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Ecological Vulnerability Assessment and Spatiotemporal Characteristics Analysis of Urban Green-Space Systems in Beijing–Tianjin–Hebei Region

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Abstract: The evaluation and analysis of the ecological vulnerability of urban green-space systems are conducive to the sustainable development of urban green-space systems. Taking the urban green-space system in the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020 as the research object, an ESSR model was first constructed, and a total of ten types of impact factors were integrated into the four dimensions of "Exposure, Sensitivity, State and Response". The weight of the impact factors was objectively determined via spatial principal component analysis, and the ecological vulnerability of the urban green-space system was evaluated via superposition analysis; the evaluation's results were graded. Moreover, the transfer matrix, center-of-gravity migration model, standard deviation ellipse, and spatial autocorrelation analysis were used to study the temporal and spatial variation characteristics of the evaluation results; then, the driving force of impact factors was analyzed based on a geographical detector. Finally, the rationality of the evaluation results was verified using the changing trend of the remote sensing ecological index (RSEI). The results show that the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region has decreased year by year for the past ten years. The distribution law of "Hebei surrounds Beijing and Tianjin" is presented in this space, and 2015 is the mutation node. In 2010, the moderately and severely vulnerable areas of Hebei surrounded the mildly vulnerability areas of Beijing and Tianjin. Moreover, in 2015 and 2020, the mildly vulnerable areas of Hebei surrounded the severely vulnerable areas of Beijing and Tianjin. Vulnerability expands slightly in the east–west direction and shrinks slightly in the north–south direction, and the center of gravity shifts towards Beijing year by year along the northeast direction. Moreover, the spatial distribution of vulnerability shows significant positive spatial autocorrelations and exhibits very obvious agglomeration. In addition, vulnerability is the result of the combined effect of various factors, and education degree, human disturbance index, and annual average precipitation are the dominant factors. The analysis results provide a reference for the effective application and sustainable development of urban green-space ecological functions.

Keywords: Beijing–Tianjin–Hebei region; urban green-space system; ecological vulnerability assessment; ESSR model; sustainability

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1. Introduction

With the rapid expansion of the city, urban green spaces are decreasing, and urban development and human activity require substantial urban green space, which makes the contradiction between the supply and demand of urban green spaces increasingly prominent. As one of the important components of the urban ecosystem, the urban green-space system can effectively reduce the serious constraints of the urbanization process on the urban–ecological environment, which is conducive to human physical and mental health [1,2], and it plays a positive role in restoring the urban environment, protecting the diversity of urban species, and improving the urban heat-island effect. Therefore, this study deeply explores the urban green space and analyzes its ecological vulnerability. The research results are conducive to further alleviating the contradiction between the supply and demand of urban green space [3–5].

In recent years, some scholars have mainly studied the social service function of urban green-space systems. Through the study of urban green-space planning and development, Covadonga et al. [6] identified the most critical factors affecting the sustainable development of urban societies and ecology. Lydia et al. [7] studied the correlation between urban green space and residents' life satisfaction. Shishir et al. [8] supported the future master plan for urban green spaces by formulating sustainable management policies for them. Syrbe et al. [9] raised the supply of urban green spaces to a strategic level. Other scholars' research on urban green-space systems mainly focuses on ecological benefit evaluation, landscape-quantity evaluation, and the comprehensive evaluation of green-space systems. Yeonsu et al. [10] studied the ecological benefits of urban green-space systems from the perspective of carbon storage in urban green spaces. In terms of landscape quantity evaluation, the main research indicators are also based on the per capita green area, green rate, and green landscape pattern. In the comprehensive evaluation of urban green spaces, "3S" technology is mainly used, combined with the evaluation model, and factors such as the number and area of green spaces are considered to evaluate the urban green-space system. These include economic benefit evaluation [11], emergency disaster-prevention evaluation [12], and social-service-function evaluation [13].

Based on existing research results, research on urban green-space systems still has the following shortcomings. First of all, with respect to current research on urban green-space systems, it emphasizes the value and role of urban green-space systems in contributing to human society but ignores the disturbance and influence of natural factors and human social factors on urban green-space systems. Secondly, under the influence of natural and human factors, urban green-space systems will show different degrees of vulnerability. The fragile urban green-space ecosystem is not only threatened by sustainable development but it is also limited in value. Therefore, the ecological vulnerability assessment of urban green-space systems not only helps people correctly understand green spaces, but also provides important theoretical support for the effective application and sustainable development of urban green spaces' ecological functions [14].

Based on the above shortcomings, this study constructs an ESSR "Exposure–Sensitivity–State–Response" model for the vulnerability of the urban green-space ecosystem in the Beijing–Tianjin–Hebei region, and it combines natural, social, and human factors to select influencing factors. The spatial principal component analysis method is used to objectively determine the weight of the factors, and GIS overlay analyses are used to quantitatively classify vulnerability to construct an urban green-space ecological evaluation index system and quantitatively measure the ecological vulnerability of urban green spaces. Furthermore, the development status of the urban green space in the Beijing–Tianjin–Hebei region is analyzed using a transfer matrix, spatial autocorrelation, standard deviation ellipse, center-of-gravity migration model, geographical detector, and other methods in order to explore the spatial and temporal distribution of ecological vulnerability in the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020. Its impact factors are analyzed thoroughly, revealing the main factors affecting the spatial pattern, in order to provide references for urban green-space planning and urban ecological sustainable development strategies for the Beijing–Tianjin–Hebei region.

2. Materials and Methods

2.1. Methodological Design Flow

Figure 1 shows the details of this study (Figure 1), which includes five parts: ESSR assessment system, ecological vulnerability assessment, spatio-temporal changes in ecological vulnerability, ecological vulnerability impact factors, and ecological vulnerability-assessment result tests.

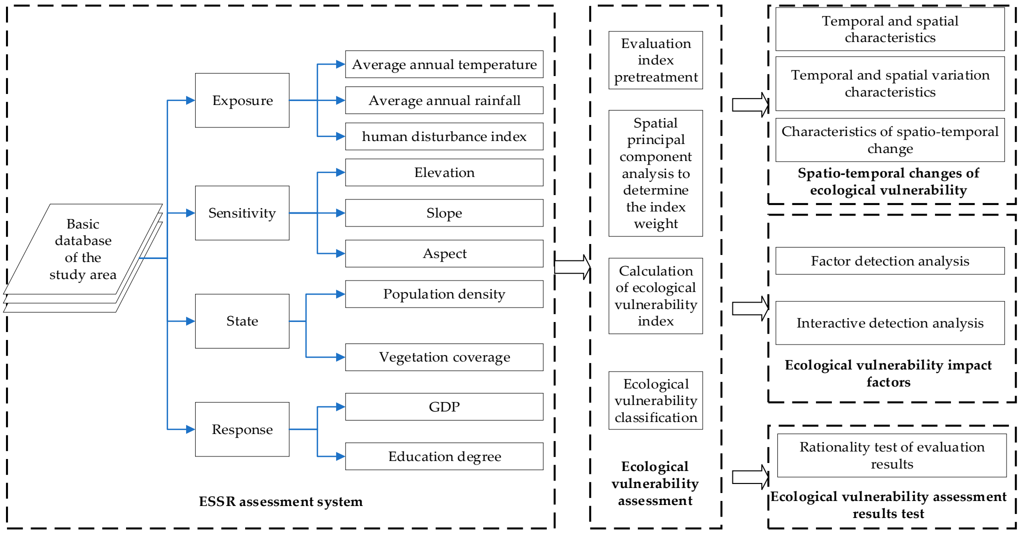


Figure 1. The framework of the research idea and methodology.

2.2. Study Area

The Beijing–Tianjin–Hebei urban agglomeration, which is located in the northern part of the North China Plain, comprises the third step of China's terrain. It is China's "capital economic circle" and the most important political, cultural, and economic core area in China.

Its geographical range is within 36°05′ N~42°37′ N, 113°27′ E~119°50′ E, its altitude is below 3000 m, its average annual precipitation is 400~800 mm, and the average temperature is 12 °C. The total area of the Beijing–Tianjin–Hebei region is 216,000 km^2, and the regional topography is complex and diverse. In 2020, the population of the Beijing–Tianjin–Hebei region reached 112.7 million, and the total GDP reached CNY 8.6 trillion. The level of urbanization is high but the ecological environment is overloaded. Thanks to several major ecological construction projects such as the Three North Shelterbelt, the regional ecological environment quality has improved in recent years, and the ecological degradation rate has slowed down (Figure 2).

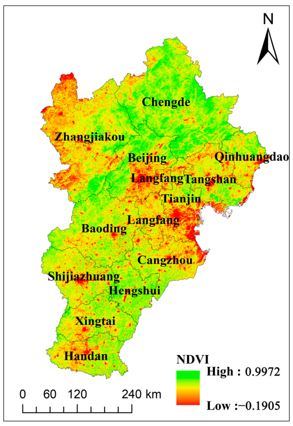


Figure 2. The boundaries of the Beijing–Tianjin–Hebei urban agglomeration.

2.3. Data Collection and Processing

The research data mainly include the remote sensing data, meteorological data, socio-economic data, etc., of the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020.

Remote sensing data include the normalized difference vegetation index (NDVI) and NPP/VIIRS night-time light data. NDVI data were obtained from MOD13Q data, and the set was downloaded from the EarthData website (https://search.earthdata.nasa.gov/ (accessed on 10 May 2023)). The maximum NDVI value of each year was calculated using the maximum synthesis method. NPP/VIIRS night-time light data from the Earth Observation Group were used (https://eogdata.mines.edu/products/vnl/ (accessed on 12 May 2023)), which belong to the National Environmental Information Center of the National Oceanic and Atmospheric Administration (NOAA) of the United States. The data were obtained for the spatialization of GDP data. Due to the lack of 2010 data, the data were replaced by 2012 data.

Meteorological data, including annual average precipitation and annual average temperature, were obtained from the National Earth System Science Data Sharing Service Platform—Loess Plateau Science Data Center (http://www.geodata.cn/data/ (accessed on 10 May 2023)).

Terrain data are mainly based on digital elevation model (DEM) data. The data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/ (accessed on 15 May 2023)), and they were divided according to administrative divisions using software. Based on the digital elevation model data, the slope and aspect data were calculated using the spatial-analysis function of the software.

Socioeconomic data include the human disturbance index, population density, and education degree. The human disturbance index was calculated from the annual land cover dataset of China, which was produced by Yang Jie and Huang Xin of Wuhan University based on Landsat images [15]. Population density data were obtained from the Distributed Active Archiving Center (DAAC) (https://sedac.ciesin.columbia.edu/ (accessed on 12 May 2023)) in the Socioeconomic Data and Applications Center (SEDAC) and Information System (EOSDIS) of the National Aeronautics and Space Administration (NASA) of the United States. The education degrees obtained from the statistical yearbooks of provinces and cities from 2010 to 2020. In order to facilitate subsequent calculations, the coordinate system of the data was finally unified as the WGS_1984_Albers projection coordinate system, and accuracy was unified to 1 km.

2.4. Methods

2.4.1. ESSR Model

The ecological vulnerability of the urban green-space system is a comprehensive representation of the degree of disturbance caused by the environment and society relative to urban green-space ecosystems, the sensitivity of urban green-space ecosystems to external stress or pressure, the state of an urban green-space system at a specific time, and the preventive behavior formulated by government departments for stable development.

Due to the rapid development of the Beijing–Tianjin–Hebei urban agglomeration, problems caused by human disturbances, such as increased population and accelerated urbanization, gradually emerged [16]. Coupled with the impact of climate change, these factors have exposed the green-space system to substantial external pressures. In addition, the urban agglomeration comprises a large number of cities of different natures, types, and scales that fall within a specific range, also rendering the urban agglomeration one of the most sensitive areas of the ecological environment. Therefore, its sensitivity will determine the impact of external pressure on the urban green-space system; exposure and sensitivity together produce a potential pressure source that affects the ecological vulnerability of the urban green-space system. In the face of potential pressure sources, the final impact of the urban green-space system can be determined by the state of the system itself and the corresponding action of the government.

Therefore, this study fully considers the comprehensive characterization of the ecological vulnerability of the urban green-space system. From the perspective of the generation and final impact of the pressure source, the characteristics of the urban green-space system are integrated, and the exposure and sensitivity of the VSD (exposure, sensitivity, and adaptability) model are introduced. This improves the problem that the PSR model (pressure, state, and response) ignores, which is the importance of exposure to the structure and function of the urban green-space system, and it emphasizes the sensitivity of the ecological vulnerability of the urban green-space system relative to its structural composition for disaster stress [17]. Using a combination of the exposure and sensitivity dimensions of the VSD model, the potential impact of the pressure source is defined. The state and response dimensions of the PSR model are retained to explain the final impact of the pressure source [18]. The model is further expanded to four dimensions. From the perspective of the pressure source, the state and sensitivity of the urban green-space system, the exposure response process and the final vulnerability results are comprehensively considered. The consideration draws on the advantages of the hierarchical organization method and clear process specification of the VSD model [19]. Simultaneously, it retains the advantages of the PSR model and embeds causal logic thinking [20]. Based on the two models, this study proposes the "Exposure-Sensitivity-State-Response" ESSR model. The interaction of the four dimensions of the model constitutes the logical relationship of "what happened, the size of the impact, the results produced, and how to deal with it", as shown in Figure 3.

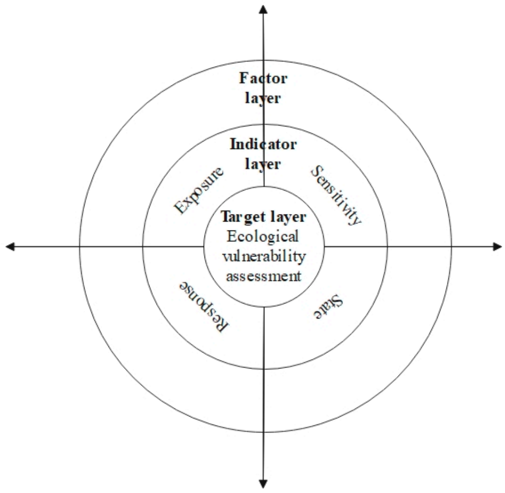


Figure 3. The architecture of the ESSR model.

2.4.2. ESSR Evaluation Model Index System

The research method of the ecological vulnerability evaluation index system of urban green-space systems should first be based on the ESSR model in order to explore the main impact factors affecting the ecological vulnerability of the urban green-space system. The selection of the ecological vulnerability impact factors of the urban green-space system in the Beijing–Tianjin–Hebei region is based on five principles: being scientific, systematic, comprehensive, applicable, and regional. Currently, in the study of the urban green-space ecosystem, related research on ecological vulnerability is scarce. Therefore, based on referring to international vulnerability models and assessment frameworks, this study draws on the relevant literature on urban ecological vulnerability index systems [21,22], as well as the ecological vulnerability index system of an urban green-space system, reported by Zhang et al. The concept and framework of urban vulnerability in China [23], the conceptual framework of regional ecological sustainability assessment based on the PSR model [24], and the framework of ecosystem vulnerability in semi-arid areas based on the VSD model [25] are used as references. Based on the analysis of the model's framework, the natural and social factors of the study area and the development law of the research object are fully considered. After combing and analyzing the frequency, applicability, and accessibility of different impact factors in many studies, impact factors were selected from the perspective of scientificity and objectivity [26]. At the same time, the selection of factors should also include natural, social, and human factors, in order to ensure that the impact factors can comprehensively evaluate the ecological vulnerability of the research object. In summary, the index system constructed based on the ESSR model is divided into the goal layer, the indicator layer, and the factor layer. The goal layer is the first level, the purpose of the evaluation is controlled from the core, and the evaluation results of the ecological vulnerability of the urban green-space system in Beijing, Tianjin, and Hebei are expressed. The indicator layer comprises the second level, which explains the evolution of ecological vulnerability relative to four dimensions: exposure, sensitivity, state, and response. The factor layer comprises the third level, and it is mainly the impact factor of the ecological vulnerability assessment of the Beijing–Tianjin–Hebei urban green-space system.

Exposure refers to the degree of the interference of environmental and social pressure on the urban green-space system, which is a parameter reflecting the degree of interference or stress from the outside world. The impact factors of exposure include annual average temperatures, annual average precipitation, and the human disturbance index. The annual average temperature (Figure 4a) is a direct reflection of whether the study area is suitable for the development of the urban green-space ecosystem. The higher the annual average temperature, the lower the ecological vulnerability of the urban green-space system. Annual average precipitation (Figure 4b) reflects the meteorological and hydrological conditions in the study area. As annual average precipitation increases, the ecological vulnerability of the urban green-space system will decrease with the increase in water resources introduced by precipitation. The human disturbance index (Figure 4c) is the expression of the disturbance degree of human activities to the urban green-space-system ecosystem [27,28].

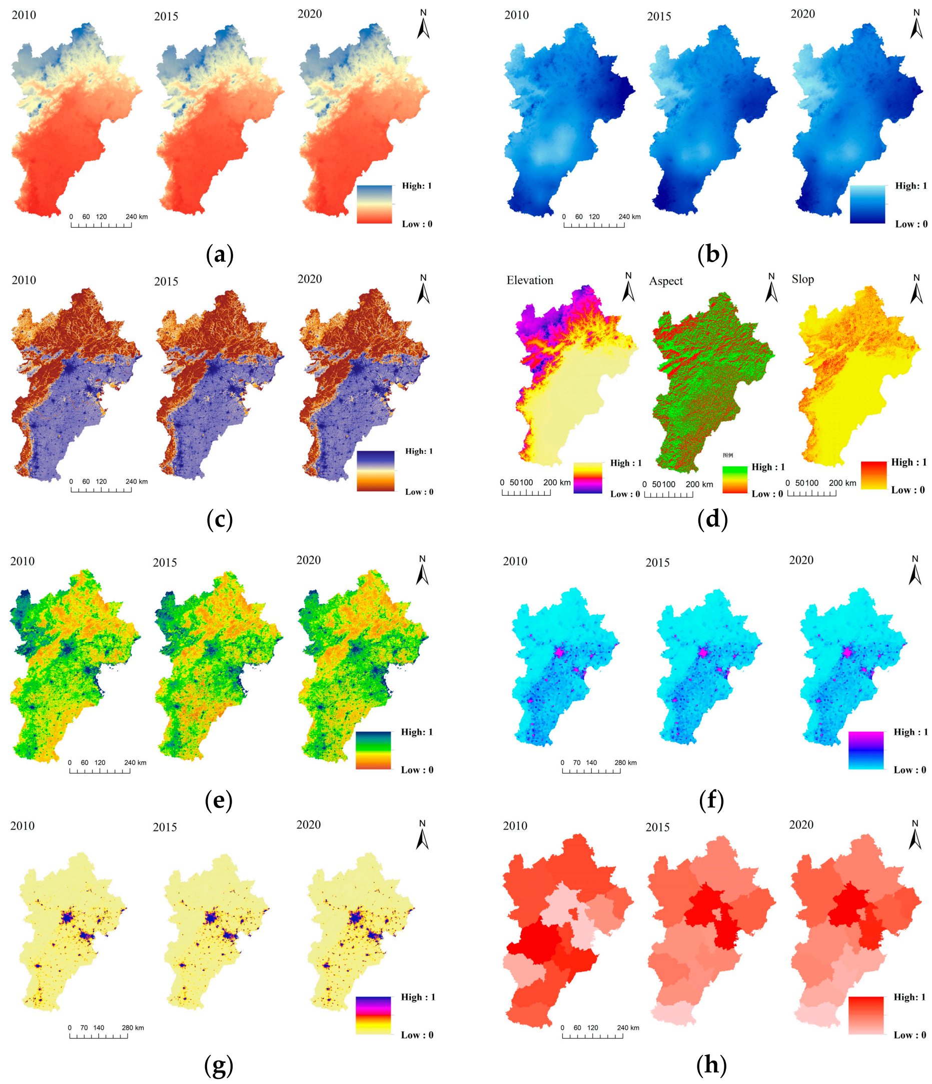


Figure 4. The impact factors of the ecological vulnerability assessment of the urban green-space system in the Beijing–Tianjin–Hebei region. (**a**) The annual average temperature. (**b**) The annual average precipitation. (**c**) The human disturbance index. (**d**) The digital elevation model, aspect, and slope. (**e**) The vegetation coverage. (**f**) The population density. (**g**) GDP. (**h**) The education degree.

Sensitivity is a measure of the degree of difficulty between the stress and the consequences of the urban green-space system. Sensitivity is related to the critical conditions of the destruction of the urban green-space system. It can be reflected by natural resource conditions and topographic features. Among them, topographic features are the basis of ecological environment sensitivity (Figure 4d) [29]: the digital elevation model is one of the important topographic factors. By observing the digital elevation model, human disturbance relative to the urban green-space system is becoming increasingly obvious. Moreover, the slope is an important factor in measuring the influence of the natural environment on the urban green-space system. The larger the slope, the more unfavorable it is to the development of a green-space system. Finally, the aspect represents the southerly area, which experiences substantial amounts of light, the rapid evaporation of water, and frequent human activities; thus, the vulnerability of the urban green-space system will be higher.

The state indicates the state of the urban green-space system when subjected to natural and human pressures [30]. It includes the state of the urban green-space system after experiencing changes, as well as other changes that occur in the state of the urban green-space system after the initial change. Therefore, the state factors include two impact factors: population density and vegetation coverage. Vegetation coverage (Figure 4e) represents the state of the urban green space ecosystem, and vegetation coverage is directly related to the ecological vulnerability of the urban green-space system. Moreover, it exhibits a negative correlation: the higher the vegetation coverage, the lower the ecological vulnerability of the green-space system [31]. Population density represents the state of human life (Figure 4f). The change in the urban green-space system may lead to the emergence of the urban ecological problems, the deterioration of ecological environment, and the introduction of impacts on human living conditions; moreover, changes may also cause reactions in the urban green-space system.

Response refers to the possible impact on the natural environment and human behavior. In this study, government departments formulate mitigation or solutions for the stable development of the urban green-space system [32]. Using GDP and residents' education degrees, GDP (Figure 4g) is an important criterion for measuring the quality of social and economic development. The higher the GDP, the better the social and economic benefits; the greater the government's financial investment in protecting the environment, the lower the ecological vulnerability of the urban green-space system [33]. The education degree (Figure 4h) refers to the government's and individual's behavior in improving the cultural level and raising awareness of ecological protection through education in order to reduce or prevent the destruction of the ecological environment. It is generally believed that the higher the degree of education, the lower the ecological vulnerability [34].

2.4.3. Index Weight Calculation of ESSR Model

1. Standardized Treatment of Impact Factors

In order to solve the dimension problem of the impact factors of the ecological vulnerability evaluation index data of the urban green-space system, range standardization was carried out [35]. In addition, there are two types of impact factors in the index. One is the positive impact factor. Such indicators are generally considered to be better when their values are greater, and Formula (1) is used for their calculations. There is also a class of negative impact factors. Such indicators are generally required to be as low in value as possible, and Formula (2) is used for their calculations. The formulas are as follows:

$$M_{ij} = \frac{Y_{ij} - \min(Y_{ij})}{\max(Y_{ij}) - \min(Y_{ij})} \tag{1}$$

$$M'_{ij} = \frac{\max(Y_{ij}) - Y_{ij}}{\max(Y_{ij}) - \min(Y_{ij})} \tag{2}$$

In the above formulas, Y_{ij}, M_{ij}, and M'_{ij} are the original value and standardized value of the *j* index in the *i* year; max (Y_{ij}) and min (Y_{ij}) are the maximum and minimum values of index *j*, respectively.

2. Principal Component Analysis

Firstly, the cumulative contribution rate of each impact factor is calculated using Formula (3) via the feature vector of the impact factor. The cumulative contribution rate is used to determine the number of main factors in the evaluation. When the cumulative contribution rate exceeds 90%, the number of main factors is determined [36].

$$a_i = \lambda_i / \sum_{i=1}^{m} \lambda_i \quad (3)$$

In the formula, λ is the eigenvector value.

When the number of main factors is determined, the variance of common factors is calculated according to Formula (4).

$$H_j = \sum_{k=1}^{m} \lambda_{jk}^2 \quad (4)$$

In the formula, H_j is the common factor variance; m is the number of principal factors; $\lambda^2{}_{jk}$ is the eigenvalue of factor j relative to principal component k. In this study, $m = 9$ and $j = 10$. Finally, the weight of each evaluation index can be obtained using Formula (5):

$$p_i = w_j = H_j / \sum_{j=1}^{10} H_j \quad (5)$$

In the formula, w_j is the relative weight of evaluation index *j*. The results are shown in Table 1.

Table 1. Index system and weight of the ESSR model.

Goal Layer	Indicator Layer	Factor Layer	Positive (+) or Negative (−)	Factor Weight in 2010	Factor Weight in 2015	Factor Weight in 2020
Ecological vulnerability assessment of the urban green-space system in Beijing–Tianjin–Hebei	Exposure	Annual average temperature	−	0.142	0.125	0.125
		Annual average precipitation	−	0.134	0.125	0.125
		Human disturbance index	+	0.143	0.125	0.125
	Sensitivity	Digital elevation model	−	0.045	0.109	0.107
		Aspect	+	0.006	0.014	0.017
		Slope	+	0.143	0.125	0.125
	State	Population density	+	0.005	0.009	0.008
		Vegetation coverage	−	0.143	0.125	0.125
	Response	GDP	−	0.109	0.118	0.118
		Education degree	−	0.130	0.125	0.125

2.4.4. Ecological Vulnerability Classification of the Urban Green-Space System

This is based on the domestic and international ecological vulnerability-rating criteria, combined with the actual characteristics of the Beijing–Tianjin–Hebei urban green-space system. The study used the natural breakpoint method to classify the ecological vulnerability index of the Beijing–Tianjin–Hebei urban green-space system in 2010, 2015, and 2020. The average value of the breakpoints in three years was taken as the classification basis, and the ecological environment's vulnerability was divided into five grades—slight vulnerability, mild vulnerability, moderate vulnerability, severe vulnerability, and extreme vulnerability [37]—which ensured the comparability of the evaluation results, as shown in Table 2.

Table 2. The classification of ecological vulnerability-assessment results of the urban green-space system in the Beijing–Tianjin–Hebei region.

Vulnerability Degree	Grade	Vulnerability Index	Ecological Character
Slightly vulnerable	I	<0.334	Exposure and sensitivity are extremely low; the green-space system is in good condition; and social response is timely. It exhibits strong resistance when encountering internal and external pressure.
Mildly vulnerable	II	0.334–0.399	Slight exposure and sensitivity; the state of the green-space ecosystem is generally fine; and social response is timelier. When encountering internal and external pressure, it exhibits strong resistance.
Moderately vulnerable	III	0.399–0.458	Has a certain degree of exposure and sensitivity; the state of the green-space ecosystem is poor; and social response is slow. It exhibits weak resistance when encountering internal and external pressure.
Severely vulnerable	IV	0.458–0.523	It has high exposure and sensitivity; the state of the green-space ecosystem is very poor; and social response is slow. When encountering internal and external pressure, it has a weak resistance.
Extremely vulnerable	V	>0.523	It has extremely high exposure and sensitivity; the state of the green-space ecosystem is bad; and social response is very slow. When faced with internal and external pressure, these areas do not have the ability to resist.

2.4.5. Spatio-Temporal Evolution Analysis Method of the Ecological Vulnerability of the Urban Green-Space System

1. Transfer Matrix

The transfer matrix can accurately quantify the transfer between states in the system during the research period. It can comprehensively and meticulously analyze the change characteristics with respect to the urban green-space system's ecological vulnerability, which is the basis for studying the structural change, and the directional change of the ecological vulnerability of the urban green-space system. According to the ecological vulnerability changes in the urban green-space system of Beijing–Tianjin–Hebei during different periods, a two-dimensional matrix was obtained. Carrying out an analysis of the two-dimensional matrix, the mutual transformation between the vulnerability degrees of the two periods can be obtained.

2. Standard Deviation Ellipse and Center-of-Gravity Migration Model

As one of the spatial statistical methods [38], the standard deviation ellipse can quantitatively explains the centrality, directionality, and expansion direction deviation of the urban green-space ecosystem's vulnerability. The center-of-gravity migration model can reflect the moving direction and distance of the ecological vulnerability gravity center of the urban green-space system, and it can reflect the change range and spatial difference of a certain geographical element within a certain period of time.

3. Spatial Autocorrelation Analysis

Spatial autocorrelation refers to the phenomenon that similar phenomena or objects in space show similar characteristics [39], and this is also observed in global and local hypothesis tests.

Global spatial autocorrelation is usually used to test the spatial pattern of the ecological vulnerability of urban green-space systems throughout the study area. It is usually calculated using global Moran's I, and the formula is as follows:

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} (x_i - \overline{x}) (x_j - \overline{x})}{\left(\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} \right) \left(\sum_{i=1}^{n} x_i - \overline{x} \right)^2} \tag{6}$$

In the formula, n is the number of spatial units involved in the analysis, x_i and x_j are the observed values of a certain attribute on space units i and j, respectively; x is the average value of a certain attribute in each space; W_{ij} is the spatial weight matrix; and I is the global spatial autocorrelation coefficient Moran's I.

The local Moran's I is the decomposition of the global Moran's I in each spatial unit, which can accurately reflect and grasp the aggregation and differentiation characteristics of spatial and adjacent units, and it highlights the aggregation state of the local ecological vulnerability areas of the urban green-space system. The formula is as follows:

$$I_i = \frac{(x_i - \overline{x}) \sum_{j=1}^{n} w_{ij} (x_j - \overline{x})}{\frac{1}{n} \sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{7}$$

In the formula, x_i and x_j are the observed values of an attribute on space units i and j, respectively; x is the average value of an attribute in each space; $\boldsymbol{w_{ij}}$ is the spatial weight matrix; and I_i represents the local Moran's I.

4. Geographical Detector

In this study, the single-factor and interactive detectors in the geographic detector [40,41] were used to quantitatively analyze the influencing factors of the spatial distribution of ecological vulnerability in the urban green-space system of the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020. The single-factor detector can quantify the spatial and temporal variation of ecological vulnerability between different independent variables, and it can detect the degree and size of its impact. The formula is as follows:

$$\mathrm{q} = 1 - \frac{\sum_{\mathrm{h}=1}^{L} N_{\mathrm{h}} \sigma_{\mathrm{h}}^2}{N\sigma^2} \tag{8}$$

In the formula, N = 1, 2. . ., for a specific type; L is the stratification of variable X or factor Y: that is, the classification or partition; N_h is the number of elements in layer h; and σ_h and σ are the variance of class h and the variance of the entire region, respectively. The range of q is [0, 1]. The larger the q value, the better independent variable X explains the change in ecological vulnerability Y, and vice versa is true as well.

The interaction detector is used to determine the interaction between different impact factors: that is, whether the interaction of evaluation factors will change its explanatory power to the ecological vulnerability index.

3. Results

3.1. The General Characteristics of the Spatial and Temporal Changes of the Ecological Vulnerability of the Urban Green-Space System in the Beijing–Tianjin–Hebei Region

3.1.1. Spatial and Temporal Distribution Characteristics of Ecological Vulnerability

The ecological vulnerability index of the urban green-space system in the study area in 2010, 2015, and 2020 was calculated using the ecological-vulnerability assessment method. The spatial distribution map of ecological vulnerability in the study area was obtained using the ecological-vulnerability classification method, and the results of different vulnerability levels within each period and the comprehensive index of ecological vulnerability were obtained.

The statistical results show that the average ecological vulnerability of the study area in 2010, 2015, and 2020 is 0.457075, 0.42809, and 0.422939, respectively. The larger the average value, the more fragile the overall ecology of the urban green-space system in the study area, and the poorer the ecological environment. The ecological vulnerability value of the urban green-space system in this study exhibited a steady downward trend. In terms of the proportion of each graded area, taking 2020 as an example, slight vulnerability, mild vulnerability, moderate vulnerability, severe vulnerability, and extreme vulnerability account for 14%, 23%, 30%, 23%, and 10% of the total study area, respectively. Among them, the areas of mild vulnerability, moderate vulnerability, and severe vulnerability account for 76% of the total area. In terms of the area change of each grade, the area of the extremely vulnerable area decreased rapidly from 42,885 km^2 in 2010 to 21,038 km^2 in 2020. The area of mildly vulnerable areas has increased steadily, from 11,515 km^2 in 2010 to 29,662 km^2 in 2020 (Figure 5). This is mainly closely related to the policy changes in the Beijing–Tianjin–Hebei region. In 2010, the "Beijing–Tianjin–Hebei metropolitan area regional planning" and other policies were proposed, which resulted in the further rapid development of the region's economy, and disturbances to the environment increased. Since the 18th National Congress of the Communist Party of China, the construction of ecological civilizations was gradually promoted. With the implementation of policies such as the "Beijing–Tianjin–Hebei Collaborative Development Program" and the "Beijing–Tianjin–Hebei Collaborative Development Ecological Environment Protection Plan", Beijing–Tianjin–Hebei cities have invested heavily in ecological environment construction, resulting in a lower ecological vulnerability index in 2020 than that in 2010, and the ecological environment gradually improved. In general, from 2010 to 2020, the area of ecologically fragile areas exhibited a decreasing trend, and ecological vulnerability improved.

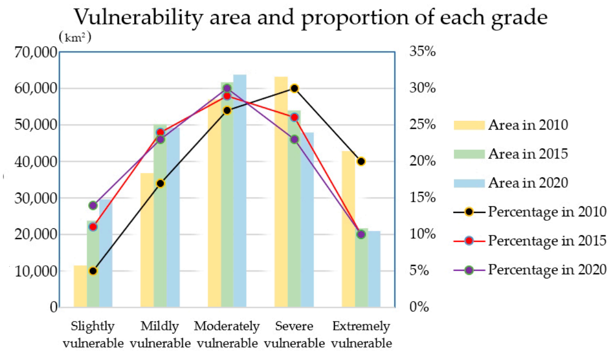


Figure 5. The vulnerability area and proportion of each grade.

From the perspective of spatial patterns, the ecological vulnerability of the study area has exhibited different spatial distributions in the past ten years, but the vulnerability characteristics are obvious, indicating that the ecological vulnerability of the Beijing–Tianjin–Hebei green-space system has a strong dependence on the urban distribution pattern. On the whole, the ecological vulnerability of the Beijing–Tianjin–Hebei region shows the following distribution law: "Hebei surrounds Beijing and Tianjin". In 2010, the ecological vulnerability of the Beijing–Tianjin–Hebei green-space system showed that the moderately and severely vulnerable areas of Hebei surrounded the mildly vulnerable areas of Beijing and Tianjin. The 2015 and 2020 distributions of mildly vulnerable areas in Hebei Province around severely vulnerable Beijing–Tianjin areas were observed. The slightly vulnerable and mildly vulnerable areas were mainly distributed in Beijing and Tianjin in 2010, and they were mainly distributed in Hebei Province in 2015 and 2020. The severely and extremely vulnerable areas changed from being mainly distributed in Hebei in 2010 to being mainly distributed in Beijing and Tianjin in 2015 and 2020 (Figure 6). This fully reflects the importance and development of the ecological environment in the Beijing–Tianjin–Hebei region since the "Beijing–Tianjin–Hebei Collaborative Development Outline" was put forward in 2014, when the effective construction of Hebei Province was the ecological environment-support area of the region.

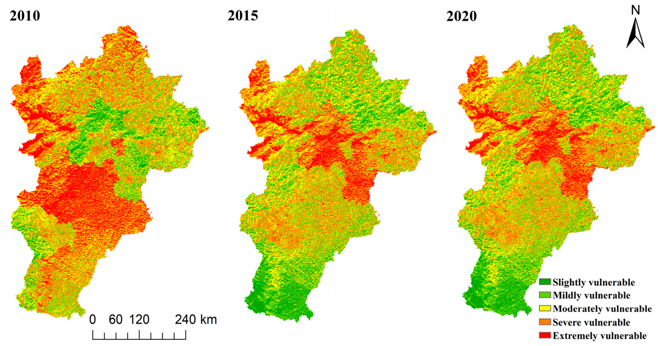


Figure 6. Spatial distribution of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region.

3.1.2. Spatiotemporal Evolution Characteristics of Ecological Vulnerability

According to the classification results of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region, the vulnerability transfer matrix of 2010, 2015, and 2020 was obtained using the superposition analysis function of the software. The 2010 transfer-out and 2015 transfer-in data are shown in the figure. Combined with Figures 7 and 8, it can be observed that the ecological vulnerability levels of the urban green-space system change frequently. In 2010, ecological vulnerability at all levels was transferred out of a total of 155,782 km^2, of which the severely and extremely vulnerable areas comprised the largest ones, with a total of 60,108 km^2 transferred out, accounting for 38% of the total area transferred out, mainly transferred to mildly and moderately vulnerable areas. In 2015, slightly vulnerable and mildly vulnerable areas accounted for the largest proportion, accounting for 37% of the total area transferred. The ecological vulnerability of the urban green-space system shows a significant improvement trend. From 2015 to 2020, the conversion between urban and green-space ecological vulnerability levels was significantly weakened. In 2015, a total of 35,053 km^2 was transferred out. Although this was mainly based on slight vulnerability and mild vulnerability in 2015, it was also based on the internal circulation of slight vulnerability and mild vulnerability, accounting for 52%. In 2020, the transfer was also dominated by slight vulnerability and mild vulnerability, accounting for 35%. The ecological vulnerability of the urban green-space system still maintained an improvement trend (Tables 3 and 4).

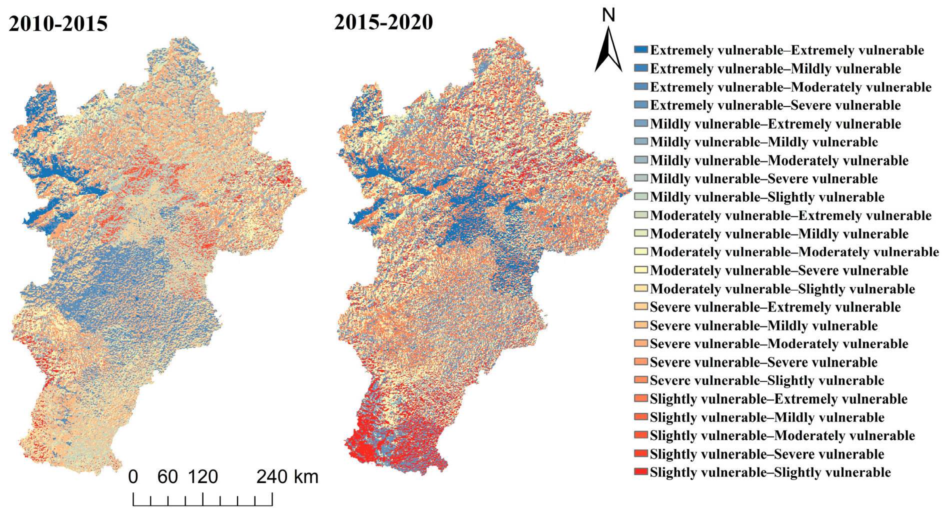


Figure 7. The spatial pattern changes of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020.

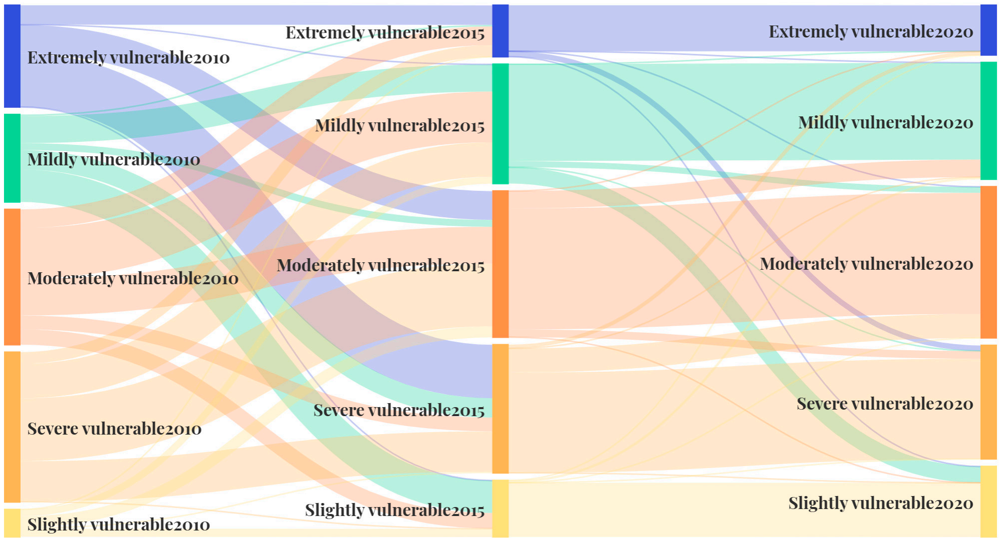


Figure 8. The mutual conversion area between different levels of ecological vulnerability from 2010 to 2020.

Table 3. The ecological vulnerability transfer matrix of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2015 (km^2).

	2010					
2015	**Extremely Vulnerable**	**Mildly Vulnerable**	**Moderately Vulnerable**	**Severely Vulnerable**	**Slightly Vulnerable**	**Grand Total**
Extremely vulnerable	8203	683	7869	4947	1	21,703
Mildly vulnerable	82	11,378	21,332	14,543	2897	50,232
Moderately vulnerable	12,119	2893	15,486	26,428	4658	61,584
Severely vulnerable	22,478	8152	5804	17,020	544	53,998
Slightly vulnerable	0	13,701	6493	158	3415	23,767
Grand total	42,882	36,807	56,984	63,096	11,515	211,284

Table 4. The ecological vulnerability transfer matrix of the urban green-space system in the Beijing–Tianjin–Hebei region from 2015 to 2020 (km^2).

	2015					
2020	**Extremely Vulnerable**	**Mildly Vulnerable**	**Moderately Vulnerable**	**Severely Vulnerable**	**Slightly Vulnerable**	**Grand Total**
Extremely vulnerable	19,382	0	2	1589	0	20,973
Mildly vulnerable	0	40,827	7357	2	978	49,164
Moderately vulnerable	0	2531	50,976	10,151	1	63,659
Severely vulnerable	2324	1	3244	42,260	0	47,829
Slightly vulnerable	0	6873	0	0	22,788	29,661
Grand total	21,706	50,232	61,579	54,002	23,767	211,286

3.1.3. Temporal and Spatial Variation Trend of Ecological Vulnerability

In this study, the land types that changed during the two research periods were extracted. The standard deviation ellipse distribution and center-of-gravity change of the two periods were obtained using spatial statistical software tools, which were used to explain the center of gravity, spatial form, ductility, and directionality of the ecological vulnerability of the urban green-space system within the study area. From the trajectory of the center-of-gravity change, during the period from 2010 to 2015, the center of gravity of the study area gradually moved northeast. At this stage, due to the proposal of the "Beijing–Tianjin–Hebei Collaborative Development Outline" in 2014, the Beijing–Tianjin–Hebei region attached importance to the ecological environment and developed it. In particular, Hebei Province has effectively constructed the Beijing–Tianjin–Hebei ecological environment-support area. Affected by the development policy, the focus of change has gradually moved to Beijing. During the period from 2015 to 2020, the center of gravity of the study area continued to move to the northeast, but it was still within the scope of Beijing and the changes were subtle; this proved that with the continuation of ecological civilization construction and investments in environmental issues in the Beijing–Tianjin–Hebei region, the ecological vulnerability of the urban green-space system within the region gradually stabilized. In 2010, the center of gravity and severe and extreme vulnerability distribution areas fell within Hebei Province, while in 2015 and 2020, the main distribution areas of severe and extreme vulnerability distribution areas moved to Beijing and Tianjin, and the center of gravity also shifted to Beijing. It can be observed that the transfer of the center of gravity reflects the changing ecological vulnerability trend of the urban green-space system to a certain extent (Figure 9).

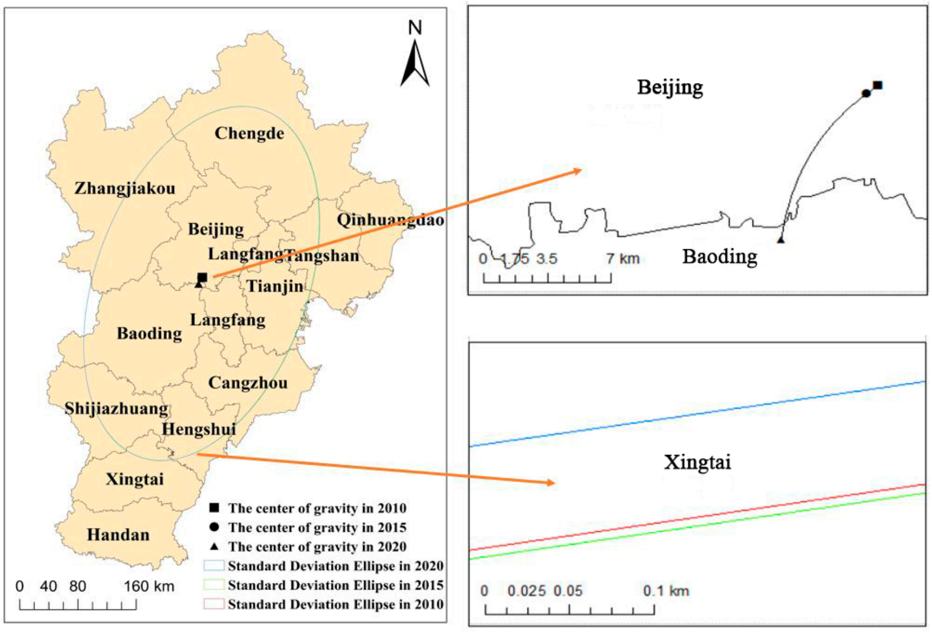


Figure 9. The standard deviation ellipse distribution and center-of-gravity shift of ecological vulnerability.

From the standard deviation ellipse parameters of the ecological vulnerability change of the urban green-space system, the standard deviation ellipse area increased year by year from 2010 to 2020, which proved that the ecological vulnerability change of the urban green-space system was dispersed year by year, but coverage was greater. The long axis of the standard deviation ellipse increased by 0.305 km, while the short axis decreased by 0.1221 km. According to the changes in the long and short axes, it can be observed that the ecological vulnerability-change space of the urban green-space system in the study area is slightly expanded in the east–west direction, and it was slightly contracted in the north–south direction. The azimuth of the ellipse is always around 18.7° (Table 5): that is, the direction is stable in the northeast–southwest direction. In summary, the ecological vulnerability of the urban green-space system within the study area in the past 10 years tended to increase, exhibiting an expansion trend in the main direction, and the direction is stable in the northeast–southwest direction.

Table 5. Standard deviation ellipse parameters of the ecological vulnerability change of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020.

Particular Year	Ellipse Area/km^2	Center Point x Coordinate	Center Point y Coordinate	Ellipse x-axis Length/m	Ellipse y-axis Length/m	Azimuth (°)
2010	119,549.9	942,357.7	4,303,636.6	146.3892	259.9709	18.7
2015	119,551.0	942,357.17	4,303,632.17	146.3915	259.9690	18.7
2020	119,742.9	942,633.97	4,303,619.87	146.694.3	259.8488	18.7

3.2. Spatial Heterogeneity of the Ecological Vulnerability of the Green-Space System in the Beijing–Tianjin–Hebei Region

3.2.1. Global Spatial Agglomeration Characteristics

Global autocorrelation can describe the overall distribution of the ecological vulnerability in the study area's urban green-space system. Via the analysis and calculation of global spatial autocorrelation, the ecological vulnerability autocorrelation parameters in the study area in 2010, 2015, and 2020 were obtained. The results showed that Moran's I exhibited a continuous upward trend from 2010 to 2020. With the vigorous promotion of ecological-environment construction, the ecological-vulnerability aggregation of the urban green-space system in the Beijing–Tianjin–Hebei region gradually increased. Since the "Beijing–Tianjin–Hebei Collaborative Development Outline" was put forward in 2014, Moran's I increased from 0.503990 in 2010 to 0.515915 in 2015. With the vigorous promotion of ecological-environment construction, Moran's I increased to 0.530715 in 2020 (Table 6), indicating that the ecological vulnerability aggregation of the urban green-space system in the Beijing–Tianjin–Hebei region has gradually increased. The ecological vulnerability of this region shows significant spatial autocorrelation, and there is positive spatial autocorrelation. That is to say that the high or low values of similar observations tended to be spatially clustered, and the grids interacted with one another. It has a very obvious agglomeration rather than a random distribution.

Table 6. Moran's I statistics of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020.

Particular Year	Moran's I Index	p Value	Z Value
2010	0.503990	0	1977.156417
2015	0.515915	0	2023.928773
2020	0.530715	0	2055.762545

Note: When $p < 0.05$, it is within the 95% confidence interval; when $p > 1.96$, representation data exhibit obvious aggregation characteristics. Representation data exhibit obvious aggregation characteristics.

3.2.2. Local Spatial Agglomeration Characteristics

In order to analyze the distribution of the green-space system in each spatial unit in the study area, local spatial autocorrelation analyses were carried out on the distribution of the ecological vulnerability of the green-space system in the three periods. By analyzing the local spatial autocorrelation LISA agglomeration map, it can be observed that the spatial aggregation characteristics of the ecological vulnerability of the urban green-space system in the study area changed substantially from 2010 to 2015, and it showed slight differences from 2015 to 2020. Moreover, high–high aggregation and low–high aggregation areas were large and substantial, exhibiting patchy distribution and significant spatial correlation, indicating that the ecological vulnerability agglomeration characteristics of the urban green-space system were obvious, and exhibiting high–high aggregation and low–high aggregation characteristics. The low–high aggregation area was distributed on the north and south sides of the high–high aggregation area. With respect to the (1) high–high aggregation area, in 2010, it was mainly distributed in Baoding City, Langfang City, and Cangzhou City in Hebei Province, while in 2015 and 2020, it was mainly distributed in Beijing and Tianjin. With respect to (2) low and high gathering areas, in 2010, the low and high gathering areas were mainly distributed in Beijing and Tianjin, Handan City, Xingtai City, Hengshui City, and Shijiazhuang City. After 2015, the main distribution range of low and high gathering areas was transferred to Hebei Province (Figure 10).

3.3. Impact Factor Analysis Based on Geodetectors

3.3.1. Single-Factor Test Results

The factor detector is used to analyze the influence degree of each index on ecological vulnerability. It can be observed from the table that there are differences in the driving forces of 10 exogenous variables in the spatial differentiation of the ecological vulnerability of the urban green-space system within the Beijing–Tianjin–Hebei region. In the past ten years, annual average precipitation, education degree, and the human disturbance index q value have been relatively high and stable, and they have been maintained above 0.1. It was proven that the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region is most affected by precipitation, residents' education degree, and human disturbance. Precipitation is an exposure factor that reflects the meteorological and hydrological conditions in the study area. The human disturbance index is the expression of the disturbance degree of human activities in the urban green-space system ecosystem. The education degree of residents is the impact factor of the response dimension. When the residents' education degree is higher, they pay more attention to the construction of ecological environments, hence resulting in an urban green-space system with lower ecological vulnerability. These three factors have a greater impact on the long-term stability of the ecological vulnerability of the urban green-space system, showing that exposure and social responses have a greater impact on the ecological vulnerability of urban green-space systems; Population density and vegetation coverage have little influence on vulnerability, and the q value is kept below 0.1. Both belong to state impact factors, reflecting that the state of the green space ecosystem itself has little impact on vulnerability (Table 7).

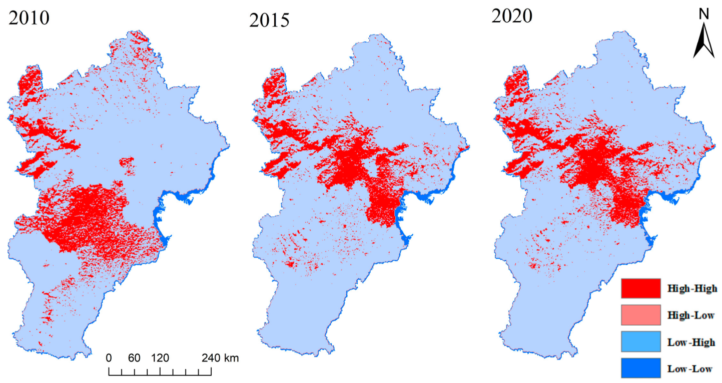
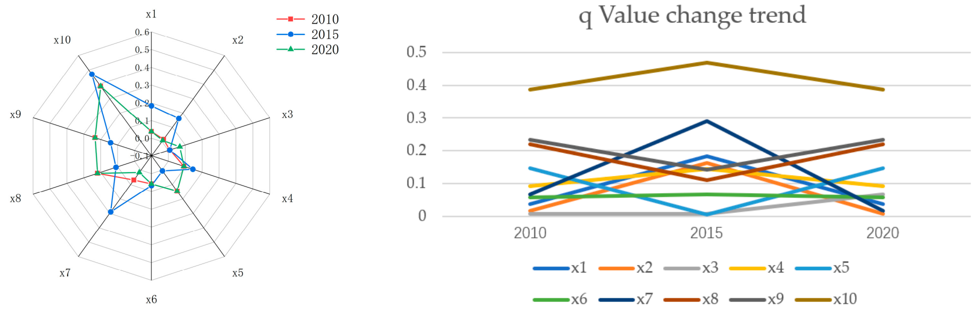


Figure 10. LISA agglomeration map of urban green space ecological vulnerability in the Beijing–Tianjin–Hebei region from 2010 to 2020.

Table 7. The statistical table of the q value and ranking of impact factors of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020.

Impact Factors	2010		2015		2020	
	q	sort	q	sort	q	sort
Digital elevation model (x1)	0.038	8	0.184	3	0.038	8
GDP (x2)	0.016	9	0.162	4	0.008	10
Population density (x3)	0.008	10	0.008	9	0.068	6
Aspect (x4)	0.092	5	0.145	5	0.092	5
Slope (x5)	0.146	4	0.005	10	0.146	4
Vegetation coverage (x6)	0.058	7	0.067	8	0.058	7
Annual average temperature (x7)	0.068	6	0.290	2	0.016	9
Annual average precipitation (x8)	0.219	3	0.110	7	0.219	3
Human disturbance index (x9)	0.233	2	0.142	6	0.233	2
Education degree (x10)	0.386	1	0.470	1	0.386	1

From 2010 to 2020, with the exception of population density and vegetation coverage, the annual average precipitation, slope, and human disturbance index exhibited a trend that first decreased and then increased, while GDP, annual average temperature, education degree, digital elevation model, and slope direction exhibited a trend that first increased and then decreased, which showed that there was a certain mutual restrictive relationship between the impact factors on ecological vulnerability (Figure 11a,b).

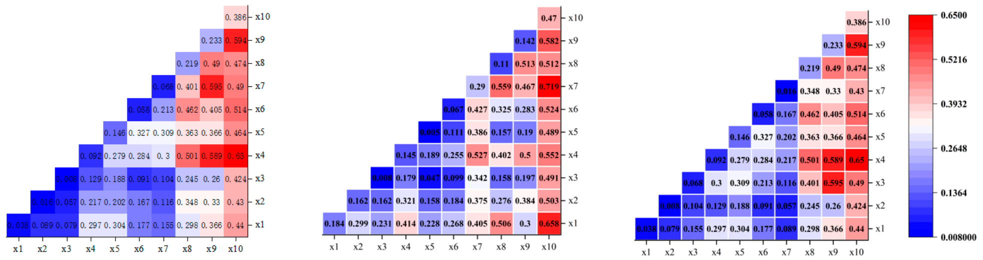


(**a**) (**b**)

Figure 11. (**a**) The q-value radar map of the detection results of the ecological vulnerability factors of the urban green-space system in the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020 was obtained. (**b**) The trend of q value change.

3.3.2. Interaction Test Results

In order to study the interpretation degree of the spatial distribution of the urban green-space system's ecological vulnerability after the interaction of any two impact factors, the geographical detector was used to interactively detect each factor. The interaction detector can evaluate whether the interaction of two independent variables will increase or decrease the explanatory power of the dependent variable, which is helpful in studying the interaction between variables. From 2010 to 2020, only two types of impact factor interaction forces (nonlinear enhancement and bivariate enhancement) were observed in the Beijing–Tianjin–Hebei region. In other words, the combined effect of any two factors is greater than the effect of a single factor, which can promote the change in the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region. It can be seen from the figure that the strongest impact on the ecological vulnerability of the urban green-space system in 2010, 2015, and 2020 is the interaction between education degree and other impact factors, followed by the human disturbance index and annual average precipitation. In addition, by comparing the results of the interaction detection of impact factors from 2010 to 2020, it can be observed that when interactions between the education degree, human disturbance index, and annual average precipitation decrease, the interaction between vegetation coverage and other impact factors increases (Figure 12a–c).



(**a**) (**b**) (**c**)

Figure 12. The interaction effect of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region in 2010 (**a**), 2015 (**b**), and 2020 (**c**).

To summarize, in the past ten years, the education degree, human disturbance index, and annual average precipitation in the study area have always been the dominant factors of the urban green-space system's ecological vulnerability. The influence degree of other impact factors on urban green-space system's ecological vulnerability is different. When the influence intensity of exposure factors represented by the human disturbance index and annual average precipitation decreases, the interaction intensity of the state impact factors represented by vegetation coverage will increase. It was proven that when external influences weaken, the state of the urban green-space system will determine its vulnerability.

In addition, the interaction results all comprise nonlinear and bivariate enhancements, which also show that the ecological vulnerability of the urban green-space system is a result of the combined effects of various factors.

3.4. Rationality Analysis of the Ecological Vulnerability Assessment Results of the Urban Green-Space System

The remote sensing ecological index (RSEI) can reflect the ecological environment's quality in the study area [42]. The average value of the remote sensing ecological index in the study area was obtained via analyses. The average value can reflect the changing trend of the ecological environment's quality. The average values of the remote sensing ecological index in the study area from 2010 to 2020 were 0.429761, 0.459899, and 0.495763, respectively (Figure 13).

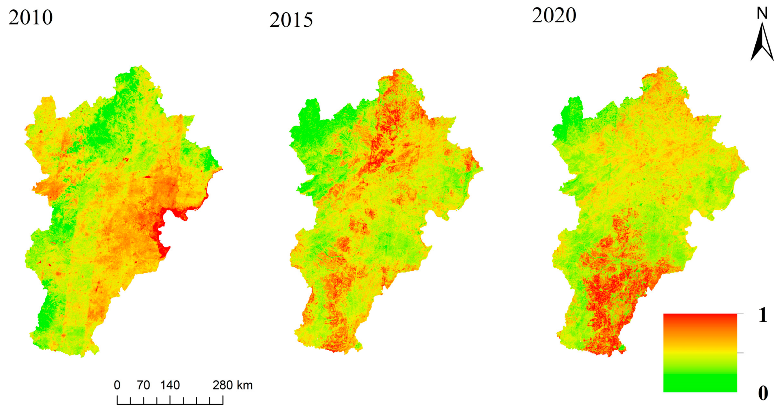


Figure 13. The spatial variation of remote sensing ecological index (RSEI) in the Beijing–Tianjin–Hebei region from 2010 to 2020.

The analyses of the evolution trend of the urban green-space system's ecological vulnerability can predict the development of ecological environment quality [43]. The ecological vulnerability of the study area decreased year by year, which proves that the ecological environment's quality is gradually increasing. This is consistent with the change trend reflected by the remote sensing ecological index.

In this study, the changing trend of the remote sensing ecological index and ecological vulnerability evaluation results was analyzed via a regression analysis, and a simple linear correlation between the two was obtained. The correlation coefficient R^2 of this study was 0.824, and the correlation significance test coefficient $R^2 = 0.824 > 0.449 = R_{0.01}$ was obtained via a regression analysis, which proves the correlation between the changing trend of the remote sensing ecological index and the ecological vulnerability index. This shows that the evaluation results of the ecological vulnerability of the Beijing–Tianjin–Hebei region are reasonable, scientific, and targeted. It can provide a reference for the planning and construction of the urban green-space system in the Beijing–Tianjin–Hebei region.

4. Discussion

4.1. The Rationality of the ESSR Urban Green-Space System's Ecological-Vulnerability Assessment

Although many experts have carried out substantial research on ecological vulnerability in recent years, the following problems still remain: (1) there is a lack of innovation in research methods; (2) a single index is used, which renders realizing ecological vulnerability evaluation difficult; (3) the effectiveness of the evaluation results is greatly influenced by subjective factors; and (4) there is a lack of rationality analysis of the evaluation results [44]. Based on the PSR and VSD models, this study innovatively constructed the ESSR model "Exposure-Sensitivity-state-Response". The advantages of this model are as follows: (1) On the basis of retaining the original causal logic, it further broadens the dimension and clearly restores the logical relationship of "what happened, the size of the impact, the results generated, and how to deal with it". (2) Taking into account the clear hierarchical framework, from the three levels of the goal layer, indicator layer, and factor layer, and with the help of the four categories of exposure, sensitivity, state, and response dimensions, ten impact factors were selected to comprehensively evaluate the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region. (3) The weight of factors is objectively determined, and the interference of human subjective factors is excluded. (4) On the basis of quantitative analysis and evaluation results, the ecological vulnerability of the urban green-space system is described qualitatively. In addition, this research study also uses the RSEI model to analyze the rationality of the evaluation results from the perspective of the change trend. The changing trend of the two exhibits a significant correlation, indicating that the ecological quality of the Beijing–Tianjin–Hebei region is on the rise, thus proving the rationality of the research results.

4.2. Discussion of the Spatial and Temporal Changes and Impact Factors of the Urban Green-Space System in the Beijing–Tianjin–Hebei Region

In the past, research on ecological vulnerability focused on static analysis within a specific period. Although it can provide detailed information on the vulnerability of the research object in a specific period, it cannot reveal the changing ecological vulnerability trend within a long period [45]. The analysis method of the spatial and temporal changes of the ecological vulnerability of the research object is also relatively simple. For example, Zhang et al. analyzed the ecological vulnerability changes of the north karst gulf coast in Southwest Guangxi based on a simple difference method [46]. Time series analyses were used to analyze the ecological vulnerability and change trends of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020. The results show that vulnerability gradually decreased from 2010 to 2020, and the quality of the ecological environment tended to improve, which was consistent with the research results of Li et al. [47].

In the analyses of impact factors, the study observed that education level, human disturbance index, and annual average rainfall were the dominant factors in the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region in the past ten years. This result is consistent with the conclusion that human disturbance and natural factors are the main impact factors for vulnerability [48].

4.3. Special Features of the Research

Different from previous research that focused on the need for urban green space for urban development, this research study begins with the ecological vulnerability of the urban green-space system itself, explores the impact of natural and human factors on the urban green-space system, and provides a scientific basis for the planning and sustainable development of urban green-space system via the analysis results.

The particularity of this research lies in its strong logic, structure, objectivity, comprehensiveness, and rationality, as well as the quantitative and qualitative analyses of the evaluation results. First of all, unlike other ecological vulnerability assessment models, the ESSR model used in this study is based on the traditional model, which provides an important foundation for subsequent research. Secondly, the study uses spatial principal component analysis to determine the weight of impact factors, which has certain objectivity. In addition, compared with other single analysis methods, the study conducted a long-term time series analysis of the ecological vulnerability of urban green-space systems, and it further conducted in-depth analyses of the evaluation results from multiple perspectives, such as spatial and temporal distributions, evolution, trends, and impact factors, providing a detailed scientific basis for the development and planning of urban green-space systems. Finally, the RSEI remote sensing ecological index was used to verify the rationality of the evaluation results.

4.4. Limitations and Prospects

Although this research study has achieved many results, it still has some limitations. In terms of the selection of impact factors, although a large number of studies have been referred to and multiple impact factors have been selected as comprehensively as possible, a unified framework and measurement standard is still missing. With the further development of the city, the factors affecting the vulnerability of urban green spaces will continue to increase. In the future, the evaluation of the vulnerability of urban green-space systems should explore the utilization of a more unified model framework and select more standard impact factors.

5. Conclusions

In this study, using the ESSR model, ten impact factors were selected from the four dimensions of "Exposure–Sensitivity– State–Response", and the factors' weights were determined via spatial principal component analysis. With the help of GIS overlay analysis, the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020 was evaluated, and the spatial and temporal changes were analyzed using a transfer matrix, spatial autocorrelation analysis, standard deviation ellipse analysis, and center-of-gravity migration model. The impact factors were analyzed using a geographical detector, which provides a theoretical basis for the planning and sustainable development of urban green-space systems.

The results show the following: (1) The ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region presents the distribution law of "Hebei surrounds Beijing and Tianjin", and vulnerability exhibits a downward trend. Moreover, the changing trend of the urban green-space system is closely related to the change in policy. (2) In the past ten years, the focus of change has gradually moved from Hebei Province to Beijing. Examining the main direction, the focus exhibits an expansion trend, and the direction is stable in the northeast–southwest direction. (3) The ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region exhibits very obvious clustering rather than random distributions. (4) In the past ten years, the education degree, human disturbance index, and annual average precipitation in the study area have always been the dominant factors of the ecological vulnerability of the urban green-space system. The ecological vulnerability of urban green-space systems is the result of the combined effect of various factors.

To summarize, the development of the social economy and the destruction of the natural environment resulted in exposure to substantial pressure. Under the influence of multiple factors such as its sensitivity and state, the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region is high. However, the positive response of national ecological protection policies and ecological restoration measures has resulted in a steady decline in the ecological vulnerability of the urban green-space system in the area, which has indirectly promoted the overall stability of the ecological environment. In the future, we should implement policies such as the "Beijing–Tianjin–Hebei Collaborative Development Program" and the "Beijing–Tianjin–Hebei Collaborative Development Ecological Environment Protection Plan"; recognize the ecological, economic, and strategic position of the Beijing–Tianjin–Hebei region; identify the ecological vulnerability characteristics of urban green-space systems in different regions; and realize the comprehensive improvement of the ecological environment and the sustainable development of the ecosystem in the Beijing–Tianjin–Hebei region.

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