves have become increasingly common, with adverse effects on human health and socio-economic development, and some evolving into meteorological disasters closely linked to human fatalities. According to statistics from the World Health Organization (WHO), the number of global heat-related deaths has increased rapidly, affecting over 166,000 people from 1998 to 2017. The growth rate of death tolls and the destruction caused by heatwaves are much higher than the sum of all other extreme weather events [40]. Coupled with the urban heat island (UHI) effect, the duration and intensity of heat may be significantly exacerbated in cities, exposing urban residents to more severe living conditions [8,41]. An urban ecosystem can alleviate heatwaves through shading and transpiration processes [42]. Tall green vegetation can reduce the absorption and storage of solar radiation by the ground, by intercepting and reflecting sunlight, thereby creating shading effects. Green vegetation can increase atmospheric humidity and lower temperatures by transpiration. These two ecological processes together contribute to controlling temperature increases in nearby areas, thus playing a vital role in mitigating and adapting to the impacts of urban heatwaves and UHI [43,44]. Research by Bounoua et al. showed that the temperature of impermeable surfaces in summer is, on average, 2 °C higher than permeable surfaces [45]. Similarly, Reis et al. have pointed out that an area of vegetation coverage of 50 square meters can reduce the temperature by 1 °C [46]. Moreover, as the spatial scale of the urban ecosystem increases, its potential for cooling and improving human thermal comfort will greatly enhance.

2.2.3. Air Quality Improvement

Air pollution is one of the frequent challenges currently faced by cities. With human production and living activities in urban areas rapidly increasing, the urban energy consumption structure is changing, resulting in a continuous increase in urban pollutant emissions [47]. At the same time, the ability of urban ecosystems to reduce air pollutants has been greatly weakened due to continuous compression and erosion, leading to the deterioration of urban air quality [48]. Additionally, climate change also has a negative impact on air quality. Polluted air seriously threatens the physical health of urban residents and the livability of the urban environment [49]. According to statistics from WHO, more than 90% of the total population lives below the standard air quality line [50]. Every year, about 3.7 million people die prematurely due to air pollution, mainly in urban areas. Urban ecosystems have the function of improving air quality. Green vegetation is proficient in absorbing, decomposing, and transforming harmful gases such as NO_2 and SO_2 through biophysical processes [51]. It can also block and adsorb dust and particulate pollutants such as $PM_{2.5}$ and PM_{10}. Additionally, some plants kill pathogens in the air by secreting volatile organic compounds and reducing O_3 levels. Studies have shown that the role of forests is often prominent, although almost all green infrastructure has the function of improving air quality, because trees have a larger leaf area compared to other plants [52].

2.2.4. Stormwater Management

A recent study has shown that green infrastructure can regulate surface runoff by maintaining or restoring it to natural levels; this is the hydrological regulation process [53]. Specifically, tree crowns and green roofs can retain rainwater before it reaches the ground, and they also play an active role in evaporation and infiltration. Urban green spaces help promote the infiltration of rainwater, thereby reducing the volume of runoff [54,55]. Urban wetlands can serve as flood storage and water conservation areas [56]; therefore, green infrastructure is considered to address flood risk effectively. Compared to traditional flood control and resistance strategies, which only focus on drainage efficiency, the ecosystem-based approach makes a prominent contribution in its versatility [57]. It can achieve the cross-scale control of rainfall runoff through plant infiltration, evaporation, and transpiration, and achieves pollutant reduction through deposition and plant absorption, etc. It improves air quality as well, regulating local temperatures and creating diverse livable environments [27]. However, considering its multifaceted benefits and cost-effectiveness, green infrastructure, compared to grey infrastructure, emerges as a more advantageous approach when dealing with climate change risks [58].

3. Data and Methods

3.1. Study Area

Shenyang city is situated at the geographical center of northeast Asia, in China, between 41°48′11.75″ N and 123°25′31.18″ E (see Figure 1). Serving as the capital city of Liaoning Province, it functions as a hub for economic, cultural, transportation, and commercial activities in Northeast China, and it is counted among the 21 megacities in China. Moreover, it plays a crucial role as a connecting point for the Belt and Road Initiative's expansion into northeastern and Southeast Asia. Established as one of China's national key industrial bases during the early years of the People's Republic of China, Shenyang boasts a robust industrial foundation and a diverse industrial landscape, with a primary focus on equipment manufacturing. It remains the largest central city and the most advanced center for equipment manufacturing and technological innovation in Northeast China. Presently, it is accelerating the development of a national central city, an advanced equipment manufacturing base, and an ecologically sustainable city, while actively promoting the comprehensive revitalization of old industrial bases.

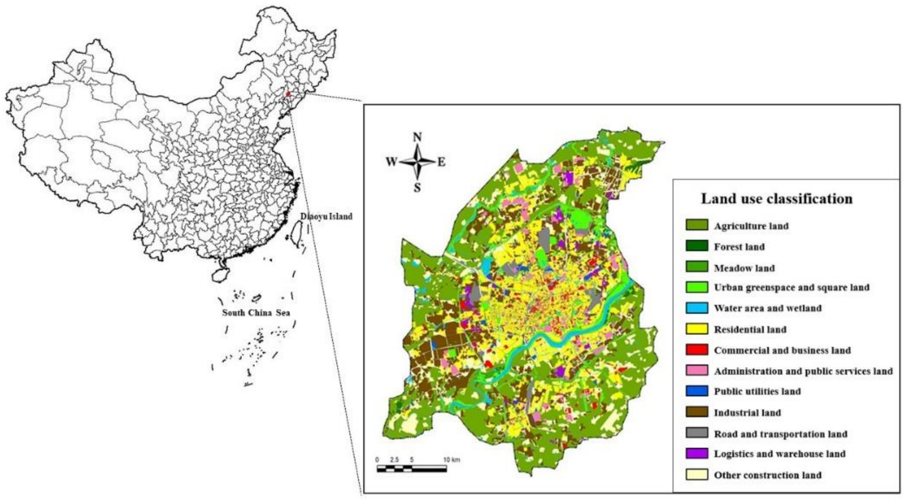

Figure 1. Location map of the study area.

It is noteworthy that, despite the significant population outflow in Northeast China in recent years, the population of Shenyang has been steadily increasing, making it one of the main drivers of the new urbanization process in the region. In 2015, Shenyang's permanent population reached 8.5 million, covering an area of 12,860 square kilometers. The population of the central urban area was approximately 5.2 million, occupying an area of 1353 square kilometers. With the city's scale continuously expanding and urbanization progressing rapidly, the urbanization rate had reached nearly 80% by 2015 (see Figure 2). Consequently, there have been significant changes in the urban landscape, accompanied by a rise in urban–rural conflicts and related issues.

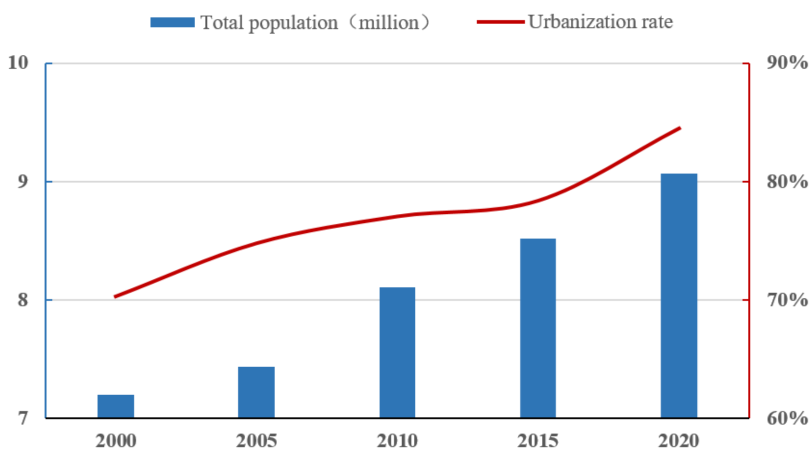

Figure 2. The resident population and urbanization rate of Shenyang from 2000 to 2020.

Shenyang is among the 60 Chinese cities severely affected by waterlogging disasters. The inadequate and uneven distribution of urban drainage pipelines, coupled with the continuous spread of impervious ground, have hindered rainwater infiltration and increased total runoff. The main areas prone to waterlogging are concentrated in the busiest parts of the city, such as Taiyuan Street and Jinlang Avenue, and other areas with low elevation, drainage system endpoints, or underpass bridges. In response to the Ministry of Housing and Urban–Rural Development of the People's Republic of China's requirements, the Shenyang Drainage and Flood Control Action Plan has been issued. This plan aims to enhance and expand drainage and flood control facilities at over a hundred vulnerable points in the city. However, the complexity and uncertainty of rain-flood hazards often lead to the rigidity and inefficacy of these heavily burdened flood control and drainage systems, making it challenging to promptly address the increasingly diverse demands of urban waterlogging.

3.2. Data Source and Processing

The effectiveness of EbA depends on the functioning of four processes: climate regulation, temperature regulation, air quality improvement, and stormwater management. Four indicators, namely carbon sequestration, cooling contribution, O_3 dry deposition rate, and surface runoff coefficient, are used to represent and assess the urban ecosystem's dynamics and its capacity for climate adaptation (see Table 2). Additionally, calculating carbon sequestration requires carbon density data obtained from the IPCC official website (https://www.ipcc.ch/data/, accessed on 15 March 2019). The Digital Elevation Model (DEM) data needed for calculating the surface runoff coefficient are generated using the ArcGIS software 10.1 platform, based on Landsat imagery of the study area, which involves steps such as terrain extraction and elevation calculation.

Table 2. Indicator description and data source.

EbA	Indicator	Effect	Data Source
Climate regulation	Carbon sequestration	Positive	Landsat image, IPCC dataset for carbon density
Temperature regulation	Cooling contribution	Positive	Landsat image
Air quality improvement	O_3 dry deposition rate	Positive	Landsat image
Stormwater management	Surface runoff coefficient	Negative	Landsat image, DEM

The land use data utilized in this study were obtained from two Landsat remote sensing images (path/row: 119/31) captured in 1995 and 2015, with an accuracy of 30 m, as well as Google Earth imagery data (with accuracies of 14 m in 1995 and 3 m in 2015). To ensure data reliability, the image data were rectified and supplemented based on the current land use status maps of the central urban area of Shenyang City, as outlined in the Urban Master Plan of Shenyang. Specifically, Landsat images were preprocessed using ENVI 5.1 software, including calibration, registration, fusion, cropping, and coordinate transformation. Subsequently, land use classification was conducted using ArcInfo Workstation interactive interpretation in accordance with the Classification Standard for Land Use Status (GB/T21010-2007 [59]), achieving an interpretation accuracy of over 90%. Land use was divided into five primary categories and 17 secondary categories, including meadow land, agriculture land, forest land, construction land, and water area and wetland. Construction land was further subdivided into nine categories. Finally, subdivided urban land was distributed into the aforementioned primary land use classification, forming a total of 13 land use types in the study area, including residential land, administration and public service land, commercial and business land, industrial land, logistics and warehouse land, road and transportation land, public utilities land, urban green space and square land, other urban construction land, farmland, forest land, grassland, and water and wetland land.

3.3. Methods

3.3.1. Calculation of EbA Indicators

(1) Carbon Sequestration

The basic principle of carbon sequestration is to estimate potential carbon storage or carbon fixation over a certain period, based on land use conditions and the carbon stocks in four pools, including aboveground biomass, belowground biomass, soil, and dead organic matter. This study employed the InVEST model to calculate the capacity of the urban ecosystem, in order to sequester carbon as follows:

$$C_{tot} = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (1)$$

where C_{tot} is the total amount of carbon stored, while C_{above} represents the amount of carbon stored in aboveground biomass, C_{below} the amount of carbon stored in belowground biomass, C_{soil} the amount of carbon stored in the soil, and C_{dead} the amount of carbon stored in dead organic matter. The carbon quantity values are obtained by multiplying the carbon density by the corresponding area. The carbon density values for different land uses are obtained from the InVEST model database through table lookup [60].

(2) Cooling Contribution

The distribution of the thermal environment in urban areas is closely intertwined with land use patterns. Current research has unequivocally shown that different land use configurations and their alterations exert varying influences on surface temperature. This variability is attributed to the distinct radiative and heat absorption characteristics exhibited by different land use types and covers, thereby resulting in disparate thermal effects within urban environments [61]. This study uses a cooling contribution metric to gauge the capacity of diverse land use types to moderate local temperatures. When ascribing cooling contribution to distinct land use categories, our approach is guided by insights gleaned from Burkhard et al. [62].

(3) O_3 Qry Deposition

Dry deposition is one of the primary processes by which atmospheric pollutants are removed. It refers to the continuous transfer of pollutants in the atmosphere to the earth's surface (such as land, water, and vegetation), due to turbulent motion, even in the absence of precipitation. In regions with low precipitation, dry deposition plays a significant role in air purification [63]. The dry deposition process is typically described based on dry deposition velocity and dry deposition flux, where dry deposition velocity usually represents the pollutant removal capacity. The formula for calculating the dry deposition velocity is as follows:

$$V_d = \frac{1}{R_a + R_b + R_c} \quad (2)$$

where R_a, R_b, and R_c represent aerodynamic drag, skin friction drag, and pressure drag, respectively. The specific values for these three parameters are referenced from the calculation method proposed by Pistocchi et al. [64]. Taking into account the types of air pollutants prevalent as well as data availability, this study has opted to use O_3 dry deposition rate as an indicator to reflect the capacity of air quality improvement in our study area.

(4) Surface Runoff Coefficient

The surface runoff coefficient refers to the ratio of runoff depth to precipitation depth or total precipitation during any given time period. This coefficient characterizes the proportion of precipitation converted into runoff and can comprehensively reflect the influence of natural geographical elements on the relationship between precipitation and runoff within a watershed. Since surface runoff is challenging to obtain directly, this study draws on a method for measuring the surface runoff coefficient based on remote sensing imagery [65], and the technical route is depicted as illustrated in Figure 3. Specifically, we divided the watershed areas using hydrological analysis modules with ArcGIS 10.1, followed by land use/cover classification, DEM slope analysis, and GIS overlay analysis. This process allowed for the calculation of area-weighted coefficients under different land cover types and slope conditions. Subsequently, based on the rationalized runoff coefficients considering the integrated slope values outlined, relevant types of areas were assigned coefficients, which enabled the acquisition of the required surface runoff coefficients for this research.

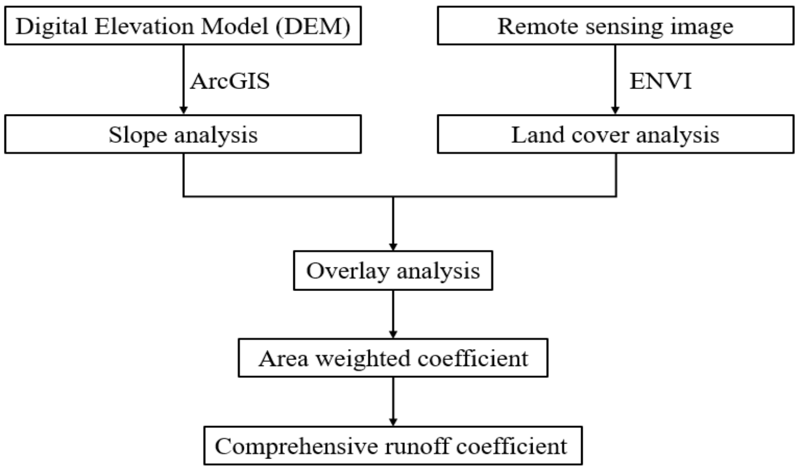

Figure 3. Technical route for surface runoff coefficient.

3.3.2. Geospatial Visualization

Following the calculation of EbA indicators, this study also utilized spatial data visualization methods. Representing the abstract calculation results through maps offers an intuitive visualization to enhance the understanding of these indicators and to discern their distribution patterns and trends. This visualization approach not only unveils the inherent relationships and dynamic changes in spatial data but, also, offers crucial insights for urban governance decision making. Geospatial visualization is conducted using the ArcGIS software 10.1 platform.

4. Research Findings

4.1. Spatial Patterns of EbA

The spatial patterns of the four indicators of EbA, as well as their evolution in the central city of Shenyang, are depicted in Figure 4.

The spatial patterns of the indicators generally display a distinct spatial differentiation, characterized by a central-peripheral structure, wherein the central area exhibits a weaker adaptation capacity compared to the peripheral regions, although each indicator has its own unique structure. This is because EbA, to some extent, relies on vegetation and water areas, which are insufficient in the central urban area in terms of quantity, scale, and diversity. Therefore, considering the spatial consistency of units with varying capabilities in adapting to climate change risks, it can be inferred that there is a synergistic effect among these four types of adaptation. This aligns with findings published by Haase et al. [66].

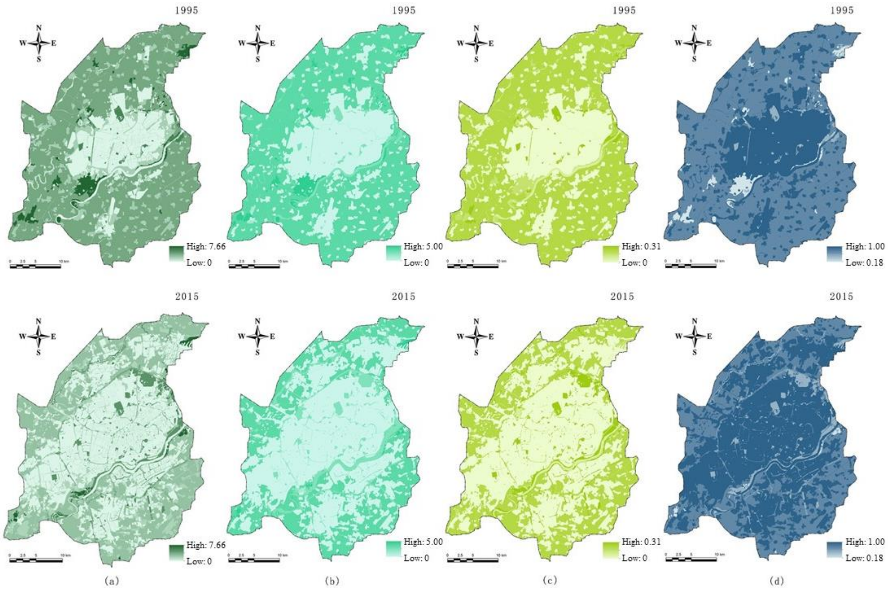

Figure 4. Spatial patterns of ecosystem-based climate adaptation indicators. (**a**) Carbon sequestration; (**b**) Cooling contribution; (**c**) O_3 dry deposition rate; and (**d**) Surface runoff coefficient.

Both in the city center and the suburban periphery, spatial units have emerged simultaneously to provide adaptation, in order to respond to different climate risks. Additionally, although large areas with strong climate adaptation capacity are located in the urban periphery, they are also scattered in the city center, particularly near West Lake, Changbai Island Park, Beiling Park, and the Qipanshan area. In recent decades, due to increasing artificial construction and expansion, natural and semi-natural areas have been extensively encroached upon or severely damaged. Consequently, the central areas with weaker adaptive capabilities have significantly expanded, while the peripheral regions with stronger adaptive capabilities have decreased in size. Furthermore, these peripheral areas have become increasingly fragmented and complex over the years. The previously well-defined patches with strong climate change adaptation capabilities, dispersed around the city center, have also significantly decreased in size. Currently, the spatial units with notable capabilities in climate change adaptation in this study area are distributed around large urban parks and extensive green areas along the Hun River.

4.2. Evolution Features of EbA

The ecosystem-based adaptation capability of the study area was classified (natural breaks) into five grades from weak to strong, as shown in Figure 5, where the first grade represents the weakest and the fifth grade represents the strongest. Subsequently, the proportions of each level were calculated, and a comparison was made between the changes observed in 1995 and 2015. The results indicate a decline in the climate change adaption capability of the central city of Shenyang. Furthermore, internal changes in the level of each indictor of climate adaptation were inconsistent. For carbon sequestration, the proportions of units with strong and weak capacities both increased, resulting in greater internal differences in climate regulation. In comparison, the internal differences in the levels of cooling contribution and O_3 dry deposition decreased, indicating a decline in the capacity for temperature regulation and air quality improvement. There were only minimal changes in stormwater management. Additionally, the evolution trajectories of temperature regulation and air quality improvement were similar, with the most significant decrease observed in these two adaptation capacities. Except for the evolution of stormwater management, which occurred primarily at lower levels with unclear changes in evolution at higher levels, the evolution of climate adaptation levels occurred between higher and lower levels.

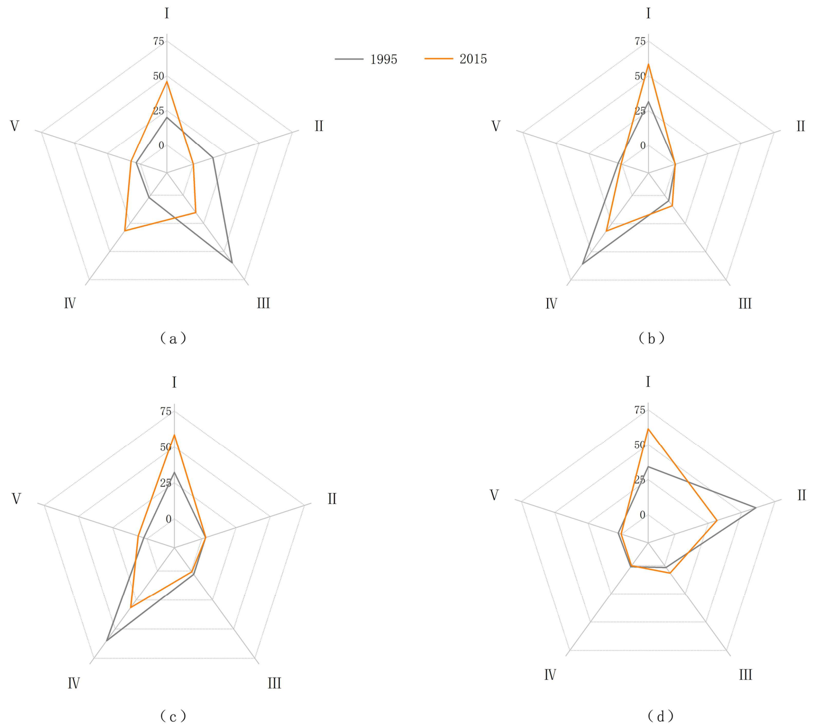

Figure 5. The area proportion of EbA indicators and their changes. (**a**) Climate regulation; (**b**) Temperature regulation; (**c**) Air quality improvement; (**d**) Stormwater management.

In summary, the spatial characteristics and variations of climate change adaptation show a similar pattern and significant differentiation in our study area. Over the past 20 years, the overall adaptability of the urban system to climate change has decreased, primarily due to the substantial destruction and encroachment of natural elements during rapid urbanization. In central urban areas, adaptability is relatively weaker, while it is stronger in peripheral regions. This can be attributed to the better performance of urban ecosystems in peripheral areas in terms of their quantity, scale, and diversity. The changes in climate adaptation level over a 20-year period indicate a significant expansion of areas with weaker capabilities in the central region, while the range of areas with stronger adaptation capabilities in peripheral regions has decreased and become more fragmented and complex. Previously prominent central patches have noticeably reduced in size, shifting from areas near the West Lake Scenic Area, Changbai Island Forest Park, Beiling Park, and Qipanshan to large urban parks and extensive green areas along the Hun River in the central city.

Regarding evolution, the internal differences in the adaptation capabilities of various aspects exhibit inconsistent changes. Internal differences increased for climate regulation, decreased for temperature regulation and air quality improvement, and remained relatively stable for stormwater management. The evolution trajectories of temperature regulation and air quality improvement are similar, with the most noticeable decrease recorded in adaptation capacity. Since the ecosystem-based climate adaptation of interest is all related to the regulation services of the urban ecosystem, there is no apparent trade-off relationship observed in their evolution processes; instead, they demonstrate a synergistic effect.

To ensure the adaptation of the urban ecosystem and to ensure that ecosystem services are adequately supplied under any circumstances, it is necessary to incorporate content related to the ecosystem-based adaptation approach into urban sustainable development strategies. This can be achieved through urban development policy and planning processes for ecological space construction and landscape pattern adjustments. However, as of now, these considerations have not received enough attention, and have not been fully integrated into urban development decision making, highlighting the urgent need to mainstream EbA and to make it a priority.

5. Mainstreaming Strategies

As climate change challenges intensify, the urban ecosystem and its adaptability are declining, as indicated by findings from the Millennium Ecosystem Assessment (MA), despite growing political will and societal awareness of the importance of functioning ecosystems [67]. Considering the potential of EbA to enhance urban climate resilience and to promote various long-term social, environmental, and economic benefits, now is an opportune time to mainstream EbA and to integrate it into urban development strategies as part of climate adaptation processes in China [68]. Presently, despite the nationwide introduction of the National Climate Change Adaptation Strategy 2035 in China, Shenyang city has yet to implement the relevant response strategies [69]. Integrating EbA into the urban development process, through institutional strengthening and capacity building, is essential for megacities like Shenyang. This process involves multiple stakeholders and requires collaboration on different scales, through diverse intervention projects and objects (Figure 6).

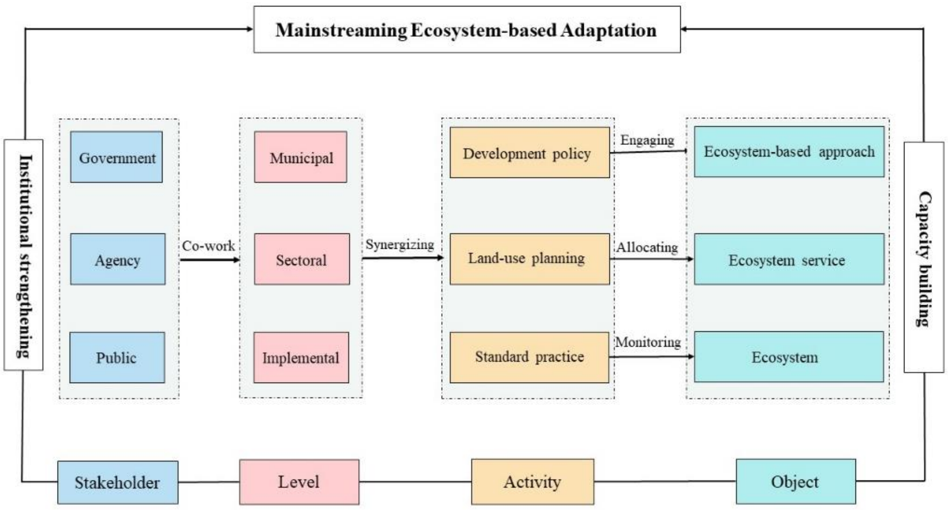

Figure 6. Framework of the mainstreaming of EbA in urban development process.

5.1. Embedded EbA as an Interdisciplinary Approach in Urban Development Policy

Considering the vital importance and potential of EbA in addressing urban climate change risks, it is imperative to focus on effective EbA management. Integrating EbA into urban development planning and policy decisions can significantly enhance the balance between ecological and socio-economic factors throughout the urban development process, thereby ensuring a stable and sufficient supply of ecosystem services. However, while current urban development decisions do not neglect ecological concerns, they often do not prioritize ecological factors, failing to recognize them as urgent issues requiring resolution. Given the global recognition of climate change as a developmental issue, EbA, as an interdisciplinary approach, should be integrated into urban development policy in order to enhance urban climate resilience, foster a more livable urban future, and to guide cities towards a more sustainable development path. Currently, this concept is transitioning from being a heuristic model, which aids in understanding human–environment interactions, towards becoming a clear management tool. To integrate EbA into urban development policy, it is crucial to understand the linkages between climate change and social-ecological systems, and to consider development priorities and ecosystem dynamics as well as potential for adaptation.

In the case of Shenyang, EbA has not been prioritized in the urban development and governance process. To build a more beautiful Shenyang, a new development paradigm with revised priorities is needed to address these interconnected challenges. The key focus of the urban development process should shift from traditional development and construction to balancing socio-economic development with the protection of the ecological environment. New urban development strategies require a more comprehensive and systematic approach to understand complex socio-ecological relationships in cities, and the interconnected causes of, and responses to, current socio-ecological challenges. Urban development that incorporates EbA, prioritizing the importance and supply–demand relationships of ecosystem services in decision-making processes, will raise awareness and facilitate the effective governance of climate change impacts on cities, thereby enhancing the resilience and sustainability of planning. Specifically, this requires optimizing the allocation of green and blue infrastructure spaces.

5.2. Coordinate the Allocation of Ecosystem Services across Urban Areas

The spatial distribution of ecosystem services, as well as their supply–demand dynamics and their interactions across different scales, significantly influences urban climate change adaptability. Occasionally, the alignment of supply–demand and spatial distribution has a more substantial impact on adaptability than other factors. For example, ecosystem services aimed at mitigating the UHI effect are largely redundant in areas far from the city center, as temperature regulating effects cannot be effectively transferred to the city center. This is an operational challenge that requires careful attention and coordination in mainstreaming ecosystem-based adaptation, in order to effectively plan the locations where adaptability-related ecosystem services are produced or supplied.

In the central urban area of Shenyang studied in this paper, rapid urbanization has led urban residents to become disconnected from local ecological conditions. The extensive destruction of farmland and ecological land around the central city has led to a significant decline in both the quantity and quality of ecosystem services available within the main urban area. From a demand perspective, the main urban area requires a more significant ecosystem for adaptation. This is due to the larger and denser population in the main urban area, resulting in a higher likelihood of exposure to climate risks and more significant potential losses after disasters. Therefore, the spatial characteristics of ecosystem service generation and provision are of primary concern in future land use planning, as they are essential for promptly and effectively mitigating and adapting to the impacts of climate change. This aspect constitutes a central focus of EbA research and makes a significant contribution to climate change adaptation strategies, especially through interdisciplinary collaboration, primarily in the field of geography.

5.3. Monitor and Evaluate the Dynamics of the Urban Ecosystem

The health and stability of urban ecosystems are closely tied to their ability to mitigate and adapt to climate risks, as well as to broader objectives like safeguarding human wellbeing and promoting sustainable development. MA findings indicate that over half of global urban ecosystems are being degraded or exploited unsustainably, underscoring a historical bias toward engineering and technological approaches in urban disaster management, often at the expense of ecological considerations. Monitoring and evaluating urban ecosystems and their biodiversity not only immediately assesses the effectiveness of adaptation measures but, also, facilitates staying updated on new information regarding climate change, risk reduction, and adaptation strategies. The continuous monitoring of urban ecosystem changes helps uncover the interactive development processes between urban socio-economic elements and ecological structures, aiding in adjusting planning implementation and fostering long-term learning. Establishing monitoring mechanisms at various spatial scales to track the status of and changes in the urban ecosystem, such as municipal and major watershed levels, lays the foundation for enhancing urban climate resilience. Thus, the continuous monitoring of urban ecosystem dynamics should be a primary strategy and tool for mainstreaming EbA, especially given the concurrent challenges of rapid urbanization and climate change.

This study indicates that EbA is weakening in the urban area of Shenyang. Linking the dynamics of the urban ecosystem at relevant levels to their capacity for climate change adaptation is essential. Specifically, it is crucial to employ technical methods such as satellite remote sensing to monitor changes in land use and land cover, including vegetation distribution, to support efforts to reduce greenhouse gas emissions. It is imperative to enhance supervision over crucial ecological areas, including natural reserves and ecological protection zones across the city, and to conduct monitoring assessments to evaluate the effectiveness of ecosystem protection and restoration efforts. The continuous monitoring and evaluation of urban ecosystem dynamics, as standard practice, contribute to enhancing ecosystems' ability to sequester carbon, regulate temperature, improve air quality, and to manage stormwater, thereby strengthening climate change adaptation.

6. Discussion

6.1. Effectiveness of Ecosystem-Based Adaptation

To gain a more intuitive understanding of the effectiveness of EbA, this study utilized Landsat imagery and air quality monitoring data to conduct two validations within the urban ecosystem of Shenyang city: temperature regulation and air quality improvement. For temperature regulation assessment, the surface temperature inversion method was employed to estimate the city's temperature distribution pattern, as depicted in Figure 7a. In conjunction with the land use pattern illustrated in Figure 1 for this study area, it is evident that areas with significant green and blue infrastructure, such as urban parks, forests, and water bodies, experience lower temperatures. To further elucidate the contribution of the urban ecosystem, a zoning statistics tool was employed to calculate the total areas with and without green infrastructure. The results illustrate that maximum and average temperatures in areas without green infrastructure are significantly higher than in those with green infrastructure, providing robust evidence of the urban ecosystem's role in local temperature regulation (see Table 3). In particular, the significance of the urban ecosystem in local temperature regulation lies in its local attribute. Unlike other ecosystem services that can be imported, temperature regulation depends entirely on the functioning of green infrastructure within a limited distance range. Therefore, EbA is irreplaceable in its role in local temperature regulation.

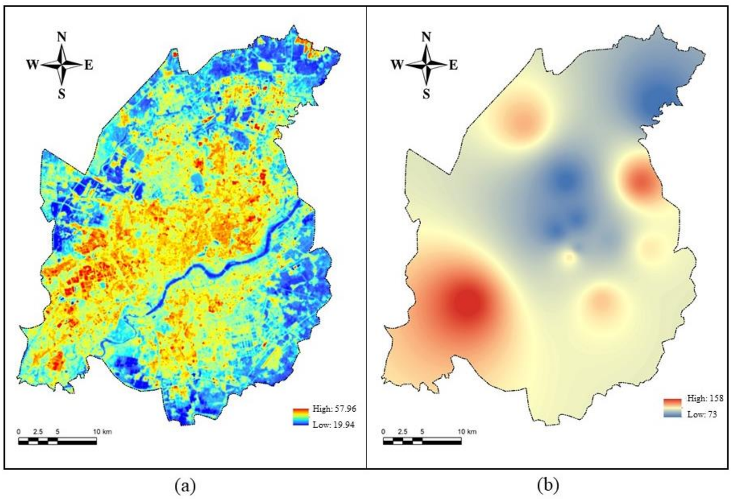

Figure 7. Effectiveness of urban ecosystem in temperature regulation and air quality improvement. (**a**) Surface temperature; (**b**) Surface air quality.

Table 3. Statistical comparison of land surface temperature between non-green areas and green areas in the central city of Shenyang, China.

	Minimum	Maximum	Average	Standard Deviation
Non-green areas	19.94 °C	57.96 °C	41.30 °C	3.15 °C
Green areas	26.41 °C	49.86 °C	35.66 °C	3.52 °C

For its air quality improvement assessment, this study utilized average Air Quality Index (AQI) data obtained from 12 monitoring stations in the central city of Shenyang in 2015 (https://aqicn.org/city/shenyang, accessed on 28 May 2016). It employed inverse distance-weighted spatial interpolation to simulate air quality across the city; this was further used to verify the coupling pattern between the urban ecosystem and air quality conditions (see Figure 7b). It was found that the spatial distribution of air quality is characterized by heterogeneity, with higher AQI levels in the northeast and central areas of the city, compared to those in the southwest and southeast areas. Combining this with the land use pattern (see Figure 1), it is evident that areas with higher AQI levels include urban forests in the northeast and large-scale urban parks in the central urban area. This result is consistent with existing research indicating that urban forests and large urban parks are primary contributors to improving air quality [6,52].

6.2. Comparative Analysis and Implementation Challenges in Mainstreaming EbA

Considering the evolving nature of climate change as a developmental concern, there is an increasing urgency to incorporate climate change adaptation into national planning efforts as a fundamental element of overarching development policies worldwide, particularly in the Global South [70]. Common patterns emerging in the mainstreaming of EbA are observed in Viet Nam, South Africa, and Mexico. In Viet Nam, EbA micro-projects are integrated into village action plans to address food security and water availability [71]. South Africa released its National Climate Change Response White Paper, emphasizing the crucial role of EbA within a comprehensive adaptation framework [72]. Meanwhile, Mexico promotes EbA principles in land use planning [73].

In China, both research and practice on mainstreaming EbA are scarce, with only limited studies focusing on mainstreaming ecological protection and biodiversity. However, given the unprecedented rate of rapid urbanization and escalating risks from climate change that cities face, the mainstreaming of EbA may serve as a timely reminder, prompting governments, relevant organizations, and the public to pay more attention to EbA in densely populated urban areas with multiple overlapping hazards, and to consider its multiple benefits and high cost-effectiveness.

While implementation varies from country to country, mainstreaming EbA is inherently gradual and time consuming. It entails a long-term, iterative approach that requires the integration of biodiversity, ecosystems, and climate considerations into national, sectoral, and local policies, plans, and budgets. Consequently, sustained support is needed for the implementation of cohesive action. While there is considerable support for incorporating EbA into sustainable planning initiatives, there is a notable absence of clear pathways for systematic implementation [68]. Furthermore, how local authorities can effectively integrate this innovative approach into their existing practices remains uncertain [17]. Although overall, the practical application of EbA is still lacking, prioritizing it as part of urban development, construction, and governance processes is important and urgent, especially considering the escalating risks of climate change and the resulting disaster losses.

6.3. Research Contributions and Limations

Traditionally, cities have relied heavily on engineering solutions to address climate risks, which, while effective in the short term, are expensive, one-dimensional, and often unsustainable in the long term. Additionally, these approaches typically address specific risks, leaving cities vulnerable to the multifaceted and unpredictable impacts of climate change. With the escalation of global climate risks, particularly in vulnerable megacities in the Global South like China, there is an increasing recognition of the necessity to transition towards ecosystem-based solutions for climate change adaptation and mitigation. However, despite gaining traction in scientific, policy, and practical circles, concrete mechanisms and mainstreaming strategies for implementing EbA in urban areas remain largely unexplored. This study aims to bridge this gap by investigating the interplay between urban ecosystem dynamics, ecosystem services capacity, and climate risk management. By establishing a solid scientific foundation, this research aims to pave the way for sustainable urban development, particularly in rapidly growing megacities in China. Additionally, it promises to advance interdisciplinary integration in geography-based studies, contributing to the broader discourse on urban sustainability.

While this study makes a unique contribution, there are still some limitations to it. For instance, it solely discusses the adaptation of urban ecosystems to climate change under normal conditions, without considering different levels of climate change risks such as heatwaves and flooding, thereby failing to simulate the resilience of urban ecosystems under multiple scenarios. Furthermore, due to limitations in data availability, this study only attempts to establish a set of universal exploration processes and research approaches to the topic, without tracking the latest development conditions in the study area. These aspects indicate directions that are worthy of further exploration.

7. Conclusions

Given the intensifying effects of rapid urbanization and climate change, there is an urgent need to accelerate progress towards resilient, livable, and sustainable development in modern cities. Despite growing consensus on the success of EbA as a solution to help urban systems adapt to climate change, its mechanisms have not yet been clearly elucidated, and EbA-related activities are often not prioritized in practice. Therefore, it is imperative to emphasize the effectiveness, dynamic evolution, and implementation of EbA for urban sustainability.

This study utilized a combined qualitative and quantitative methodology to examine the effectiveness and spatiotemporal dynamics of EbA in response to urban climate change. It then proposes a framework and specific strategies for mainstreaming EbA in urban areas that face escalating risks from rapid urbanization and global climate change. By integrating urban ecosystem dynamics, ecosystem services, and climate risk mitigation and adaptation, this study provides scientific analysis to promote long-term sustainability in urban socio-ecological systems. It enhances the contribution of interdisciplinary integration, based on geography, to urban sustainability, providing a scientific basis for megacities looking to advance climate change adaptation and broader sustainability goals.

Urban ecosystems primarily contribute to climate change mitigation and adaptation through their capacity in the global climate regulation, temperature regulation, air purification, and stormwater management provided by multiple ecosystem services. The sustainable and resilient supply of ecosystem services, along with their supply–demand configuration, play crucial roles in EbA in addressing climate change risks. In the central urban area of Shenyang, the spatial patterns of EbA exhibit a central-peripheral pattern with significant spatial differentiation, showing a weaker capacity in the central urban area and a stronger capacity in peripheral areas. Over the 20-year period from 1995 to 2015, the capacity of EbA declined. The evolution trajectories of EbA levels in local temperature regulation and air quality improvement are similar, showing a significant decline in capacity, while remaining relatively stable for stormwater management.

EbA, as a cross-cutting approach to understanding and coordinating the complex feedback between humans and the environment, is gaining popularity for its significant potential in enhancing urban climate change adaptation and social-ecological resilience. However, despite its cost-effectiveness, existing urban development planning and policy processes often fail to incorporate EbA. To facilitate the mainstreaming and effective implementation of EbA in urban areas, this paper creatively proposes an operational framework and specific strategies, including embedding EbA in urban development policy, coordinating the allocation of ecosystem services throughout urban areas via land use planning, and regularly monitoring and evaluating the dynamics of the urban ecosystem. The results of this study have significant implications and provide reference value for megacities undergoing rapid urbanization and climate change, particularly those in China and in the wider Global South.

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