Spatiotemporal Evolution of Ecological Risk and Geographical Detection of Its Driving Factors in Semi-arid Regions: A Case Study of Yanchi County, Ningxia (Postprint)

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Abstract

An in-depth exploration of the changing patterns of landscape patterns in semi-arid regions and clarification of the spatiotemporal evolution characteristics and influencing factors of ecological risks are of great significance for optimizing landscape patterns in semi-arid regions, preventing and managing ecological risks, and promoting sustainable and high-quality regional development. Taking Yanchi County in Ningxia Hui Autonomous Region as an example, this study constructs an ecological risk model through landscape pattern indices based on land use data from 2000 to 2020, and conducts a comprehensive investigation into its landscape pattern changes, spatiotemporal evolution of ecological risks, and influencing factors by integrating geostatistical analysis and the geographical detector model. The results indicate: (1) From 2000 to 2020, the area of cultivated land and unused land in Yanchi County decreased, while all other land types showed an increasing trend, among which construction land expanded at the fastest rate with an average annual growth rate of 6.90%. (2) From 2000 to 2020, the number of landscape patches, patch density, landscape shape index, and Shannon' s diversity index in Yanchi County increased, while the largest patch index and contagion index decreased, indicating that the landscape pattern exhibited a development trend toward fragmentation, complexity, and dispersion. (3) From 2000 to 2020, the ecological risk index in Yanchi County decreased from 0.1465 to 0.1312, with the area proportion of high, relatively high, and moderate risk zones decreasing by 5.25%, 24.21%, and 5.44%, respectively, while the area proportion of low and relatively low risk zones increased by 14.11% and 20.79%, respectively, presenting a spatial distribution pattern of high risk in the north and low risk in the south. (4) With the growing social demands and intensifying human activities, the influence of natural factors on the spatial differentiation pattern of ecological risks has gradually weakened, while the role of socioeconomic factors has continuously strengthened.

Full Text

Geographical Exploration of the Spatial and Temporal Evolution of Ecological Risk and Its Influencing Factors in Semi-Arid Regions: A Case Study of Yanchi County in Ningxia

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Abstract: Investigating the changing patterns of landscape structure in semi-arid regions and clarifying the spatiotemporal evolution characteristics and influencing factors of ecological risk hold significant theoretical and practical importance for optimizing landscape patterns, preventing and managing ecological risks, and promoting sustainable, high-quality regional development. Taking Yanchi County in Ningxia Hui Autonomous Region as an example, this study employs land use data from 2000 to 2020 to construct an ecological risk model based on landscape pattern indices. Combined with geostatistical analysis and the geographic detector model, we conduct a comprehensive investigation of landscape pattern changes and the spatiotemporal evolution of ecological risk and its influencing factors. The results indicate that: (1) From 2000 to 2020, the area of cultivated land and unused land in Yanchi County decreased, while all other land use types showed increasing trends, with construction land expanding at the fastest rate (6.90% annually). (2) During this period, the number of landscape patches, patch density, landscape shape index, and Shannon' s diversity index increased, while the largest patch index and contagion index decreased, revealing a development trend toward landscape fragmentation, complexity, and dispersion. (3) The ecological risk index decreased from 0.1465 to 0.1312. The proportion of high, relatively high, and moderate risk areas declined by 24.21%, 5.25%, and 5.44% respectively, while low and relatively low risk areas increased by 20.79% and 14.11% respectively, exhibiting a spatial distribution pattern of higher risk in the north and lower risk in the south. (4) With growing social demands and intensifying human activities, the influence of natural factors on the spatial differentiation pattern of ecological risk has gradually weakened, while the role of socioeconomic factors continues to strengthen.

Keywords: landscape pattern; ecological risk; spatiotemporal evolution; geographic detector; semi-arid regions

1 Introduction

Land use represents one of the most direct manifestations of human exploitation and utilization of natural environments [?]. Changes in land use can alter ecosystem structure and processes, thereby affecting ecological functions and jeopardizing ecosystem health and safety [?]. Ecological risk assessment constitutes a comprehensive evaluation of the probability and severity of adverse consequences to ecosystems from natural disasters and human activities, serving as a crucial environmental management approach that provides scientific evidence for regional ecological protection and governance [?]. Since the advent of the "Anthropocene," human activities have intensified, continuously modifying and reshaping surface ecological processes, while global ecological process changes have reconfigured surface landscape morphology, forming differentiated landscape patterns [?]. Under the dual pressures of changing global landscape patterns and ecological functions, the ecological environment exhibits multidirectional evolution, with ecosystems facing unprecedented threats and challenges to sustainable development [?]. Particularly in semi-arid regions, which are highly sensitive to global change and human activities, the ecological environment is extremely fragile, and landscape patterns are susceptible to external disturbances that trigger ecological risks [?].

Currently, ecological risk assessment primarily follows two research paradigms: source-sink theory and landscape pattern theory, both of which reflect the integrated response of probability and loss [?]. Source-sink theory-based ecological risk assessment primarily employs pressure-state-response and ecological adaptability cycle models to comprehensively measure risk sources, receptors, hazard characteristics, and exposure-effect relationships across different spatial scales [?]. However, this approach is only applicable to areas with obvious ecological stress factors, and most studies focus on cross-sectional analyses at specific times, lacking expression and exploration of spatiotemporal evolution characteristics of ecological risk [?]. In contrast, landscape pattern-based ecological risk assessment focuses on the intrinsic correlation between ecosystem structural composition, pattern changes, and ecological risk [?]. Evaluating ecological risk from the perspective of pattern-process coupling not only reveals regional ecological risk spatiotemporal evolution characteristics and spatial differentiation patterns but also provides quantitative description and spatial expression of risk levels for ecological functions and processes under specific spatial patterns [?], facilitating understanding of spatiotemporal dynamic changes in ecosystem structure and function and their ecological effects under human disturbance [?]. Existing research has achieved certain results in landscape pattern-based ecological risk assessment, forming an internationally significant structural framework in theoretical architecture and methodology [?], with its increasingly sophisticated theoretical system and evaluation methods providing strong theoretical foundations and technical support for ecological risk research.

Yanchi County, located in the core area of semi-arid regions, represents a region with multiple couplings of climate, topography, soil, vegetation, and resource utilization. Compared with other areas, Yanchi County responds more rapidly and with amplification effects to external changes and human disturbances [**?**]. Therefore, taking Yanchi County as a case study and employing land use data to construct an ecological risk model based on landscape pattern indices, combined with geostatistical analysis and geographic detector models, this research explores landscape pattern change characteristics and spatiotemporal evolution patterns of ecological risk and their influencing factors in semi-arid regions, aiming to provide scientific support for land resource allocation, landscape pattern optimization, and coordinated sustainable regional development.

1.1 Study Area Overview

Yanchi County is located in eastern Ningxia Hui Autonomous Region [Figure 1: see original paper], under the jurisdiction of Wuzhong City, with geographical coordinates between 37°10 –38°12 N and 106°31 –107°46 E. It represents a typical farming-pastoral ecotone and semi-arid region in China. The county borders the Mu Us Sandy Land to the north and the Loess Plateau to the south, situated at the intersection of Shaanxi, Gansu, Ningxia, and Inner Mongolia. It constitutes a typical ecologically fragile area in western China and an important ecological barrier and functional zone with significant ecological strategic importance. The terrain slopes from high in the south to low in the north, with an average elevation of approximately 1,600 m, mean annual temperature of about 8.3°C, and arid climate with low rainfall (approximately 296 mm annually), decreasing from southeast to northwest. Due to unique natural conditions and unreasonable human activities, the human-land relationship is tense, with severe ecological problems including land desertification, salinization, and vegetation degradation. In 2020, the county governed 8 towns/townships and 98 villages with a total population of approximately 172,000 and GDP of 8.87 billion RMB.

2 Data and Methods

2.1 Data Sources and Processing

This study utilized land use data and influencing factor data. Land use data for 2000, 2010, and 2020 were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) with 30 m spatial resolution, including six major types: cultivated land, forestland, grassland, water bodies, construction land, and unused land. Influencing factor data included natural factors (elevation, slope, mean annual temperature, mean annual precipitation, normalized difference vegetation index (NDVI), soil organic matter content), socioeconomic factors (land use intensity, human disturbance degree, population density), and accessibility factors (distance to roads, distance to water bodies, and distance to town centers). Mean annual temperature and precipitation data were downloaded from the National Earth System Science Data Center (http://www.geodata.cn); elevation and NDVI data were extracted from the Geospatial Data Cloud platform (http://www.gscloud.cn/); land use intensity and human disturbance degree were calculated following methods in reference [?]; soil data were obtained from the Chinese Soil Database of the Institute of Soil Science, Chinese Academy of Sciences (http://www.issas.ac.cn/); and population density data were downloaded from Worldpop (http://www.worldpop.org/). Accessibility factor data were obtained through buffer zone calculations.

2.2 Methods

2.2.1 Landscape Pattern Analysis Landscape pattern represents the free combination and arrangement of landscape patches with different shapes and sizes within a specific spatial range, reflecting the interaction between landscape element spatial heterogeneity and ecological processes [?]. Landscape pattern indices serve as digital expressions of spatial information and concentrated manifestations of landscape pattern evolution information [?]. By analyzing changes in landscape pattern indices, we can reveal characteristics and patterns of spatial landscape evolution [?]. Referencing existing research [?] and based on the ecological implications of landscape pattern indices, we selected 6 indices to analyze and investigate landscape element quantity, shape, and spatial distribution characteristics (Table 1).

2.2.2 Ecological Risk Assessment Model Drawing on relevant studies [?], we constructed an ecological risk assessment model based on landscape pattern indices. Following landscape ecology principles, we divided the study area into 2 km × 2 km evaluation units based on the average patch area principle. We then constructed the ecological risk index using land use type area proportions and landscape loss degree indices, where landscape loss degree is characterized and calculated by landscape disturbance degree and landscape vulnerability [?]. The calculation formula is:

$$ERI_x = \sum_{i=1}^{n} \frac{A_{xi}}{A_x} \times R_i$$

where ERI_x represents the ecological risk index of evaluation unit x; A_{xi} denotes the area of landscape type i in evaluation unit x (km^2); R_i is the loss degree index of landscape type i; and A_x is the total landscape area of evaluation unit x (km^2). We used the natural breaks method to classify ecological risk into five levels: low, relatively low, moderate, relatively high, and high risk areas. The construction and calculation process of ecological risk indices are shown in Table 2.

2.2.3 Geographic Detector Model The geographic detector model, developed by Wang Jinfeng [?], is a statistical method for analyzing spatial heterogeneity of geographic objects and revealing their driving factors. This study employed the factor detector in the geographic detector model to explore the main driving factors influencing the spatial differentiation of ecological risk [?]. The calculation formula is:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where q represents the detection value of ecological risk influencing factors; h is the classification number of the independent variable; L is the total number of evaluation units; N_h and N are the numbers of units in each stratum and the entire region, respectively; and σ_h^2 and σ^2 are the variances of ecological risk in each stratum and the entire region, respectively.

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3 Results

3.1 Landscape Pattern Change Analysis

3.1.1 Land Use Change Analysis As shown in Table 3, grassland and cultivated land were the most widely distributed land use types in Yanchi County from 2000 to 2020, accounting for approximately 78.9% of the total area, followed by unused land and forestland (about 19.1%), while construction land and water bodies accounted for the smallest proportion (only 2.82% of the total area). From 2000 to 2020, cultivated land area showed a declining trend, decreasing by 300.14 km^2, with its proportion dropping from 29.19% to 24.61%. Forestland increased rapidly, with its proportion rising from 3.60% to 7.41% (a change rate of 105.83%). Grassland initially increased then decreased slightly, but the overall decline was minimal. Water body area continued to expand gradually, increasing from 10.15 km^2 to 16.94 km^2. Construction land expanded rapidly, growing from 77.53 km^2 to 184.48 km^2 (an increase of 137.95%) with an average annual growth rate of 6.90%.

3.1.2 Overall Landscape Characteristics Analysis Table 4 shows that from 2000 to 2020, the number of patches in Yanchi County increased from 4,685 to 5,344 (a 14.31% increase), and patch density increased from 0.90 to 1.04 per 100 hm^2 (a 15.56% increase), indicating increased landscape fragmentation and a trend toward more dispersed spatial patterns. The largest patch index decreased slightly by 0.58%, suggesting weakened control of dominant patch types over the landscape. The landscape shape index showed the opposite trend, increasing slightly by 4.20%, indicating that landscape shapes became more irregular, complex, and diverse. Shannon' s diversity index increased annually by 4.20%, demonstrating increasingly rich and diversified landscape types. The contagion index decreased by 2.30%, consistent with the largest patch index trend, indicating reduced aggregation of landscape types and a more scattered spatial distribution.

Table 5 reveals that from 2000 to 2020, patch numbers and densities of different land types showed varying trends. Forestland, water bodies, construction land, and unused land increased annually, while cultivated land and grassland first decreased then increased. Grassland had the largest largest-patch index, followed by cultivated land, with forestland and unused land between 1.0–2.2, and other land types fluctuating between 0–0.3. Landscape shape indices showed similar trends to patch numbers but with smaller variation amplitudes, with grassland and cultivated land having the most complex shapes. The landscape separation index of cultivated land and unused land increased, while other land types decreased, with construction land and water bodies showing the largest decreases (94.64% and 83.53%, respectively), indicating that these landscape patches tended toward aggregation, though their separation index values remained relatively high.

3.2 Ecological Risk Spatiotemporal Evolution

3.2.1 Spatiotemporal Evolution Characteristics As shown in Table 6, the ecological risk index in Yanchi County decreased from 0.1465 to 0.1312 between 2000 and 2020. The proportions of high, relatively high, and moderate risk areas decreased by 24.21%, 5.25%, and 5.44%, respectively, while low and relatively low risk areas increased by 20.79% and 14.11%, respectively. Spatially, high-risk areas were mainly distributed in Qingshan Township, Huamachi, and Gaoshawo, with a northward shift trend and a decreasing area proportion. Relatively high-risk areas were primarily found in Huamachi, Wangmin, Fengjigou, and Mahuangshan townships. Moderate-risk areas were mainly distributed in Fengjigou, Dashuikeng, Mahuangshan, and eastern Wangmin. Low and relatively low risk areas gradually shifted northward and expanded, primarily distributed in Gaoshawo, northern and eastern Huamachi, and Dashuikeng and Hui' anpu areas. Overall, ecological risk transitioned from being dominated by moderate and relatively high risk levels to moderate and relatively low risk levels, with risk levels clearly decreasing, ecological environmental quality gradually improving, and ecosystem health levels significantly increasing.

3.2.2 Ecological Risk Area Transfers Table 7 shows significant differences in conversion degrees among different risk levels from 2000 to 2020, mainly concentrated in transfers from high-risk to low-risk areas, with a total converted area of 4428.85 km^2. Among these, 370.91 km^2 of high and relatively high risk areas converted to low and relatively low risk areas, accounting for 92.27% of the total converted area, while only 2 km^2 of low-risk areas converted to high-risk areas (7.73% of converted area). In terms of conversion rates, moderate risk to relatively low risk, and relatively high risk to moderate risk showed the highest conversion rates at 127.81 km^2/year and 126.62 km^2/year, respectively. This indicates that ecological risk in the study area primarily transferred from high to low risk levels, with regional ecological risk gradually mitigating.

3.2.3 Ecological Risk Analysis by Landscape Type Figure 3 shows that in 2000, cultivated land was dominated by moderate risk areas (44.12%), while in 2020 it was dominated by relatively high risk areas (41.60%), with high and moderate risk areas decreasing but relatively high risk areas increasing 2.27-fold, indicating intensified risk for cultivated land. Forestland high-risk areas decreased by 27.08%, while low-risk areas increased by 41.60%, with moderate risk areas slightly decreasing, showing reduced risk levels for forestland. In 2000, grassland was mainly distributed in moderate and relatively high risk areas (79.16%), while in 2020 it was primarily in relatively low and moderate risk areas, with high-risk area decreasing and low-risk area increasing, indicating continuously decreasing risk levels for grassland. Water bodies were mainly in moderate risk areas in 2000, but in relatively high risk areas in 2020, with increased risk likely due to water conservancy facility construction and development land expansion. Construction land and unused land remained dominated by moderate, relatively high, and high risk areas, with high-risk areas increasing, closely related to construction land expansion, unused land development, and land stock renewal.

3.3 Analysis of Ecological Risk Influencing Factors

Figure 4 reveals that the spatial differentiation pattern of ecological risk in the study area is primarily influenced by socioeconomic development, followed by natural environmental factors, while regional accessibility has the smallest impact. From 2000 to 2020, human disturbance degree, land use intensity, and mean annual precipitation showed the highest factor contribution rates (53.41%), representing the main influencing factors of landscape risk during this period. By 2020, the influence of socioeconomic factors continuously strengthened while natural factors' influence declined to varying degrees, with mean annual precipitation showing the most significant change, likely related to persistent drought in the region during 2020. Regional accessibility factors contributed less than 18.22% to ecological risk, indicating weak explanatory power for spatial differentiation of ecological risk, which is related to the spatial distribution of landscape types since construction land accounts for only 2.82% of the total area. Overall, with growing social demands and intensifying human activities, the influence of natural factors gradually weakens while socioeconomic and regional accessibility factors strengthen.

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4 Discussion

Land use and landscape pattern changes represent concrete manifestations of environmental evolution in semi-arid regions, playing crucial roles in supporting socioeconomic development and maintaining regional ecological security [?]. Achieving coordinated human-land system development and maintaining ecosystem stability amidst these changes represents a shared goal for ecological risk assessment and management in semi-arid regions [?]. Yanchi County, as a typical farming-pastoral ecotone and ecologically fragile area in China, is extremely sensitive to land use changes.

From 2000 to 2020, land use changes in Yanchi County mainly occurred among cultivated land, forestland, grassland, and unused land, with forestland and grassland increasing while cultivated land and unused land decreased, consistent with findings by Huang Yue et al. [?] and Yang Yafang et al. [?]. These changes result from both socioeconomic development constraints and natural conditions, as well as implementation of national policies including the Grain for Green Program, ecological county strategy, mountain closure for grazing prohibition, and grassland restoration projects, which continuously promote and transform the land use pattern.

Landscape patterns reflect how natural conditions and human activities affect ecosystems. The increasing number of patches, patch density, and landscape shape index, along with decreasing contagion index, indicate that Yanchi County's landscape pattern is developing toward fragmentation, complexity, and dispersion, consistent with Cheng Linlin et al. [?] but differing from Liu Shuqin et al. [?], possibly due to different study periods and administrative boundaries. The ecological risk level in Yanchi County decreased, showing a north-high-south-low distribution pattern, consistent with Huang Yue et al.' s [?] findings from an ecological vulnerability perspective. From north to south, elevation and precipitation increase while temperature decreases, with landscape types transitioning from unused land, construction land, and grassland to forestland, grassland, and cultivated land, resulting in decreasing ecological risk. From 2000 to 2020, significant changes in ecological risk levels occurred, mainly manifested as transfers from relatively high risk to moderate risk and from moderate risk to relatively low risk, with risk increase areas scattered. High and relatively high risk areas decreased by 318.5 km^2, indicating continuous improvement in ecological environmental quality.

Ecological risk degree is closely related to landscape types and their spatial distribution patterns [?]. High-risk areas in Yanchi County are mainly distributed in the northern region with extensive unused land and construction land, while low-risk areas are primarily in the southern region with extensive forestland, grassland, and cultivated land, consistent with findings by Gong Jie et al. [?], Huang Muyi et al. [?], and Liu Shiliang et al. [?] in different ecological regions (Bailong River, Chaohu Lake, and Red River basins), but differing from Lü Leting et al. [?], mainly due to concentrated distribution of construction land resulting in lower landscape loss degree and ecological risk.

This study reveals the spatiotemporal evolution characteristics of ecological risk in Yanchi County through an ecological risk assessment model based on landscape pattern indices from a pattern-process coupling perspective. The results align with Yanchi County' s ecological environment, demonstrating that landscape ecological risk can effectively reflect human activity impacts on ecosystems. Semi-arid regions are complex systems influenced by multiple factors. While the landscape ecology perspective can objectively reflect regional ecological risk, it has difficulty characterizing impacts from natural disasters and human interference [?]. Future research should strengthen investigations of regional environmental changes and human activity impacts on ecological risk to clarify their mechanisms, providing scientific support for ecological risk reduction and habitat restoration in semi-arid regions.

5 Conclusions

Based on land use data, this study constructed an ecological risk model and integrated geostatistical analysis with the geographic detector model to comprehensively investigate landscape pattern changes, spatiotemporal evolution patterns of ecological risk, and influencing factors in semi-arid regions. The main conclusions are:

1) Grassland and cultivated land were the primary land use types in Yanchi County from 2000 to 2020. The overall land use structure exhibited rapid construction land expansion, cultivated land shrinkage, forestland and grassland increase, and water area expansion. Influenced by natural environment and human activity disturbances, the landscape pattern overall developed toward fragmentation, complexity, and dispersion.

2) The ecological risk index in Yanchi County decreased from 0.1465 to 0.1312 between 2000 and 2020. Ecological risk transitioned from being dominated by moderate and relatively high risk levels to moderate and relatively low risk levels, with overall risk levels declining and a spatial distribution pattern of higher risk in the north and lower risk in the south.

3) The spatial differentiation of ecological risk in Yanchi County is mainly influenced by human disturbance degree, land use intensity, mean annual precipitation, NDVI, elevation, and mean annual temperature. With growing social demands and intensifying human activities, the influence of natural factors gradually weakens, while the influence of socioeconomic and regional accessibility factors continues to strengthen.

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