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Assessment of Urban Ecological Resilience and Its Influencing Factors: A Case Study of the Beijing-Tianjin-Hebei Urban Agglomeration of China

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Abstract: Climate change and rapid urbanization bring natural and anthropogenetic disturbance to the urban ecosystem, damaging the sustainability and resilience of cities. Evaluation of urban ecological resilience and an investigation of its impact mechanisms are of great importance to sustainable urban management. Therefore, taking the Beijing-Tianjin-Hebei Urban Agglomeration (BTHUA) region in China as a study area, this study builds an evaluation index to assess urban ecological resilience and its spatial patterns with the resilience surrogate of net primary production during 2000–2020. The evaluation index is constructed from two dimensions, including the sensitivity and adaptability of urban ecosystems, to capture the two key mechanisms of resilience, namely resistance and recovery. Resilience-influencing factors including biophysical and socio-economic variables are analyzed with the multiple linear regression model. The results show that during 2000–2020, the spatial pattern of urban ecological resilience in the BTHUA is characterized by high resilience in the northwest and relatively low resilience in the southeast. High resilience areas account for 40% of the whole region, mainly contributed by Zhangjiakou and Chengde city in Hebei Province, which is consistent with the function orientation of the BTH region in its coordinated development. Along with urbanization in this region, ecological resilience decreases with increased population and increases with GDP growth; this indicates that, although population expansion uses resources, causes pollution and reduces vegetation coverage, with economic growth and technological progress, the negative ecological impact could be mitigated, and the coordinated development of social economy and ecological environment could eventually be reached. Our findings are consistent with mainstream theories examining the ecological impact of socio-economic development such as the Environmental Kuznets Curve, Porter Hypothesis, and Ecological Modernization theories, and provide significant references for future urbanization, carbon neutrality, resilience building, and urban ecological management in China.

Keywords: urban resilience; land use/cover change; urbanization; carbon neutrality; Beijing-Tianjin-Hebei urban agglomeration

1. Introduction

Land use change induced by urbanization has greatly changed the physical conditions of urban ecosystems. Meanwhile, external risks faced by urban systems, such as climate

change, require resilient urban ecosystems to provide a solid urban foundation to support urban production and livelihood [1]. Measures such as emission reduction are taken in urban systems to adapt to environmental change along with urbanization, for example, China is taking the lead in committing to achieving carbon neutrality in 2060 [2]. These measures would further change urban ecosystems with the goal of enhancing resilience. Unlike the sustainability concept, which is too comprehensive and hard to quantify in social-ecological systems, the resilience concept is derived from ecosystems and proves to be a good analytical tool for urban systems [3]. To quantitively assess urban ecological resilience and elucidate its driving mechanisms is of great importance to guide sustainable urbanization, mitigate climate change impact and achieve high-quality development.

The concept of ecological resilience is a measure of the persistence of an ecosystem and refers to the ability of a system to absorb natural and anthropogenic disturbances while still maintaining the interplay between population or ecosystem state variables and maintaining system function [4]. Ecological resilience in urban systems is a complex of socio-economic human activities and biophysical habitats [5]. An urban ecosystem is a specific type of ecosystem that integrates human activities into the biophysical sphere. In recent years, there has been much research on urban resilience that originates from social-ecological resilience. The urban system itself is a more complex system than an ecosystem, as an ecosystem is only one of the subsystems within the complex urban system, which includes society, economy, culture, ecology and environment, etc. [6,7] Urban resilience refers to the capability of urban systems to remain intact or quickly recover to desired levels in the face of shocks or stresses [8,9]. As resilience in different scales embeds different connotations and mechanisms, this research focuses on urban resilience to theoretically conceptualize and empirically explore resilience in urban systems.

Utilization of the resilience concept must be based on the characterization and measurement of resilience. According to its concept, resilience can be measured by the rate of return of ecosystem state after change or disturbance, and the measurement of resilience is, in effect, the measurement of threshold-crossing [10]. Therefore, detecting an ecological threshold along disturbance gradients is essential to protecting the threshold from being crossed [11]. Previous research selects a key indicator or index to evaluate ecosystem resilience [12–15] or quantifies the economic value of resilience [16]. For urban resilience, a popular measurement is to build a comprehensive evaluation index with indicators representing the resilience of urban elements [17–19] or resilience process [20–22]. However, there are also scholars who believe that instead of seeking accurate metrics to measure resilience or trying to develop a general resilience index, it might be better to use surrogates or proxies [23,24]. As a matter of fact, evaluation of the previously mentioned resilience indicators is resilience surrogates in the sense that they demonstrate the impact factor of resilience rather than resilience (threshold-crossing) itself.

However, many resilience assessments tools, especially comprehensive evaluation indexes, tend to use state variables or cross-section data to measure resilience [17,25,26], while resilience is a process concept that encompasses two processes, namely resistance and recovery [27], making its measurement difficult as threshold-crossing often does not happen [24]. Therefore, in this study, drawing upon the assessment of economic resilience, where the change rate of GDP (also known as the sensitivity index) is used to measure resilience of the economic system [28], a resilience evaluation index is built to measure urban ecological resilience. Specifically, we use the change of net primary productivity (NPP) as the resilience surrogate. A concrete calculation method will be presented in the following method section. The surrogate selection of NPP is referenced from research that uses normalized difference vegetation index (NDVI) and GPP to quantify ecosystem resilience [29,30].

In terms of the impact factors of ecological resilience, as mentioned before, some studies use the impact factor of resilience to quantify system resilience and identified factors such as climate (e.g., precipitation, sunshine hour, temperature), hydrology (e.g., surface and groundwater resources), and land cover factors [31]. Among them, land cover is

an important and widely studied impact factor of ecosystem services and resilience [5,32,33]. Research shows urbanization increases land cover fragmentation, thus decreasing urban ecological resilience. In addition to biophysical factors, social-economic factors, such as GDP, population, land use, industrial structure, infrastructure, institutional arrangements, etc. also influence the resilience in urban systems [3,34–36]. An urban system, as a complex adaptive system, has a socio-economic subsystem that directly contributes to system resilience with its own urban functions, such as engaging in social production, providing employment, increasing productivity, and improving the livelihood of urban residents. Meanwhile, it influences system resilience indirectly through the interactions with the ecological-environment subsystem, which also directly impacts urban ecological resilience.

Therefore, this study sets out to measure urban ecological resilience with the empirical case of the Beijing-Tianjin-Hebei Urban Agglomeration and explore the impact factors including physical geographical factors (temperature, precipitation, elevation, slope, land cover type) and socio-economic factors (GDP, population, industrial structure, urbanization rate and carbon emission). Rationales for impact factor selection will be presented in the empirical results section. In doing this, we aim to empirically assess the ecological impacts of urbanization through the quantification of urban ecological resilience and explore the influencing mechanism of urban change on ecosystems. The following sections of this paper are structured as follows. The next section presents the overall methodology of this study with elaborations on the case study, research data and method. The empirical results are illustrated in Sections 3 and 4, with Section 3 presenting the resilience assessment result and analyzing the spatial difference of ecological resilience in the study region. Section 4 demonstrates the impact factor analysis and the correlation between ecological resilience and various impact factors. Section 5 concludes this paper by discussing the empirical, methodological, and theoretical implications and contributions of this study.

2. Methodology

2.1. Study Area

Previous empirical studies indicate that from 2006 to 2013, there was an N-shaped relationship between urbanization and ecological efficiency, and other studies show that from 2008 to 2017 [37], ecological efficiency slightly declined along with China's urbanization [38], while the current new-type urbanization in China (Refer to "The National New-type Urbanization Plan (2014–2020)" from National Development and Reform Commission of China: https://www.ndrc.gov.cn/xwdt/ztzl/xxczhjs/ghzc/201605/t20160505_971882.html?code=&state=123 (accessed on 30 April 2022)) that emphasizes the improvement of ecological environment, has yielded good ecological outcomes in pollution reduction and energy efficiency increase [39]. This study explores the ecological consequence of urbanization in China. Specifically, we selected the Beijing-Tianjin-Hebei Urban Agglomeration (BTHUA) region in China as the case study area to empirically assess ecological resilience and its influencing factors (Figure 1). The research was conducted on a 1 km × 1 km grid scale to observe fine-scale variation of urban ecological resilience change, and the research period is set from 2000–2020 to observe the rapid urbanization in China in the last twenty years and its ecological impacts.

The BTHUA region, also known as the Capital Economic Circle, is one of the major urban agglomerations in China, with high levels of urbanization and industrialization, though it suffers from ecological and environmental problems such as water resource shortage, air pollution, extensive land use and forest degradation, urban floods, and heatwave, etc. This region is semi-arid and semi-humid, has a temperate and warm temperate continental monsoon climate with an average temperature of 1 °C to 15 °C, abundant light, uneven spatial distribution of annual precipitation (about 300 mm to 750 mm from west to east), and the average annual evaporation is generally 900 mm to 1000 mm. The region is divided into plateau, mountain hills, basin and plain from northwest to southeast.
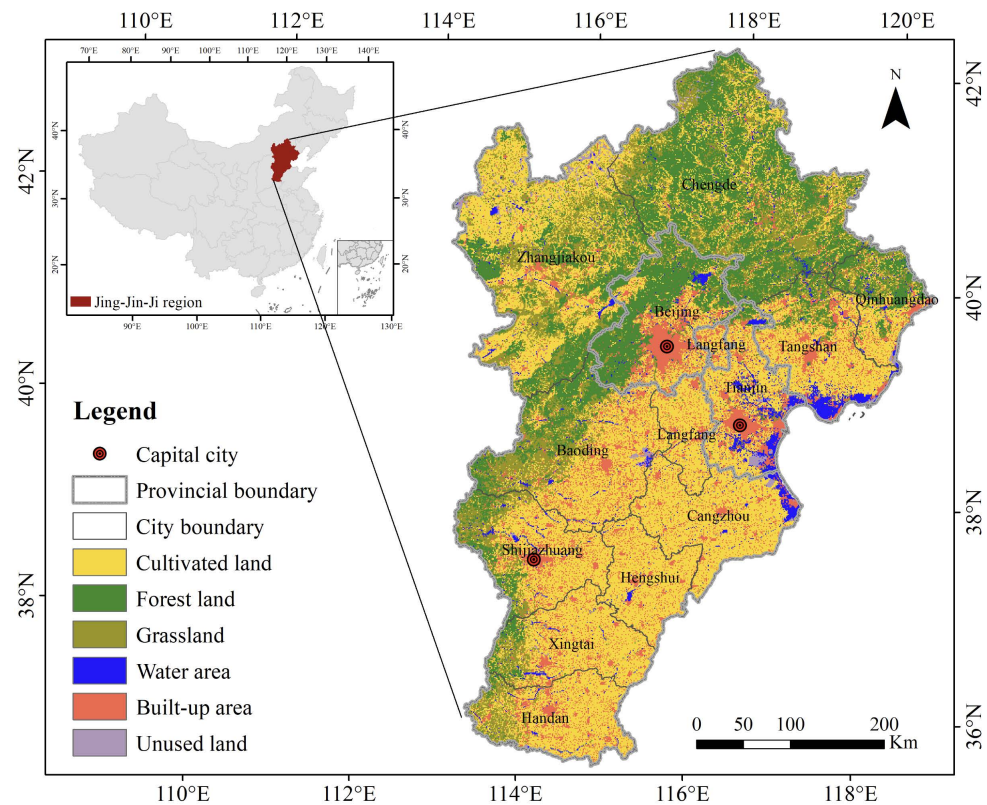
Figure 1. Location, land use and administrative division of the Beijing-Tianjin-Hebei Urban Agglomeration.

Currently, under the national policy of "Coordinated Development of the Beijing-Tianjin-Hebei Region", the overall positioning of the BTHUA region is "a world-class city cluster with the capital as the core, a new engine for economic growth driven by innovation and coordinated development, and a demonstration area for ecological restoration and environmental improvement" (Source: Outline of Coordinated Development of the Beijing-Tianjin-Hebei Region issued by State Council in 2015). Now, this region is still in the middle of industrialization and undergoing rapid urbanization and is also the main area of population inflow. In 2021, the permanent resident population rate in Beijing, Tianjin and Hebei were 87.5%, 84.88% and 61.14%, respectively (Data source: https://data.cnki.net/, accessed on 15 May 2022). In the future, this region will continue to host population inflow, with the ecological environment pressure, the contradiction of space resources utilization and the lack of regional infrastructure caused by urbanization expected to be more prominent [39].

2.2. Data Source

The data used for evaluating ecological resilience and driving factors of ecological resilience changes mainly include the Net Primary Production (NPP) data, meteorological data, topographic condition information, land use/land cover data, gridded GDP and population data, and carbon emission data. The NPP data for the years 2000–2020 with a spatial resolution of 500 m was derived from the MODIS MOD17A3HGFV06 product of vegetation NPP. The daily temperature and precipitation station monitoring data for the years 2000–2020 were obtained from the National Meteorological Information Center, and then the annual average temperature and precipitation were calculated and interpolated into a 1 km grid based on Kriging interpolation. The digital elevation model (DEM) and land use/land cover, population density and GDP per unit area with a spatial resolution of 1 km for the years 2000, 2005, 2010, 2015 and 2019 (using the population and GDP of 2019 to approximately represent that of 2020 due to data availability) were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences. The

CO_2 emission data for the years 2000–2020 with a spatial resolution of 1 km were derived from the Open-source Data Inventory for Anthropogenic CO_2 (ODIAC) datasets. All the data were interpolated or resampled into 1 km × 1 km resolution.

2.3. Method

In the quantification of ecological resilience, an evaluation index is built in this study. The resilience assessment results are classified with the natural breaks method as an objective classification method and in the impact factor analysis, a multiple linear regression model is adopted. For the resilience evaluation index, NPP is selected as the resilience surrogate. The evaluation model is constructed from two dimensions, including sensitivity and adaptability of urban ecosystems, to capture the two key mechanisms of resilience, namely resistance and recovery [27].

Sensitivity is the system's responsiveness to disturbance during normal operation. For a particular ecosystem, sensitivity is defined as the degree to which an ecosystem responds to disturbances such as climate change [40–42]. In this study, NPP is used to characterize ecosystem function. System sensitivity is represented by the interannual fluctuations of NPP from 2000 to 2020 to reflect the degree of dispersion of NPP from the average. The calculation formula is as follows:

$$S = \frac{\sum_{i=1}^{n} |P_i - \overline{P}|}{\overline{P}} \tag{1}$$

where i is the year ($n = 21$), P_i is the NPP value in year i. $\overline{P}$ is the mean value of NPP. S is the sensitivity index, which reflects the dispersion of NPP relative to the mean value over a specific time period.

Adaptability is the ability of a system to maintain and restore its structure in the face of disturbances [43]. Ecosystem adaptation, which is the self-regulation mechanism of an ecosystem, can be regarded as a measure to keep the system in a relatively stable state. In a certain period, the trend of variability of an ecosystem is used to measure its departure from homeostasis, which can be called ecosystem adaptation. If the variability trend decreases or does not change, the system tends to be relatively stable. Increased variability indicates that unstable systems adapt to changes and may indicate increased vulnerability [3,44]. Over a certain period, ecosystem adaptation, the self-regulating capacity of the system, can be expressed as the slope of a linear trend line fitting the interannual variability of NPP. In this study, adaptation is represented by the slope of a linear fitting trend line for the interannual variability of NPP from 2000 to 2020:

$$y = Ax + B \tag{2}$$

$$A = \frac{n \sum xy - (\sum x)(\sum y)}{n \sum x^2 - (\sum x)^2} \tag{3}$$

where x is the time series from 2000 to 2020, y is the annual change rate of NPP, which is the annual absolute value change of NPP. It is the annual value of NPP minus the average value of NPP from 2000 to 2020. A is the changing trend of NPP variability, which is the regression slope of data sets y and x and indicates ecosystem adaptability; B is the intercept.

Resilience is a function of the characteristics, amplitude, and range of change rate, as well as the sensitivity and adaptability of the ecosystem [27,45]. Resilience is negatively correlated with sensitivity and positively correlated with adaptability. The levels of adaptability, sensitivity and resilience in each region are relative, and the sensitivity and adaptability calculated according to the preceding formula may not be in the same dimension. To analyze regional differences in resilience, the calculation results of sensitivity and adaptability should be standardized respectively before resilience calculations [46]. The resilience formula is as follows:

$$R = A - S \tag{4}$$

where *R* ecosystem resilience, *S* is sensitivity index, *A* is adaptability index.

3. Spatial Pattern of Urban Ecological Resilience in the BTHUA Region

The urban ecological resilience in the BTHUA region ranges from −0.23 to 0.74, with the mean value being 0.48, and is classified with the natural break method (Figure 2). The results show that during 2000–2020, urban ecological resilience in the BTHUA demonstrates discontinuous regional variance and a relatively small degree of dispersion, with the coefficient of variation being 0.1036. The overall spatial pattern is characterized by high resilience in the northwest and relatively low resilience in the southeast. Most of the regions are at middle-to-high ecological resilience levels, indicating high resilience in the Beijing-Tianjin-Hebei region over the past twenty years, which could be attributed to the improvement of the ecological environment in this region, especially since the coordinated development from 2015 during the 13th Five-Year-Plan period (2016–2020).
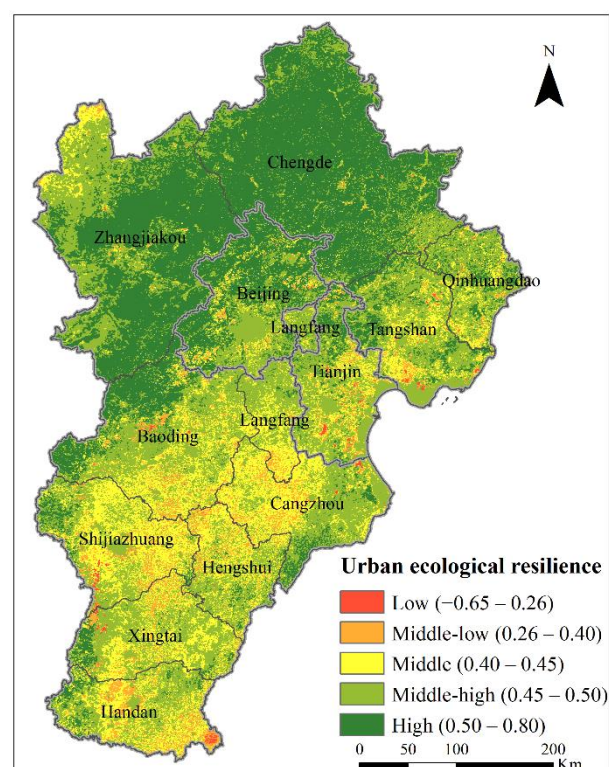
Figure 2. Spatial pattern of urban ecological resilience in the BTHUA region.

High resilience areas are concentratedly distributed and account for 40% of the whole region, mainly contributed by Zhangjiakou and Chengde city, as well as areas along the Taihang mountains in Baoding, Shijiazhuang, Xingtai and Handan cities in Hebei Province. This is consistent with the function orientation of Hebei Province as the "ecological environment support area" in the BTHUA region. While Beijing is mainly covered by high and middle-high resilience areas, with north and southwest Beijing being more resilient than the southeast. The good resilience performance in Beijing is also consistent with Beijing's development orientation in this region to serve as the "ecological restoration and environmental improvement demonstration area". Along the coastal lines in Qinhuangdao, Cangzhou and Tangshan, there are also areas with high resilience.

The middle-high resilient regions cover 27% of the whole region and are relatively concentrated in Beijing, Tianjin, coastal regions in Hebei Province and areas along the Taihang mountains. Areas with middle resilience account for 27% of the whole region and are relatively concentrated in south Hebei. Middle-low resilience regions account for 5% of the study area and are distributed in Tianjin and south Hebei. Low resilience areas, accounting for less than 1%, are scattered across the region, with continuous distributed

low resilience mainly in the southeast corner of Handan, northwest of Xingtai, southwest of Shijiazhuang, northeast of Cangzhou, central Baoding, north Tangshan in Hebei and middle and south Tianjin. This is attributed to the vegetation reduction along with land-use change induced by urbanization in these areas.

As for land-use type, areas with high resilience are mainly forest and grassland; middle-high areas are grassland, waterbody and cultivated land; middle resilience areas are mainly grassland, cultivated and built-up land; and middle-low and low resilience areas are mainly cultivated and built-up land. The empirical results in this region show that cultivated and built-up land, disturbed by anthropogenic activities, demonstrates higher ecological risk and lower resilience. These lands with lower resilience are mainly located in the plain area of the BTHUA region between the Taihang mountains in the northwest and coastal lines in the southeast, covering southeast Beijing, central Tianjin, Shijiazhuang, central Tangshan, Qinhuangdao, Handan, Xingtai, Hengshui, Cangzhou, southeast Baoding, and Langfang cities in Hebei. These areas are also the highly urbanized areas in this region with dense populations, and they carry the burden of regional socio-economic development. However, the areas with high forest and grassland coverage are less influenced by human disturbance and exhibit high resilience levels. These areas are mainly in the Taihang mountains, Yanshan mountains, and Bashang grassland in mountain hill regions; forest and grassland can conserve water, clean air, regulate climate, and improve greening rate, forest coverage, air quality and biodiversity, generating positive ecological benefits.

Our findings show that high ecological resilience areas are mainly located in ecological land use-dominated areas, for example, mountain hills with forest landscapes. This indicates that during urbanization, ecological land is better preserved and subjected to less disturbance, and low resilience is mainly in built-up and cultivated land of plain areas. Though cultivated land has certain ecological regulating functions, contributing to ecological resilience and anthropogenic use of cultivated land, for example, pesticide application and mechanized production as well as intensive and irrational use, can cause ecological damage and reduce the resilience of ecosystems. The ecological benefits of built-up land are limited. If the development mode is not reasonable, for example, extensive built-up land use, which will result in the disorderly spread and expansion of built-up land, it will increase the negative impact on the ecosystem. Therefore, during urbanization, ecological protection and restoration projects should be implemented to conserve ecological land by protecting forests, grasslands, wetlands, and other key ecological resources, and to improve ecosystem function and stability.

For now, China is implementing 'Planning for Major Ecological Protection and Restoration Projects in the Northern Sand Control Belt (2021–2035)' in the study region (Source: http://www.gov.cn/zhengce/zhengceku/2022-01/14/content_5668161.htm, accessed on 15 June 2022), to promote comprehensive ecological management in Zhangjiakou, Chengdu, Yanshan and Taihang mountains and Baiyangdian in Xiongan New District in Baoding. According to this plan, by 2035, the quality and stability of natural ecosystems such as forests, grasslands, rivers and lakes, wetlands and deserts will be significantly improved to enhance ecological service and resilience. This will help achieve carbon peak and carbon neutrality and build an ecological security barrier in northern China, laying a solid ecological foundation for realizing the goal of building a beautiful China. While this study consolidated the necessity of implementing such a plan, its effects on ecological resilience-building deserve further research attention.

4. Impact Factors of Urban Ecological Resilience in the BTHUA Region

To analyze the correlation between urban ecological resilience and its impact factors (Table 1), a multiple linear regression model is built. Impact factors are selected based on previous studies and data availability. In this study, we try to include both physical geographical and socio-economic factors. For biophysical factors, climate factors including temperature and precipitation play important roles in the formation of ecosystem structure and function. They directly impact the growth of vegetation and thus tend to impact

ecological resilience. In the study region, the annual mean temperature is decreasing from the southeast to the northwest (Figure 3a), while precipitation is concentrated in east Hebei plain and south Hebei (Figure 3b). Vegetation coverage is also significantly affected by topography and correlated with elevation and slope. The topography of the study region is high in the northwest and low in the southeast, tilting from the northwest to the southeast (Figure 3c). The slope rises from the southeast to the Taihang Mountains and drops to the northwest after the Taihang Mountains (Figure 3d).

**Table 1.** Descriptive statistics of resilience impact factors.

Variable	Unit	Obs.	Mean	Std. Dev.	Min	Max
Temperature	10 °C	145,490	0.97	0.40	0	1.50
Precipitation	1000 mm	145,490	0.40	0.18	0	0.66
Elevation	1000 m	145,490	0.34	0.49	0	2.72
Slope	10°	145,490	0.24	0.27	0	2.68
Population	100 person/km^2	145,490	2.86	6.77	0	194.13
GDP	Million yuan/km^2	145,490	14.90	85.39	0	4668.85
Carbon emission	100 ton/km^2	145,490	0.50	8.90	0	1690.38
Percentage of built-up land	%	145,490	0.01	0.02	0	0.10

Socio-economic factors, including population, GDP, carbon emission, and built-up land, mark the impact of human activities on the urban ecosystem. As an important approach to regional sustainable development, urban resilience is a coordinated and optimized combination form of multiple factors such as economy, population, land and market. Among them, the built-up area is the spatial carrier of regional resource convergence and diffusion, which influences urban resilience through multiple forms of resource combination. Reasonable population spatial pattern and economic development pattern are the main ways for cities to deal with natural disasters and urban diseases. In the study region, the selected socio-economic indicators all show the characteristics of clustering towards the urban center (Figure 3e–h).

The multiple linear regression results show that from the biophysical side, ecological resilience in the BTHUA region decreases with the increase of temperature and precipitation, showing that ecosystems in the high temperature and heavy rainfall areas in this region are less stable. Resilience decreases by 0.0389 for every 10-degree Celsius increase in temperature, and by 0.0089 for every 1000 mm precipitation increase, and the results are significant with a P value less than 0.001 (Table 2). Elevation and slope determine the spatial distribution of vegetation types to a large extent, and the degree of ecological resilience increases with the increase of average elevation in the region, with a 0.0093 increase in ecological resilience for every 1000 m elevation increase. In addition, ecological resilience in the study region increases by 0.0303 with every 10-degree slope increase. The system resilience is significantly correlated with topography (with P values both less than 0.001).

However, from the socio-economic side, urban ecological resilience is positively related to GDP and negative related to population and built-up land. For every extra 100 people per unit km^2 area, resilience decreases by 0.0187%, while when built-up land expands, resilience tends to decrease significantly. For every 1 million increases in GDP per unit km^2 area, resilience increases by 0.00187%. It shows that the level of economic development has a significant positive impact on urban resilience. This can be attributed to the high overall economic development level in the BTHUA region; resources could be allocated to technological (new technologies that increase resources efficiency and reduce pollution) and institutional (stringent environmental protection policies and enforcements) advancement, generating benign ecological and environmental effects.
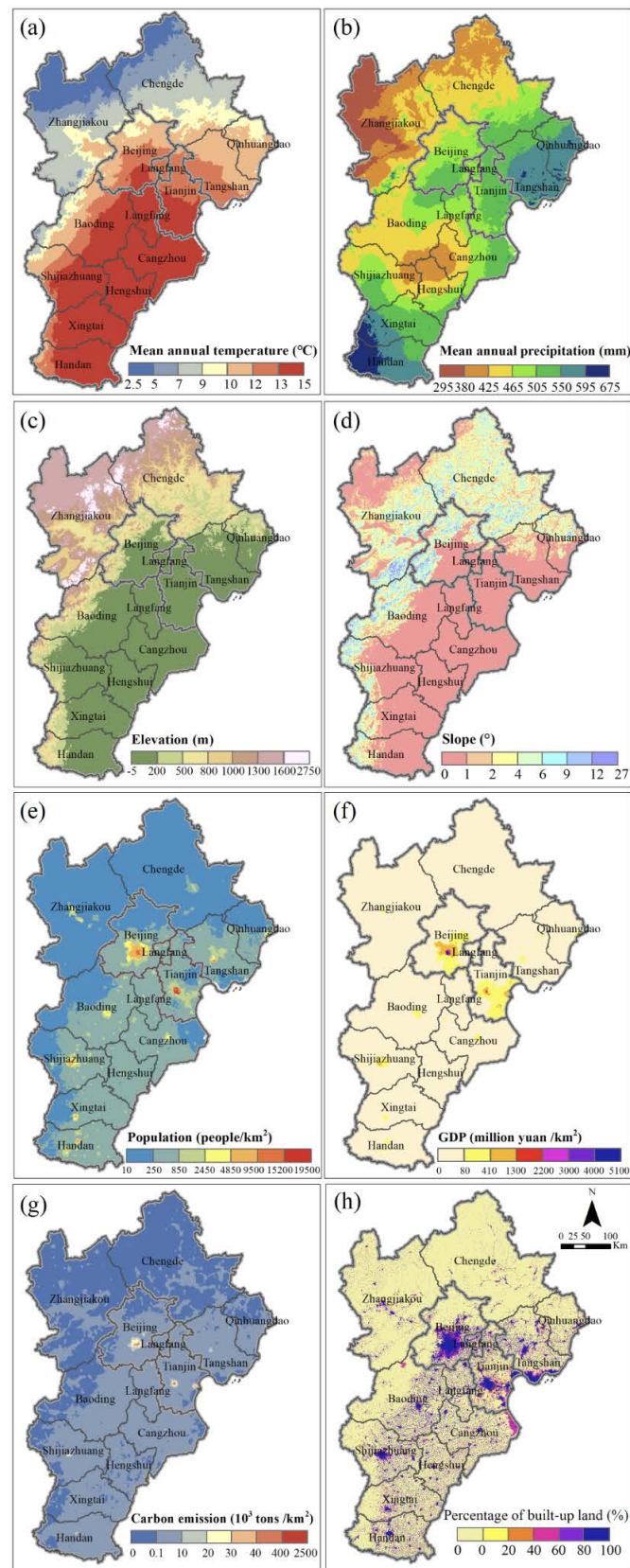
Figure 3. Spatial pattern of resilience impact factors. (**a**) temperature; (**b**) precipitation; (**c**) elevation; (**d**) slope; (**e**) population; (**f**) GDP; (**g**) carbon emission; (**h**) built-up land.

Table 2. Regression results of the resilience impact factor analysis.

Ecological Resilience	Coef.	Std. Err.	T Value	P > |t|	[95% Conf.]	[Interval]
Temperature	−0.0389109	0.0003445	−112.94	0	−0.0395862	−0.0382357
Precipitation	−0.0089104	0.0006421	−13.88	0	−0.010169	−0.0076518
Elevation	0.0093375	0.000271	34.46	0	0.0088064	0.0098687
Slope	0.0303164	0.0004737	63.99	0	0.0293879	0.0312449
Population	−0.0001872	0.0000214	−8.76	0	−0.000229	−0.0001453
GDP	0.0000187	1.56×10^{-6}	11.98	0	0.0000156	0.0000218
Carbon emission	7.94×10^{-6}	0.0000128	0.62	0.536	−0.0000172	0.0000331
Percentage of built-up land	−0.2533065	0.0072481	−34.95	0	−0.2675127	−0.2391003
Constant	0.5158112	0.0004737	1088.84	0	0.5148827	0.5167396

Along with urbanization in this region, ecological resilience decreases with population boost and built-up land expansion and increases with GDP growth; this indicates that, though urban expansion takes up resources, causes pollution and reduces ecological resilience, with technological and institutional progress generated by economic growth, the negative environmental impact could be mitigated and we could eventually reach the coordinated development of social economy and ecological environment. In addition, as ecological resilience is calculated from NPP change, it shows the destruction of vegetation by population expansion and urbanization. However, such damage could be mitigated by technological advances and institutional change along with economic development. The results in this study are consistent with mainstream environmental theories such as the Porter Hypothesis (the Porter Hypothesis holds that strict environmental standards stimulate innovation and improve environmental quality to offset the conflict between economic development and environmental protection [47,48]. Interpretations of the Porter Hypothesis show that stringent environmental regulations boost the environmental services sector, induce technological innovation, and provide some firms with an early mover advantage; large firms benefit more than small firms because of their lower compliance costs [49]), the Environmental Kuznets Curve (the Environmental Kuznets Curve (EKC) holds that economic modernization will reconcile the conflict between economic and environmental interests [50]. EKC is about the relationship between environmental degradation and growth at different levels of economic development. At low levels of income, people pay attention to growth and worry little about the environment, so growth produces degradation; at higher incomes, people pay more attention to the environment compared to growth, therefore degradation declines with increasing incomes, making the relationship between growth and degradation takes the shape of an upside-down U) and Ecological Modernization (Ecological Modernization is a model of environmental governance originating from Europe in the 1980s, which holds that the capitalist economy could solve this problem through technological advances that mitigate the trade-off between economy and environment, with the participation of civil society actors in addition to state and market actors in a democratic setting [51–53]. According to ecological modernization theory, the conflict between industrial development and environmental protection could be resolved through environmental innovation without fundamental changes to production and consumption) theories.

5. Discussion and Conclusions

In this study, with the BTHUA as the case study area, urban ecological resilience and its spatial pattern are assessed to quantify the ecological impacts of urbanization. The results of the ecological resilience assessment show high ecological resilience areas are mainly in ecological land with forest and grassland as the main landscape. Therefore, it is important to protect key ecological resources to improve resilience through the provision of ecosystem services [54]. The current "Planning for major ecological protection and restoration projects in the northern sand control belt" in this region should be duly implemented. In addition, as the results indicate the difference in spatial resilience pattern, with the overall spatial pattern

being characterized by high resilience in the northwest and relatively low resilience in the southeast, future development in the BTHUA region should adhere to the spatial orientation of regional coordinated development, which position Hebei as the ecological support area and Beijing as the ecological restoration demonstration area. This also indicates that the use of geospatial information on resilience could provide effective management references [55].

The resilience impact factor analysis integrates both natural-physical and socio-economic indicators. From the physical side, climate and topographical factors are found to have a significant impact on urban ecological resilience. From the human side, the economy, population and land use are also correlated with urban resilience. The empirical case in the BTHUA region indicates that along with urbanization, ecological resilience is negatively related to population and built-up land expansion and positively related to GDP growth. To explore the reasons for such an impact, although urban expansion utilizes resources, causes pollution and reduces resilience, economic growth and technological and institutional advancement could mitigate negative ecological impact. The findings are consistent with the Environmental Kuznets Curve, the Porter Hypothesis, and Ecological Modernization theory and the like, which also examine the environmental/ecological impact of socio-economic development. With further economic development in this area, the environmental and ecological burden could be eased with advanced technology and stringent regulation. The carbon neutrality scheme, for example, is a case in point, as it promotes technological (e.g., energy efficiency increase, electrification, renewable energy technology, etc.) and institutional changes (e.g., carbon pricing, carbon tax, carbon market, green finance, etc.) to conserve resources and reduce pollution.

The empirical results in this study provide important policy references for future urbanization, carbon neutrality, resilience building and urban ecological management in this region in specific and in China in general. With the findings on the ecological impact of urbanization in this study, future urbanization in China should integrate the concept and principles of ecological civilization into the whole process of urbanization and pursue a new type of urbanization characterized by an intensive, smart, green and low-carbon growth pattern (both ecological civilization and new-type urbanization are political discourses in China. Ecological civilization was first introduced into Chinese ideology in 2007 at the 17th Congress of the Communist Party, endorsed by President Xi in 2013 in environmental law and policy-making and written into the constitution in 2018. It aims at solving ecological and environmental problems with technological innovation as well as improved governance institutions. New-type urbanization is a guideline put forward in the report of the 18th National Congress of the Communist Party. New-type urbanization is characterized by urban-rural integration, city-industry interaction, conservation and intensification, ecological livability and harmonious development. It is characterized by coordinated development and mutual promotion of large, medium and small cities, small towns and new-type rural communities). With the carbon neutrality program expecting to drastically change the industrial structure as well as urban-rural relations, it is very important for the future urban development mode to find a realistic path of carbon neutrality from the coordination of urban and rural ecology. Carbon neutrality itself would contribute to the strengthening of urban resilience, and urban resilience governance should focus on all urban subsystems, including economic, social, natural and built-up environment, etc., as system elements interacting with each other and contributing to the emergence of the complex urban system.

To explore the change mechanism of urban ecological resilience from the perspective of resilience characteristics and the temporal and spatial differences of urban ability to prevent and defuse ecological risks, we clarify that the important task of ecological governance in urban zones is a favorable way to realize ecological risk prevention and control in resilient cities. In previous studies, resilience assessment can be categorized into two groups: compound index systems that capture as many resilience characteristics as possible and the use of a single indicator as a resilience surrogate. Though compound index systems excel in capturing complex resilience characteristics, they are generally based on static

indicators and describe system states. However, for single indicator evaluation, threshold-crossing can be measured. In this study, the change rate of NPP is measured to characterize threshold-crossing. In addition, the resilience surrogate methods that use a single indicator require fewer data and are more operable in empirical studies. The resilience evaluation index in this study can easily be applied in other cases with available data.

The urban ecological resilience index we built is a methodological contribution as well as a new conceptualization of ecological resilience, which uses the NPP change to quantify the sensitivity and adaptability of urban ecosystems to shocks. With the urban system as a special type of ecosystem that integrates human activities with natural habitat, and with its complex adaptive system nature, the analysis in this study integrates urban elements in different dimensions and analyzes their impact on urban ecosystem resilience. The application of complex adaptive system theory in ecosystem resilience research is also one of the theoretical contributions of this study to further bridge social–physical complex networks, as previously done by Cavallaro et. al. [56]. One empirical advantage of this study is that it was conducted on a grid-scale, while most other urban resilience research is done on a prefectural city level. Further, as we were constrained by the availability of grid-scale socio-economic data, which generally depend on administrative statistical units, some key factors (for example, industrial structure) might be omitted in this research. This constitutes our future research agenda, provided that fine-scale data are available or when the research is conducted upscale.

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