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Research Article

Spatial and Temporal Variations in the Ecological Vulnerability of Northern China

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Ecological vulnerability is the focus of research on global environmental impact, regional sustainable development, ecological civilization, and green development. There are eight deserts and four sandy lands in northern China. The ecological environment is sensitive to climate change and human activities. It is of great significance to carry out long-term sequential ecological vulnerability assessments. Therefore, taking northern China as the research area, this paper selects 13 data indicators such as climate, topography, and soil based on the ecological sensitivity-ecological recovery-ecological pressure model (SPR) and uses the spatial principal component analysis method (SPCA) to quantitatively evaluate the spatial and temporal differentiation characteristics and driving forces of ecological vulnerability in this area from 1980 to 2020. The results showed that areas with extreme, severe, and moderate vulnerability dominated northern China, accounting for 74.58% of the total area. The analysis revealed a decrease in ecological vulnerability from west to east and north to south. Meanwhile, from the perspective of timing, the overall level of ecological vulnerability showed an upward trend before 2000, and the overall level of ecological vulnerability continued to decline after 2000, and the quality of the ecological environment improved. During the study period, areas in northern China with severe vulnerability and slight vulnerability showed a change of 15.53% and -14.01%, respectively. The main reason for the change in ecological vulnerability is the frequent transformation between forest land, grassland, water, and cultivated land. In addition, the study found a spatial autocorrelation of ecological vulnerability of northern China and a significantly positive correlation. After 2000, the spatial aggregation of vulnerability was high-high cluster, which was mainly distributed in northwest China. The study's findings will provide a robust scientific basis for ecosystem management and sustainable development.

1. Introduction

Ecological vulnerability theory originated from the ecological transition zone theory proposed in the early 20th century, which refers to the sensitivity of ecosystems to external interference [1]. Due to global environmental change and the intensification of human-land relation research, ecological vulnerability assessment, restoration and reconstruction, and sustainable development management have become research hotspots globally [2, 3]. Ecological vulnerability can reflect the causes of ecosystem changes in specific regions to a certain extent. It is of great practical significance for regional eco-environmental protection, rational utilization of resources, ecological sustainable development, and ecological protection. At the same time, it provides reference and decision-making support for ecological restoration projects [4].

The current evaluation methods include the comprehensive index method and analytic hierarchy process [5, 6]. Boori et al. built a drive-pressure-state-impact-response (DPSIR) model based on remote sensing (RS), geographic information system (GIS), and AHP and selected 23 indicators to analyze the spatiotemporal changes in ecological vulnerability of the Russian Republic of Tatarstan [7]. Li et al. used the entropy weight analysis to comprehensively evaluate the ecological vulnerability of the Karst mountainous areas of southwest China [8]. Ma et al. used the "pressure-state-response" evaluation model and selected 18 indicators to comprehensively evaluate the ecological vulnerability of the Three Gorges Reservoir Area from 2001 to 2010 [9]. Researchers have improved their understanding of ecological vulnerability using different models, but with few limitations. Although these models can be used to analyze the driving force objectively, they are not suitable for exploring the spatial changes and comprehensively evaluating ecological vulnerability specifically for a region. At the same time, when these methods assign weights to each factor, human subjective factors considerably influence the results. Therefore, it is urgent to adopt more objective quantitative research methods to reduce the subjectivity of artificial effect, improve the objectivity and accuracy of ecological vulnerability assessment, and comprehensively assess the ecological vulnerability situation in the region by analyzing spatial heterogeneity characteristics and overall change trends.

Recently, China has developed "The Belt and Road Initiative" to enhance economic development; it has improved the strategic position of northern China. As a part of this initiative, it is important to discuss the sustainable development of northern China from the perspective of ecological vulnerability. In the past, scholars paid more attention to the ecological vulnerability of a small region, which did not reflect the overall characteristics. Ecological vulnerability is actually the result of a series of comprehensive factors dominated by the regional environment itself. Therefore, it is necessary to monitor and evaluate the spatial characteristics and evolution patterns of the research area from a global perspective and macrosystem thinking. The present study based on the SRP model, the slope, temperature, precipitation, and other data from 1980 to 2020 which are selected as vulnerability evaluation indicators in northern China. Using the SPCA method, the spatial and temporal distribution of ecological vulnerability in northern China is explored, the spatial pattern and evolution process of ecological vulnerability are clarified, and the ecological vulnerability is scientifically monitored and evaluated in northern China. The study's findings will reveal the protection and sustainable development of ecological functions of northern China and provide a reference for further research on ecological vulnerability in this area.

2. Data Sources and Research Methods

2.1. Study Area. Northern China (28°–55°N, 67°–125°E) has a total area of 5.64×10^6 km^2, accounting for about 58.6% of the total land area of China. The administrative division has 15 provinces (cities and autonomous regions), including Beijing, Tianjin, Heilongjiang, Jilin, Liaoning, Hebei, Henan, Shandong, Shanxi, Inner Mongolia, Shaanxi, Ningxia, Gansu, Qinghai, and Xinjiang. The area mainly has temperate monsoon, continental, and plateau mountain climates. The landforms in northern China are complex and diverse, and the terrain is variable. The topography is mainly plateaus, mountains, basins, and plains, including the Altai Mountains, the Aljin Mountains, the Tianshan Mountains, the Kunlun Mountains, the Qilian Mountains, the Tarim Basin, the Junggar Basin, the Turpan Basin, and the Songnen Plain (Figure 1). This region has temperate mixed forests, cold temperate coniferous forests, temperate grasslands, deciduous broad-leaved forests, subtropical evergreen broad-leaved forests, temperate deserts, and cold vegetation from the east to the west. The soil types are complex and diverse; regions from east to west have mainly black soil, cold brown soil, black calcium soil, brown soil, yellow-brown soil, gray calcium soil, gray desert soil, and brown desert soil. The annual precipitation in this area gradually decreases from the southeast (1000 mm) to the northwest (100 mm), with a temperature ranging from -5°C to 20°C.

2.2. Data Sources and Preprocessing. Digital elevation data were obtained from the geospatial data cloud platform (http://www.gsclound.cn), with elevation, slope, topographic fluctuation, and river network density details based on the digital elevation model (DEM). The meteorological data were obtained from the China Meteorological Data Network (http://data.cma.cn), which uses the Kriging interpolation method to interpolate the annual average precipitation data and the annual average temperature data. Vegetation coverage data were derived from the NASA website (http://search.earthdata.nasa.gov) to calculate the normalized vegetation index using the pixel dichotomy model and the raster calculator. Land use data and soil erosion intensity data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn), and the bioabundance index of northern China was calculated. Data on population density, per capita GDP density, and primary productivity were derived from the *China Statistical Yearbook*; these data were obtained by dividing the statistics in the Yearbook by the area of the administrative region.

2.3. Construction of an Ecological Vulnerability Index System

2.3.1. Metric Selection. The SRP model (the concept model of "ecological sensitivity-ecological resilience-ecological pressure") is a comprehensive evaluation model that reflects the quality of the ecological environment based on the habitat quality index [10]. Ecological sensitivity demonstrates the ability of an ecological environment to resist interference. Elevation, slope, topographic fluctuation, and river network density were selected to reflect the topographic characteristics. The average temperature and average precipitation were used to reflect the changes in meteorological factors. The land use types were used to reflect the changes in surface factor. The soil erosion intensity was used to reflect the changes in soil factor. Meanwhile, ecological resilience refers to the ability of an ecosystem to recover after being damaged by an external disturbance. Vegetation coverage, bioabundance index, and net primary productivity were selected to reflect ecological resilience. Ecological pressure refers to the degree of interference caused by human social activities to the ecosystem. Population density and GDP per capita were used to reflect the environmental impact of human activities and economic development [11].

2.3.2. Standardization of Indicators. The nature and attributes of each indicator used to assess the ecological vulnerability are different; therefore, ecological vulnerability can be

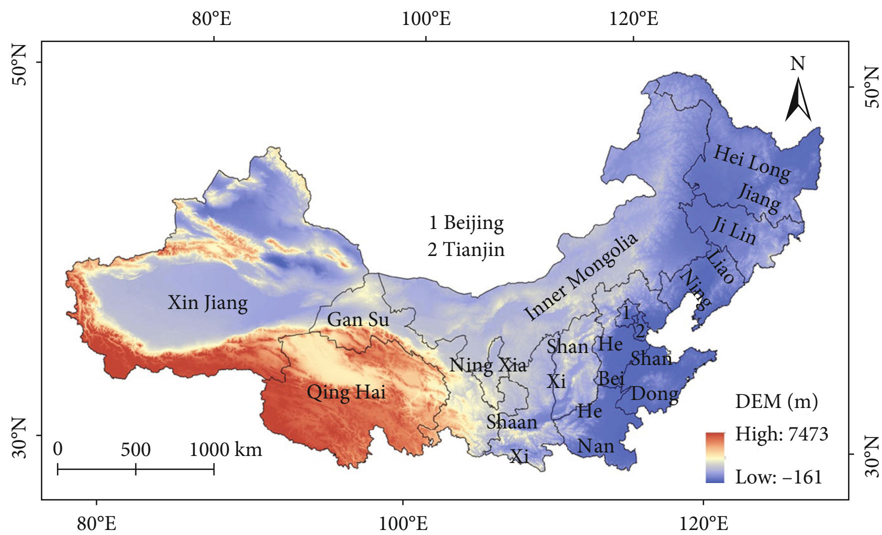

Figure 1: Elevation of the research area.

assessed directly. According to the ecological vulnerability impact of each index, this study divided the evaluation index into positive and negative indicators (Table 1). The index standardization adopted the extreme difference standardization method, using the formula as follows [12]:

$$R_T = \frac{X - X_{min}}{X_{max} - X_{min}}, \quad R_G = \frac{X_{max} - X}{X_{max} - X_{min}}, \tag{1}$$

where R_T is the standardized value of the forward indicator, R_G is the standardized value of the negative indicator, and X_{max} and X_{min} indicate the maximum and minimum values of indicator X.

2.3.3. Ecological Vulnerability Index. Spatial principal component analysis (SPCA) is based on the principle of mathematical statistics. By rotating the spectral-spatial coordinate axis of the feature, multiple spatial index data are converted into a few comprehensive layers. When calculating the weights of ecological sensitivity, ecological resilience, and ecological pressure indicators by SPCA, the artificial weight of the index is reduced. At the same time, the main components of the ecological vulnerability of northern China in 1980, 1990, 2000, 2010, and 2020 were analyzed. Finally, north China's ecological vulnerability index (EVI) was calculated based on the top five main components, including a major component greater than 85%. EVI was calculated as follows [13]:

$$EVI_n = R_1 PC_{1n} + R_2 PC_{2n} + \cdots + R_n PC_{kn}, \tag{2}$$

where EVI_n is the ecological vulnerability index, $R_1, R_2 \cdots R_n$ indicate the corresponding indicator weights, $PC_{1n}, PC_{2n} \cdots PC_{kn}$ indicate the main components with a cumulative contribution rate greater than 85%, and n is the year. The larger the ecological vulnerability index, the more fragile the ecological environment in the region, conversely, the better the ecological environment in the region.

Further, to compare the ecological vulnerability across various periods, the results of ecological vulnerability in 1980, 1990, 2000, 2010, and 2020 were standardized as follows [14]:

$$SEVI = \frac{EVI - EVI_{min}}{EVI_{max} - EVI_{min}} \times 10, \tag{3}$$

where SEVI is the standardized value of the ecological vulnerability index, which ranges from 0 to 10; EVI is the ecological vulnerability index of the research area; EVI_{max} is the maximum value of the ecological vulnerability index within the research area; and EVI_{min} is the minimum value of the ecological vulnerability index within the research area.

Referring to the environmental characteristics and the histogram distribution and standard deviation of the ecological vulnerability in northern China and comprehensively considering north China's unique ecological and environmental attributes, the EVI of northern China was classified according to the natural breakpoint method. The ecological vulnerability of northern China was divided into five levels: slight vulnerability [0–1.5], light vulnerability (1.5–3.0], moderate vulnerability (3.0–5.1], severe vulnerability (5.1–7.1], and extreme vulnerability (7.1–10].

2.3.4. Spatial Autocorrelation Analysis. Spatial autocorrelation analysis is an important method of monitoring the relevance of spatial properties and their changes using a collection of spatial data analysis methods and technologies [15]. At present, spatial autocorrelation for a single element can be described by two indicators: global Moran'*I* and local Moran'*I*. The global Moran'*I* index characterizes the correlation degree of ecological vulnerability of the adjacent space units and reveals the impact of spatial structural elements on ecological vulnerability. Meanwhile, the local Moran'*I* index

Table 1: Ecological vulnerability evaluation index system in northern China based on SRP model.

Target layer	Criterion layer	Basic index layer
Ecological sensitivity	Topographic factors	Elevation (+), slope (+), topographic fluctuation (+), river network density (-)
	Surface factor	Land use types (+)
	Soil factor	Soil erosion intensity (+)
	Meteorological factors	Average temperature (-), average precipitation (-)
Ecological resilience	Vegetation factors	Vegetation coverage (-), bioabundance index (-), net primary productivity (-)
Ecological pressure	Social factors	Population density (+), GDP per capita (+)

Note: +/- indicates forward indicators and negative indicators, respectively.

expresses the spatial distribution structure and distribution characteristics of ecological vulnerability and shows the overall law of spatial variation. The spatially related local indicator cluster diagram (LISA) was used to evaluate the spatial clustering by calculating the local Moran'I index. It mainly includes five aggregation modes: high-high cluster, high-low outlier, low-high outlier, low-low cluster, and not significant.

The global Moran'I index was calculated as follows:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(X_i - \bar{X}\right)\left(X_j - \bar{X}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}. \quad (4)$$

Meanwhile, the local Moran'I index was calculated as follows:

$$I = \frac{\left(X_i - \bar{X}\right)}{S^2}\sum_{j} W_{\mathrm{ij}}\left(X_j - \bar{X}\right). \quad (5)$$

I is the Moran'I index; X_i, X_j indicate the mean of the vulnerability index in the i and j evaluation units; $\bar{X}$ is the mean vulnerability of all evaluation units; W_{ij} is the spatial weight matrix; and S is the sum of the elements of the spatial weight matrix.

3. Results and Analysis

3.1. Temporal Variations in Ecological Vulnerability in Northern China. Between 1980 and 2020, the areas with severe vulnerability and extreme vulnerability in northern China showed a 15.53% and 6.38% increase, respectively; the areas showed a 14.01%, 11.83%, and 2.17% decrease, respectively (Figure 2). Meanwhile, the areas with slight vulnerability, light vulnerability, and moderate vulnerability in northern China showed a 26.84%, 17.80%, and 21.96% decrease, respectively, from 1980 to 2000. However, the areas with severe and extreme vulnerability showed a 60.26% and 8.14% increase. Among them, Gansu, Shandong, and Henan Provinces mainly had areas that transformed from slight vulnerability to moderate and severe vulnerability, while Heilongjiang, Jilin, Liaoning, Inner Mongolia, and Shaanxi Provinces had areas that transformed from moderate to severe and extreme vulnerability. This change occurred due to the rapid socioeconomic development during the 1980–2000 period, especially in the agricultural field, which led to a continuous decline in the ecological conditions and the ability to change the ecological environment, subsequently increasing ecological vulnerability. From 2000 to 2020, the areas with extreme and severe vulnerability decreased by 1.63% and 27.91%, respectively, while the areas with moderate, light, and slight vulnerability increased by 25.39%, 7.26%, and 14.92%, respectively. Among them, Heilongjiang Province, Jilin Province, Inner Mongolia Autonomous Region, Shandong Province, Hebei Province, Beijing City, and Tianjin City mainly transformed from severe vulnerability to moderate vulnerability, probably due to the large-scale conversion of farmlands to forests, grasslands, and lakes in response to regional ecological problems and the establishment of nature reserves and other nature conservation activities, subsequently reducing the ecological vulnerability.

3.2. Spatial Variations in Ecological Vulnerability in Northern China. From 1980 to 2020, the ecological vulnerability of northern China was mainly concentrated at three levels: extreme vulnerability, severe vulnerability, and moderate vulnerability (Figure 3). In 2000, northern China's extreme vulnerability and severe vulnerability reached the maximum, accounting for 54.57% of the area, while moderate vulnerability reached the minimum, accounting for 22.32% of the area. In 1980, the areas with different ecological and environmental vulnerability levels in northern China were in the following order: moderate vulnerability > extreme vulnerability > light vulnerability > severe vulnerability > slight vulnerability (28.60% > 25.55% > 20.62% > 16.81% > 8.42%). By 2020, the areas under the different ecological vulnerability levels were in the following order: moderate vulnerability > extreme vulnerability > severe vulnerability > light vulnerability > slight vulnerability (27.98% > 27.18% > 19.42% > 18.18% > 7.24%).

Further analysis showed that the ecological vulnerability of northern China decreased from west to east and from north to south. The western part, including Xinjiang, Gansu, north-central Ningxia, northwest Qinghai, north Shaanxi, and western Inner Mongolia, had mainly areas with extreme vulnerability and severe vulnerability, probably because these areas had less precipitation and large evaporation, poor vegetation cover, and shallow soil layer. Meanwhile, areas with light vulnerability and slight vulnerability were mainly distributed on the south side of Xinjiang and Qinghai, located in the protected zone and at a high altitude. The eastern part, including Heilongjiang, Jilin, Liaoning, and eastern Inner Mongolia, had areas with severe vulnerability and

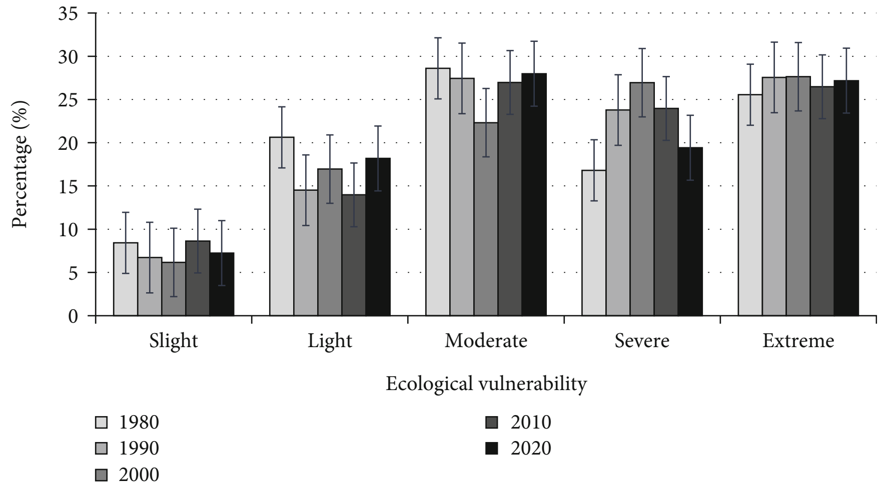

Figure 2: Characteristics of different levels of ecological vulnerability in northern China.

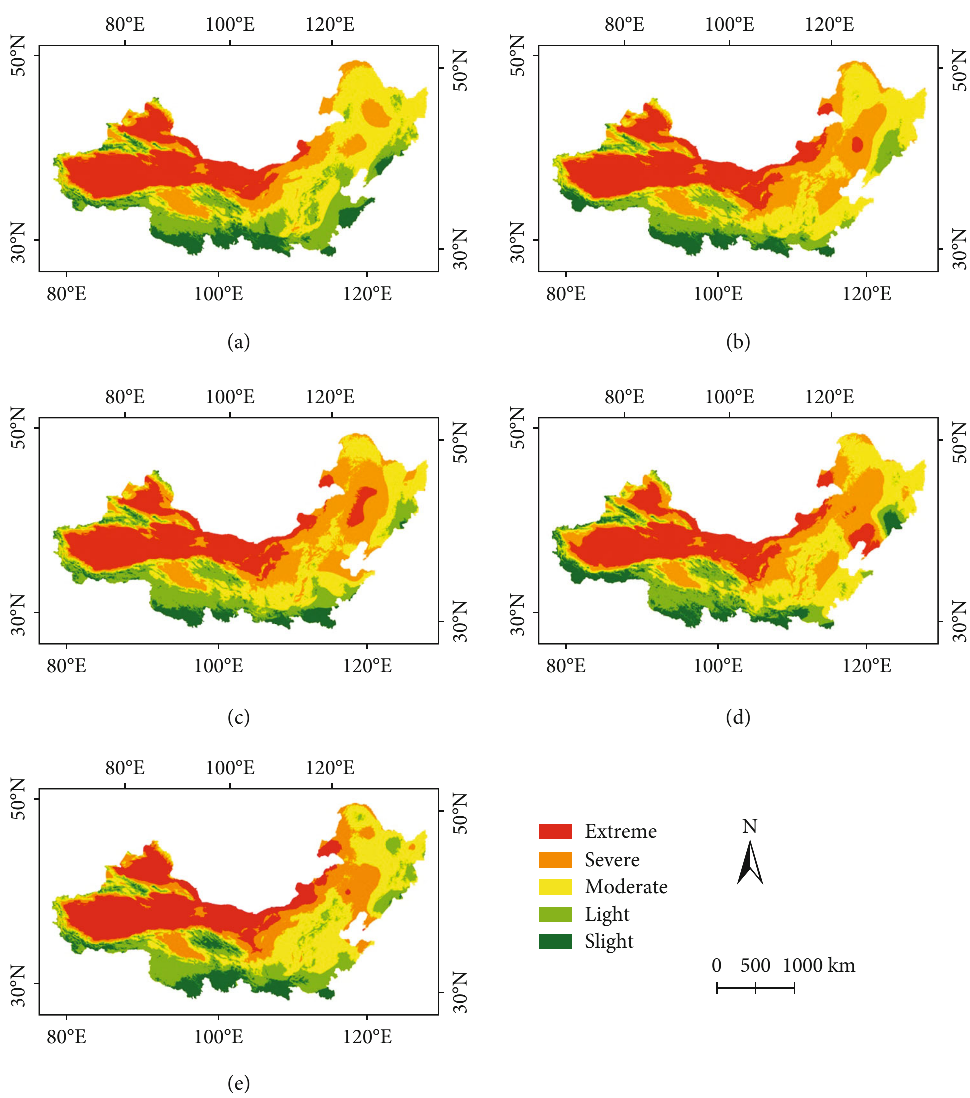

Figure 3: Spatial distribution of ecological vulnerability in northern China: (a) 1980; (b) 1990; (c) 2000; (d) 2010; (e) 2020.

moderate vulnerability because the average annual temperature was relatively different, the winter was long and cold, the summer was short and warm, and the soil was frozen for a long time. Meanwhile, areas with light vulnerability and slight vulnerability were mainly distributed in the southern part of Jilin and Liaoning, with mountains located in nature reserves. The central part of the research area, including Beijing, Tianjin, Shandong, Shanxi, Hebei, and Henan, belonged to a semiarid region. The ecological vulnerability of areas from north to south gradually reduced from severe to slight vulnerability, with increasing average annual temperature. At the same time, Qinghai, Shaanxi, Henan, and Shandong had a relatively humid climate due to Qinghai Lake and the Yellow River. Therefore, the vulnerability of these ecological habitats was relatively low.

3.3. Spatiotemporal Variations in Ecological Vulnerability among the Different Land Use Types in Northern China. Various evaluation indicators were graded and assigned according to the graded assignment method. According to the water resource capacity of different land uses, the land uses were arranged from low to high in the following order: forest land and water < grassland < cultivated land < urban land < unused land. Overall, the area of forest land, grassland, and water body area in northern China initially decreased and then increased from 1980 to 2020 (Figure 4), reaching the lowest value in 2000. Forest land, grassland, and water area accounted for 5.11%, 35.47%, and 2.28% of the total area in 2000. The cultivated land area first increased and then decreased, reaching a maximum of 575,280 km^2 in 2000, which accounted for 10.20% of the total area. From 1980 to 2020, the area under construction increased by 31.20%. Thus, the research area showed changes in ecological vulnerability mainly due to the conversion of forest land, grassland, water, and cultivated land. The forest land, grassland, and water areas decreased by 17.64%, 4.78%, and 8.80%, respectively, from 1980 to 2000, while the cultivated land increased by 27.50%. From 2000 to 2020, the cultivated land area decreased by 30.88%, while the forest land, grassland, and water areas increased by 35.42%, 10.18%, and 22.37%, respectively, mainly due to the continuous reclamation by humans, resulting in forest land, grassland, water bodies, and converted cultivated land.

The areas with slight and light vulnerability in the western ecoregion of the study area were mainly distributed in forest land, grassland, and water. Areas with moderate vulnerability and severe vulnerability were primarily distributed in the cultivated land and the urban and rural construction land, while the extremely vulnerable regions in the northwest were almost entirely concentrated in the unused land. Meanwhile, areas with slight vulnerability were widely distributed in grassland because of the better ecological background of forest land, grassland, and water areas and the larger grassland in the northwest region. The areas with slight vulnerability and light vulnerability in the eastern ecological area were mainly distributed in Changbai Mountain and other areas. The area mainly had forest land and was a nature reserve. Meanwhile, areas with moderate and severe vulnerability were mainly distributed in the cultivated land, grassland, water, urban land, and unused land. The areas with slight vulnerability and light vulnerability of the central ecoregion were mainly distributed in forest land, grassland, and water. In contrast, moderately vulnerable and severely vulnerable areas were primarily distributed in the cultivated land and urban land in other areas, with less unused land.

3.4. Spatial Aggregation Characteristics of Ecological Vulnerability in Northern China. From 1980 to 2020, the ecological vulnerability of northern China showed significant spatial aggregation, with an almost similar overall trend (Figure 5). The high-high cluster was mainly distributed in Xinjiang, western Inner Mongolia, northwestern Qinghai, northern Gansu, and north Ningxia; most of these regions were extremely vulnerable. The low-low cluster was mainly distributed in the eastern and central regions and slightly in north Xinjiang; most regions were dominated by slightly vulnerable, lightly vulnerable, and moderately vulnerable areas. The remaining aggregation evaluation units were not significant. Besides, aggregation expansion and migration were detected over the years. In 2000, the low-low cluster in northern China reached maximum due to the frequent conversions of the forest land, grassland, cultivated land, and urban land, resulting in a strong ecological vulnerability. Since 2000, the expansion of high-high clusters in the northwest mainly occurred in the Taklimakan Desert in Xinjiang, as China has been transforming via a semigovernance and semiutilization method, maintaining the green planting of the Taklimakan Desert while continuously exploiting minerals and resources in the desert and maximizing the use of resources in the desert.

4. Discussion

4.1. Driving Force of Ecological Vulnerability. Northern China is affected by the comprehensive factors of natural conditions and humanistic factors, and the land use has changed dramatically [16]. Environmental factors are one of the causes of regional ecological vulnerability [17]. This study found that the spatial variations in ecological vulnerability are mainly related to topographic, meteorological, and soil factors, which is consistent with the previous. For example, Guo et al. analyzed the driving mechanisms of ecological vulnerability in the northern semiarid desert grassland ecological area and found that the intensity of natural factors, such as topography, temperature, and precipitation, was significantly related to the changes in vulnerability [18]. Similarly, the present study found that the changes in temperature and precipitation greatly changed the hydrothermal balance of northern China, which had a significant impact on the environment, changing the ecosystem process. This conclusion confirms the conclusion of predecessors regarding ecologically fragile areas in parts of northern China; for example, Zhang et al. found that vegetation coverage and precipitation were the main driving factors controlling the spatial and temporal changes in ecological vulnerability in the Loess Plateau. The group also detected that vulnerability varied greatly across regions and land use types [19]. Therefore, the research results of the natural factors of this study on ecological vulnerability are convincing [20].

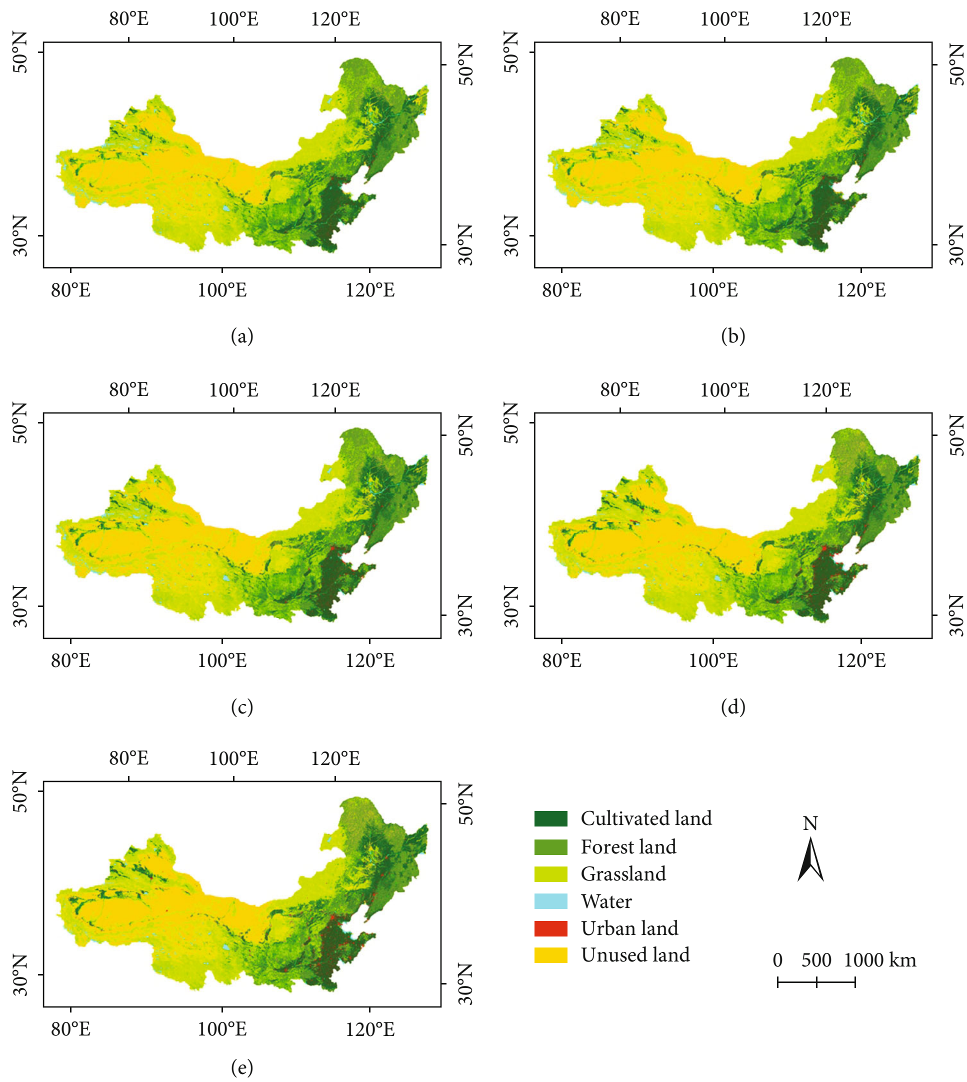

Figure 4: Monitoring the dynamics of land use in northern China: (a) 1980; (b) 1990; (c) 2000; (d) 2010; (e) 2020.

Anthropogenic activity is another factor affecting the ecological vulnerability of the region [21]. The changes in land use type reflect the human influence on nature and are one of the key factors affecting ecological vulnerability, which is consistent with the previous research results [22]. For example, Tian et al. used RS-based and GIS-based technologies to evaluate the ecological vulnerability under land use changes around Hangzhou Bay [23]. The construction land increased significantly in this area, reflecting urbanization. Research has also proven that the changes in ecological vulnerability in northern China may be related to the continuous expansion of cultivated land. Due to the intensification of human activities, the areas under cultivation and construction have significantly changed. Due to the geographical location of northern China and population increase, large areas of forest land, grassland, and water have been converted into cultivated land and construction land, which shows the continuous socioeconomic and urban-rural development and urbanization and the increasing impact of human activities. The research results are consistent with those of Zhou et al. [24]. They proved the significant impact of land use change on ecological vulnerability in Huinan County of China. Forestlands of Huinan County have been transformed into cultivated lands, leading to changes in ecological vulnerability. In recent years, China has systematically restored "mountains, fields, forests, lakes, and grasses," coordinated the balance between agricultural production and ecological brittleness in northern China, and took appropriate measures to curb the increase in ecological vulnerability. This is in line with the support of national policies for ecological construction and environmental protection [25].

From the research results, the spatial distribution status and spatial pattern of ecological vulnerability are relatively reasonable, which shows that the selection of indicators, evaluation criteria, and evaluation methods of ecological vulnerability assessment are feasible. There are many methods for evaluating ecological vulnerability. Which method is more scientific and reasonable to evaluate ecological vulnerability and how to build a more scientific evaluation index system need to be studied in depth. The evaluation criteria for the ecological vulnerability of indicator factors proposed in this study are based on existing standards, so they need to be further studied.

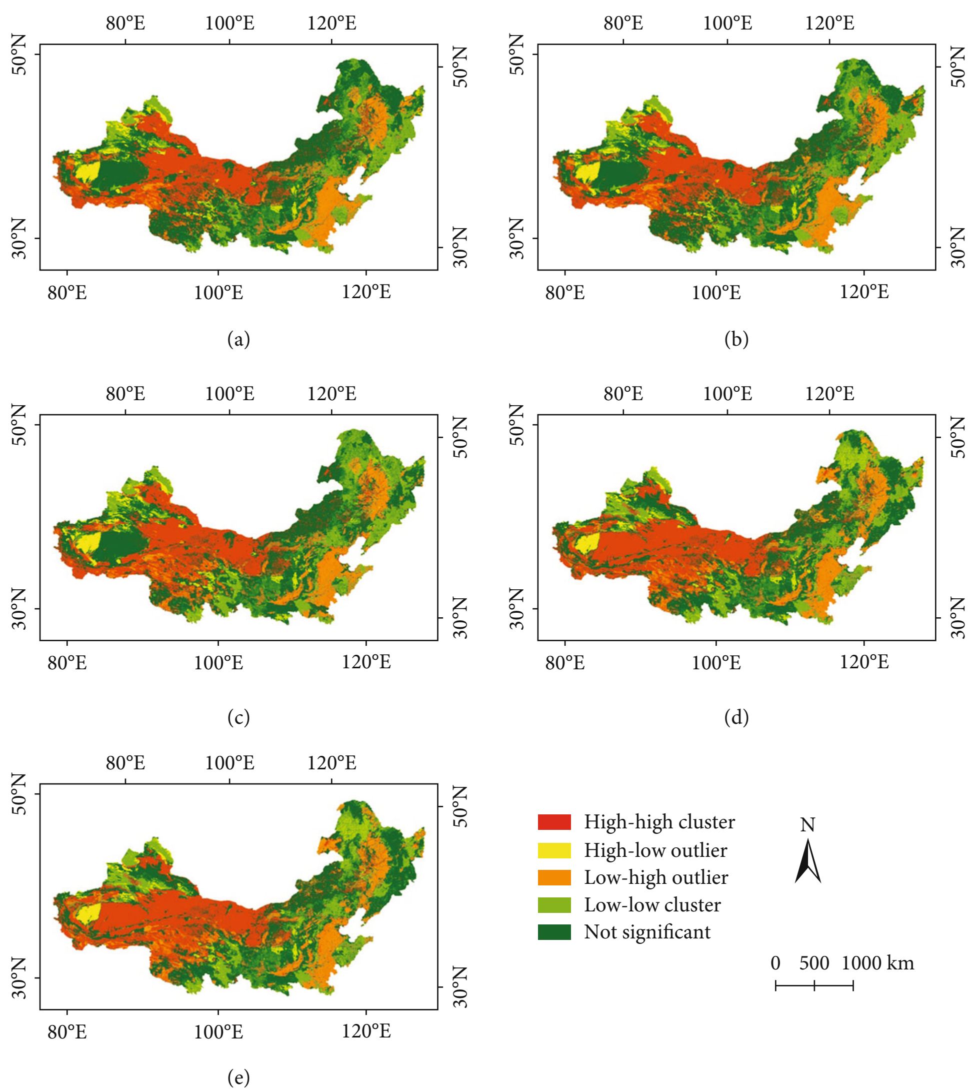

Figure 5: Local spatial autocorrelation LISA cluster map in northern China: (a) 1980; (b) 1990; (c) 2000; (d) 2010; (e) 2020.

4.2. Ecological Management and Optimization Strategy for Northern China. Northern China has unique geographical features, including climate, vegetation, soil, and hydrology, as well as distinct social, economic, and cultural characteristics [26]. To help decision-makers plan strategies to improve the ecological environment, northern China is divided into six ecological optimization areas: ecological protection areas, ecological monitoring areas, ecological concern areas, ecological restoration areas, ecological control areas, and ecological optimization areas.

Ecological protection areas are composed of slightly vulnerable and lightly vulnerable areas throughout the year. Ecological reserves are mostly nature reserves and should maintain ecological protection policies and protect the ecological environment quality [27]. In addition, to support the "green water and green mountains are golden mountains and silver mountains" concept, we should strengthen publicity and education, enhance the people's awareness, and create an atmosphere to protect the treasured plants [28]. Ecological monitoring areas are composed of extremely vulnerable areas throughout the year. This is because the area has less precipitation and evaporates vigorously; therefore, the impact of human activities should be reduced, and buffer zones should be established on the edge. We should also aim to control the degradation of land, soil, and vegetation caused by misuse of land, overgrazing, and overirrigation and curb further desertification [29]. Ecological concern areas are composed of moderately vulnerable and severely vulnerable areas throughout the year. Moreover, human activities are frequent in this area. Therefore, human activity is mainly farming, the soil quality should be protected, and ecological stability should be maintained. We should comprehensively plan for land use and regional ecological governance, adapt local conditions, promote strengths and avoid weaknesses, strengthen soil and water conservation and desertification control measures, and encourage comprehensive regional development [30].

Ecological restoration areas have low ecological vulnerability. The region has changed from high to low vulnerability. Due to improved protection, the ecological policies in the region are constantly decreasing; therefore, we should aim to maintain the original environmental policies [31].

We should continue to implement ecological forest-bearing areas; grasp the agricultural, forestry, and animal husbandry structure; and establish green barriers. Ecological control areas are those with increasing ecological vulnerability. The region has transformed from low to high vulnerability mainly due to economic development. Moreover, the primary industry accounts for a relatively high proportion in this region, but the ecological management lags behind. Therefore, we should strengthen people's awareness of protecting the environment and formulate new environmental policies [32]. We should also completely utilize solar energy, geothermal energy, wind energy, and other natural resources. Ecological optimization areas demonstrate fluctuating ecological vulnerability. The irrational social activities of human being led to the continuous degradation of the ecological environment. Therefore, the government has been implementing ecological projects, such as converting farmland to forests and grassland to lakes, to maintain ecological stability [33].

5. Conclusion

The study found that northern China has areas (>70.96%) with extreme vulnerability, severe vulnerability, and moderate vulnerability. From 1980 to 2020, the overall ecological vulnerability in northern China increased first and then decreased. Here, the ecological vulnerability increased until 2000, beyond which it increased. Thus, from 2000 to 2020, the quality of the ecological environment and the stability of the ecosystem have improved.

The ecological vulnerability in northern China gradually weakened from west to east and from north to south. During the study period, the areas with severe vulnerability increased (15.53%), while those with slight vulnerability decreased (-14.01%). The vulnerability of the ecological environment has a significant spatial autocorrelation and a significant positive correlation. It is a significant high-high cluster in the western part of the research area, and the aggregation characteristics have migrated and expanded spatially.

Spatiotemporal variation of ecological vulnerability in northern China is mainly affected by natural factors and human activities in the region. Further, our study found that natural factors, such as temperature and precipitation, and human activities resulted in spatiotemporal variations in ecological vulnerability in northern China. At the same time, the socioeconomic factors contribute to ecological vulnerability, and their impact tends to gradually increase.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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