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Landscape Pattern Identification and Ecological Risk Assessment Employing Land Use Dynamics on the Loess Plateau

Sen Chang, Zhen-Zhong Dai, Xing Wang, Zhi-Yuan Zhu and Yong-Zhong Feng *

College of Agronomy, Northwest A&F University, Xianyang 712100, China; 2022055028@nwafu.edu.cn (S.C.); 2022060023@nwafu.edu.cn (Z.-Z.D.); jiaxing0103@163.com (X.W.); zhuzhiyuan@nwafu.edu.cn (Z.-Y.Z.)
* Correspondence: fengyz@nwsuaf.edu.cn

Abstract: The Loess Plateau region is characterized by fragmented habitats and ecological vulnerability. Analyzing the changes in land use and ecological risk within the region is of great significance for promoting high-quality development of the Loess Plateau. The study utilized land use data from 2000, 2010, and 2020 in the Loess Plateau region to assess the spatio-temporal variation in land use patterns and landscape ecological risks, aiming to provide valuable references and decision support for ecological risk management and sustainable development in the area. The results indicated that the main land use types in the region are grassland and cropland. From 2000 to 2020, forest, grassland, and water areas increased by 1.39×10^6, 6.25×10^5, and 7.09×10^4 ha, respectively. The impervious area increased rapidly, growing from 9.77×10^4 ha in 2000 to 1.85×10^6 ha in 2020. The cropland decreased by 1.82×10^6 ha from 2000 to 2020, with 4.61×10^5, 4.95×10^6, and 8.91×10^5 ha of cropland converted to forest, grassland, and impervious area, respectively. The fragmentation of the ecological landscape in the region has decreased, and the diversity and richness of landscape types have increased. The fragmentation of cropland, forest, and grassland has decreased, and landscape patches have become more concentrated. High-value areas of landscape ecological risk in the region show a trend of continuous aggregation, altering the dispersion pattern of high-risk areas. Currently, high-risk areas of landscape ecology in the Loess Plateau region are mainly concentrated in northern Shaanxi and some areas along the Yellow River, such as Yulin, Yan'an, Ordos, and others. Currently, the ecological environment remains a bottleneck constraining the high-quality development of the Loess Plateau. It is necessary to persist in coordinated governance and ecological engineering construction, and improving the quality of ecological environment is a prerequisite for consolidating the social foundation and leading the high-quality development of the ecological industry on the Loess Plateau.

Keywords: the Loess Plateau; land use; landscape pattern; risk assessment

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1. Introduction

The Loess Plateau, characterized by its rich resources, long history of development, and immense growth potential, holds a pivotal position in China's socioeconomic advancement and ecological security. However, its unique regional ecological structure, shaped by a combination of natural factors such as topography and social factors like population dynamics, renders the system's functionality comparatively fragile. Consequently, the region confronts severe ecological challenges, including soil erosion and wetland degradation. Undulating terrain, steep slopes, fragmented habitats, and an exceptionally fragile ecological environment further exacerbate these problems. The sustained influence of both natural endowment and human activities imposes tremendous pressure on the ecosystem, necessitating urgent efforts to enhance comprehensive regional ecological management and environmental governance. The development of a distinctive ecological industrial system in this region necessitates the holistic consideration of the regional ecosystem, effectively harmonizing the relationships between ecological conservation, agricultural production, and social development. It requires a comprehensive approach that encompasses mountains, rivers, forests, croplands, lakes, grasslands, and deserts, thereby establishing a robust ecological foundation for social production from multiple dimensions. To this end, the nation has undertaken various ecological projects, including land conversion to forests (grasslands), soil and water conservation, and the construction of protective forests in the "Three-North" region. However, ecological conservation efforts still face significant challenges. In 2019, General Secretary Xi Jinping highlighted the imperative to balance rational development and resource utilization with their sustainability, promoting resource recycling, during the symposium on ecological conservation and high-quality development in the Yellow River Basin. The significance of ecological protection in the Loess Plateau has become increasingly prominent.

Against the backdrop of ecological conservation and high-quality development becoming a national strategic in the Yellow River Basin, a comprehensive understanding of the changing ecological conditions and the distribution of ecological risks in the Loess Plateau region can provide decision-making support for regional ecological management and risk prevention [1]. Initially, ecological risk assessment was primarily employed to evaluate environmental pollution processes associated with individual sources of risk [2–4]. However, in recent years, with the continuous development of theories and models of ecological risk assessment, research on ecological risk assessment has increasingly focused on the general impact of ecosystems and the spatial characteristics of ecological risks, expanding the scale of assessment to the regional level [5,6]. Furthermore, as research progresses, ecological risk assessment based on the perspective of land use, utilizing landscape indices and relative risk models as the main approaches, has gradually become the mainstream method [7–9]. Some studies have utilized various landscape pattern indices to construct ecological risk indices, thereby evaluating ecological risks at different scales such as regional cities [10,11] and watersheds [12]. Based on the assessment of ecological risks at the county level, Hou et al. and Li et al. further analyzed the driving factors of ecological risks and proposed corresponding risk prevention and control strategies [13,14]. In general, the evaluation methods and assessment systems for analyzing ecological risks through the establishment of evaluation models have reached a certain level of maturity. However, these approaches primarily focus on single factors or specific issues related to regional development [15], lacking comprehensive research that systematically reflects the spatio-temporal characteristics of the ecological patterns in the Loess Plateau region. As a result, a unified consideration of regional ecological risk governance in the Loess Plateau region has not yet been established.

Based on this premise, this study utilizes land use data from 2000, 2010, and 2020 in the Loess Plateau region to analyze the temporal and spatial variations of land use patterns in northern Shaanxi area over a long time series. This is achieved through the calculation of landscape pattern indices and the construction of an ecological risk assessment model at the grid scale. The study aims to reveal and diagnose the spatio-temporal differentiation of ecological risks in the region. Based on these findings, ecological risk zones are delineated, and targeted suggestions for ecological governance, zoning, and control in the Loess Plateau region are proposed. This quantitative analysis and decision-making framework aim to provide valuable reference and decision-making support for ecological risk prevention and control as well as high-quality development in the Loess Plateau.

2. Materials and Methods

2.1. Study Area Description

The Loess Plateau, spanning an area of approximately 640,000 km^2, is situated in the central and northern regions of China's Yellow River basin (33°41′–41°16′ N, 100°52′–114°31′ E). This vast expanse encompasses seven provinces: Gansu, Henan, Inner Mongolia, Ningxia, Qinghai, Shanxi, and Shaanxi (Figure 1), making it the largest and most concentrated loess region worldwide. Renowned for its distinctive landforms, rich cultural heritage, and delicate ecosystems, the Loess Plateau has a long history of human settlement. However, the region has been grappled with significant challenges, including severe soil erosion, sparse vegetation, high population density, low productivity, and soil and water loss [16,17]. As a result, it has become one of China's focal points for population, resource, and environmental conflicts [18]. Featuring a semi-arid continental monsoon climate, the area experiences cold and dry winters, as well as hot and rainy summers, with pronounced seasonal and annual temperature variations. The average annual temperature ranges from 7 °C to 13 °C, and the average annual precipitation varies between 400–600 mm. Rainfall is sporadic and exhibits significant regional disparities. The combination of high evaporation rates, sediment-laden water systems, and the loose soil texture of the loess soil contributes to the fragile ecological environment and severe soil erosion observed within the region. The Loess Plateau boasts a diverse ecosystem, serving as a habitat for numerous endangered species and possessing considerable ecological value. Over time, various external factors, such as human economic activities, climate change, and land restoration policies, have exerted varying degrees of influence on the ecosystem provided by the region.

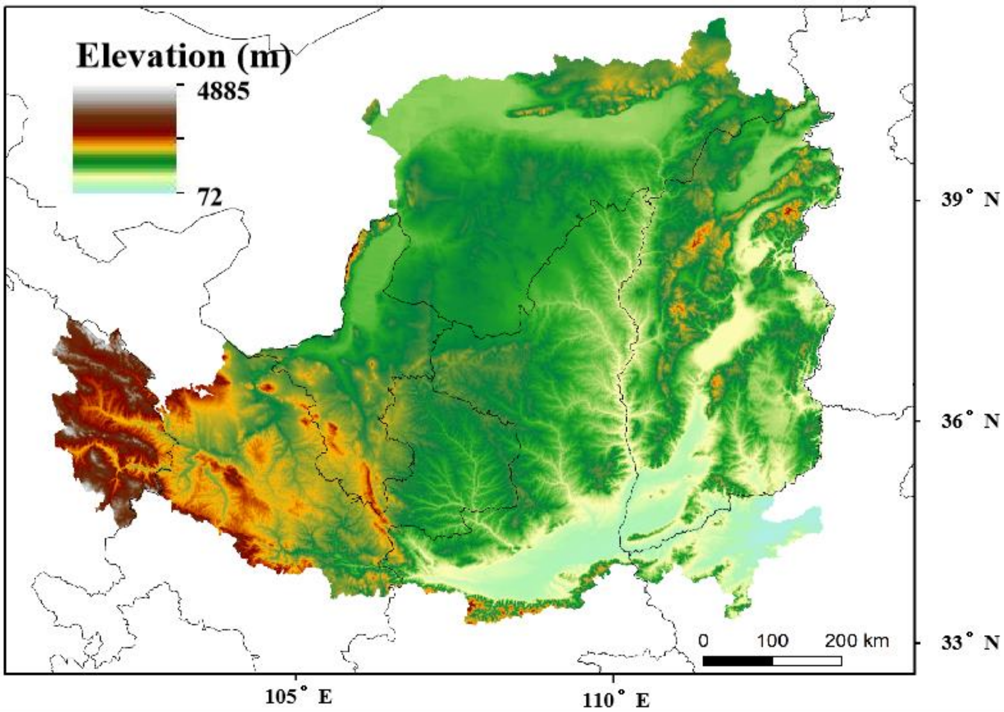

Figure 1. The geographical location of the Loess Plateau in China.

2.2. Data Source

Land use data in 2000, 2010, and 2020 were obtained using publicly available information from the Global Geographic Information Public Goods (GlobeLand30, http://www.globallandcover.com, accessed on 22 April 2023), as well as the administrative division data obtained from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (http://www.resdc.cn, accessed on 10 April 2023). Precise delineation of the land use data was performed by cropping it based on the administrative boundaries of the study area, thereby yielding land use data for the Loess Plateau region in the years 2000, 2010, and 2020. The predominant land use categories within the study area encompass cropland, forest, shrub area, grassland, water area, barren area, impervious area, wetland, and snow/ice (Figure 2).

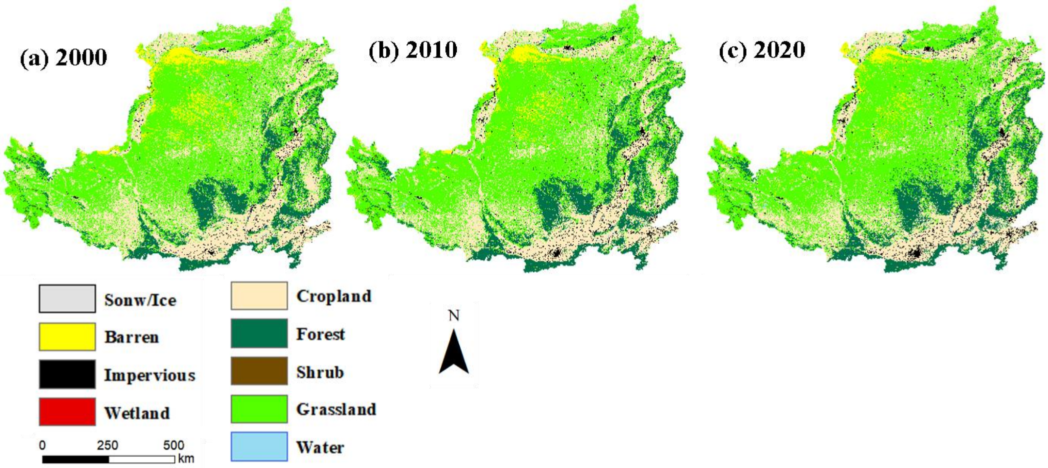

Figure 2. Distribution of land use types on the Loess Plateau from 2000 to 2020.

2.3. Land Use and Land Cover (LULC) Changes

The application of the dynamic degree formula to a single LULC enables the calculation of LULC changes within a specified time range in the study area, resulting in the following equation [19]:

$$K_{LULC} = \frac{U_B - U_A}{U_A} \times \frac{1}{T} \times 100\% \tag{1}$$

where K_{LULC} refers to the dynamic range of a particular LULC type over the duration of the study period. Both U_A and U_B represent the area occupied by a specific LULC type at the beginning and end of the study period, respectively, and expressed in units of hectares (ha). T represents the length of the study period, expressed in yr^{-1}.

According to Chen et al. [20], the changes in land use types over decades can be explained by constructing transition matrices. The article uses an LULC transfer matrix to represent the transition rules between different LULC, as shown in the following equation [21]:

$$S_{T+1} = P_{ij} \times S_T \tag{2}$$

$$P_{ij} = \begin{bmatrix} P_{11} \ldots P_{1n} \\ \vdots \ddots \vdots \\ P_{n1} \ldots P_{nn} \end{bmatrix} \tag{3}$$

$$0 \le P_{ij} < land \sum_{j=1}^{N} P_{ij} = 1, (i, j = 1, 2, \ldots\ldots n)$$

where the transition matrix, denoted by P_{ij}, represents the probability that type i is transferred to type j in LULC. i, j represent the first and second LUCC type. S_T and S_{T+1} represent the status of land use at time T and time $T + 1$, respectively. N represents the number of LULCs in the study area.

2.4. Landscape Pattern Index

Changes in landscape pattern have a significant impact on regional ecological processes and functions, resulting in variations in ecosystem services [22]. Landscape indices serve as vital metrics for assessing landscape patterns, effectively condensing regional landscape pattern information, and efficiently representing the spatial structure and change characteristics of the regional ecological environment. In accordance with the research objectives and the characteristics of the Loess Plateau region, this study selected six landscape pattern indices to characterize the number, shape, and spatial distribution of land use elements in the Loess Plateau. The selected indices include the number of patches (NP), patch density (PD), edge density (ED), landscape shape index (LSI), average patch area

(Area_MN), Shannon diversity index (SHDI) and splitting index (SPLIT). These indices are capable of reflecting the landscape structure and dynamic changes within the study area [23–25], and were calculated using Fragstats 4.2 software (https://fragstats.org/, accessed on 10 April 2023).

2.5. Ecological Risk Assessment

Based on the perspective of landscape ecology, a regional ecological risk assessment model (*ERI*) was developed by incorporating the landscape disturbance index and the vulnerability index. The landscape disturbance index (U_i) reflects the degree of loss experienced by different landscape types after disturbances. A higher value of the disturbance index indicates a greater ecological risk. In the equation, C_i represents the landscape fragmentation index, S_i denotes the landscape isolation index, and K_i signifies the landscape dominance index. The variables n_i, A_i, A, m_i, M, and N represent the number of patches, total area, total landscape area, number of sampling units with the occurrence of patch type i, total number of sampling units, and the total number of patches, respectively. The coefficients a, b, and c represent the weightings of the respective indices on landscape disturbance, and based on previous research [26], the values of a, b, and c are assigned as 0.5, 0.3, and 0.2, respectively.

$$U_i = aC_i + bS_i + cK_i \tag{4}$$

$$C_i = \frac{n_i}{A_i} \tag{5}$$

$$S_i = \frac{A}{2A_i}\sqrt{\frac{n_i}{A}} \tag{6}$$

$$K_i = \frac{1}{4}\left(\frac{n_i}{N} + \frac{m_i}{M}\right) + \frac{A_i}{2A} \tag{7}$$

The landscape fragility index (V_i) has been shown to reflect the sensitivity of different landscape ecosystems to external disturbances. According to a previous study [27], the fragility index values for various landscape types are as follows: cropland (0.133), grassland (0.092), water area (0.294), forest (0.037), shrub (0.052), wetland (0.294), impervious area (0.02), and barren area (0.373). It is noteworthy that higher fragility index values correspond to reduced resilience of landscape types to external perturbations.

The ecological risk assessment model transforms the landscape spatial structure of land use types into spatial-scale ecological risk, thereby characterizing the extent of ecological loss within the assessment units. In the equation, ERI_k represents the ecological risk index of the assessment unit k; n denotes the number of landscape types; A_{ki} denotes the area of the i-th landscape type within the assessment unit k, measured in square kilometers (km^2); and A_i represents the area of the assessment unit k, also measured in square kilometers (km^2).

$$ERI_k = \sum_{i=1}^{n} \frac{A_{ki}}{A_i}(U_i V_i) \tag{8}$$

Considering the average size of landscape patches within the study area and the data-processing capacity, this study divided the study area into a grid of 18 km $\times$ 18 km, resulting in a total of 2183 ecological risk assessment units. Based on the actual distribution of the ecological risk index (*ERI*) during the three temporal periods, the study area was classified into three levels of ecological risk, namely the high-risk area, the moderate-risk area, and the low-risk area, using the natural break-point classification.

3. Results

3.1. Land Use Changes in the Loess Plateau Region

The area and changes of the main land use types in the Loess Plateau region from 2000 to 2020 are presented in Table 1. Grassland and cropland are the main land use types in the Loess Plateau region, with grassland covering the largest proportion. Overall, during the period of 2000–2020, the areas of forest, grassland, water area, and impervious area increased by 139.46×10^4, 62.46×10^4, 7.09×10^4, and 87.17×10^4 ha, respectively. However, the areas of cropland, shrub area, wetland, and barren area decreased by 182.23×10^4, 16.11×10^4, 0.01×10^4, and 97.84×10^4 ha, respectively. Compared to the period of 2000–2010, the land use changes during 2010–2020 showed a slower decline in cropland and an increased proportion of forest. The growth of forest and grassland is closely related to the national policies of returning cropland to forest and grassland that have been implemented since 2003. The ecological governance projects in the Loess Plateau have to some extent adjusted the land use structure and changed the ecological conditions for agricultural production. Currently, rapid urbanization is occurring in some areas of the Loess Plateau, leading to a significant expansion of construction land, which has increased from 97.71×10^4 ha in 2000 to 184.88×10^4 ha in 2020.

Table 1. Land use changes in the Loess Plateau region from 2000 to 2020.

Land Use Type	Area ($\times 10^4$ ha)			Change Rate (%)	
	2000	2010	2020	2000–2010	2010–2020
Cropland	1970.92	1817.44	1788.69	−7.79	−1.58
Forest	760.15	823.22	899.61	8.30	9.28
Shrub	35.88	23.88	19.77	−33.46	−17.20
Grassland	3004.25	3127.09	3066.71	4.09	−1.93
Water area	22.67	27.17	29.76	19.85	9.56
Wetland	1.43	2.53	1.41	77.37	−44.16
Barren	266.43	195.77	168.59	−26.52	−13.88
Impervious	97.71	142.35	184.88	45.68	29.88

The analysis of land use transfer matrix provides information on the land type transitions in the Loess Plateau region (Figure 3). From 2000 to 2020, the areas of cropland transformed into forest, grassland, and impervious area were 46.14×10^4, 494.73×10^4, and 89.12×10^4 ha, respectively. Cropland and grassland (23.22×10^4 ha) were the main sources for the expansion of the construction land. On the other hand, grassland showed a net transfer of 140.36×10^4 ha to forest. Although cropland in the Loess Plateau region declined during the period of 2000–2020, there were still 368.85×10^4 ha of grassland and 15.46×10^4 ha of forest converted into cropland.

3.2. Ecological Landscape Characteristics in the Loess Plateau Region

During the period from 2000 to 2020, the overall characteristics of ecological landscape patterns in the Loess Plateau region showed a decreasing trend in NP, PD, ED, and LSI, while an increasing trend in AREA_MN (Table 2). It indicates a reduction in the fragmentation degree of the ecological landscape and a trend towards concentrated land use distribution in the region. The decrease in LSI by 16.85% reflects a decrease in the diversity of landscape shape types in the region. SHDI showed a significant increase with a growth rate of 0.81%, suggesting an increase in the richness of landscape types in the Loess Plateau region. Overall, the ecological landscape pattern in the Loess Plateau region has experienced an improvement in its fragmentation and dispersion, leading to a more concentrated land use pattern.

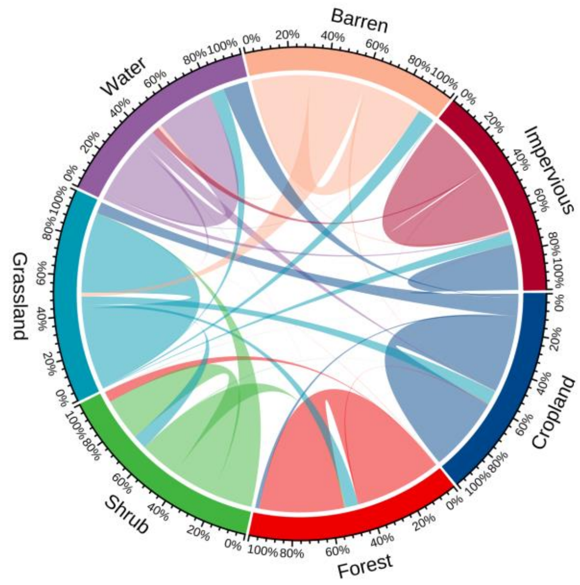

Figure 3. Land use transfer matrix in the Loess Plateau region from 2000 to 2020.

Table 2. Changes in ecological landscape pattern indices in the Loess Plateau region.

Year	NP	PD	ED	SHDI	LSI	AREA_MN
2000	7,298,315	11.85	71.05	1.23	1396.64	8.44
2010	6,318,064	10.26	63.30	1.22	1244.54	9.75
2020	5,972,818	9.70	59.06	1.24	1161.33	10.31
Change rate from 2000 to 2020 (%)	−18.16	−18.16	−16.88	0.81	−16.85	22.19

However, as observed in Table 3, there has been a decrease in NP and PD for cropland, forest, grassland, shrub area, water area, and barren area, while there has been an increase in the NP for impervious area, indicating different trends in the fragmentation levels of various land use types in the region. Additionally, LSI for cropland has also decreased, indicating a trend toward more regular-shaped patches. Compared to cropland, forest, and grassland, other land use types have a higher SPLIT, indicating a greater degree of patch separation. The separation indices for cropland, forest, grassland, and impervious area have decreased, suggesting a trend toward patch concentration.

3.3. Evaluation of the Landscape Ecological Risk in the Loess Plateau Region

There is significant spatio-temporal variation in landscape ecological risk in the Loess Plateau region (Figure 4). From 2000 to 2020, the proportion of high-risk areas increased from 24.05% to 27.12%, while low-risk areas also increased. However, there was a significant decrease in moderate-risk areas, which decreased by 3.25%. Overall, there is a trend of continuous aggregation of high-risk areas in the landscape ecological risk of the Loess Plateau, changing the dispersion pattern of high-risk areas. Spatially, it is evident that the high-landscape-ecological-risk areas in the Loess Plateau region are mainly concentrated in northern Shaanxi and along the Yellow River, including areas such as Yulin, Yan'an, and Ordos.

Table 3. Landscape pattern index changes of land use types in the Loess Plateau region.

Type	Year	NP	PD	LSI	SPLIT
Cropland	2000	2,435,328	3.95	1618.46	267.40
	2010	1,829,039	2.97	1409.95	227.25
	2020	1,573,323	2.55	1317.71	179.58
Forest	2000	782,865	1.27	830.63	2369.54
	2010	709,628	1.15	792.15	1684.26
	2020	755,625	1.23	833.84	1386.65
Grassland	2000	1,940,013	3.15	1692.58	9.63
	2010	1,596,307	2.59	1410.76	8.38
	2020	1,653,188	2.68	1272.58	8.69
Shrub	2000	409,868	0.67	777.21	816,633,635
	2010	316,421	0.51	650.27	1,085,732,987
	2020	243,258	0.39	550.84	1,106,684,316
Water	2000	45,212	0.07	211.32	5,098,361.81
	2010	38,223	0.06	190.27	2,368,355.09
	2020	36,827	0.06	185.29	2,538,421.80
Impervious	2000	668,600	1.09	799.73	1,534,872.82
	2010	657,582	1.07	813.37	479,668.29
	2020	708,164	1.15	849.61	220,786.96
Barren	2000	479,543	0.78	657.55	6054.43
	2010	406,348	0.66	612.19	15,985.18
	2020	331,418	0.54	537.65	23,102.42

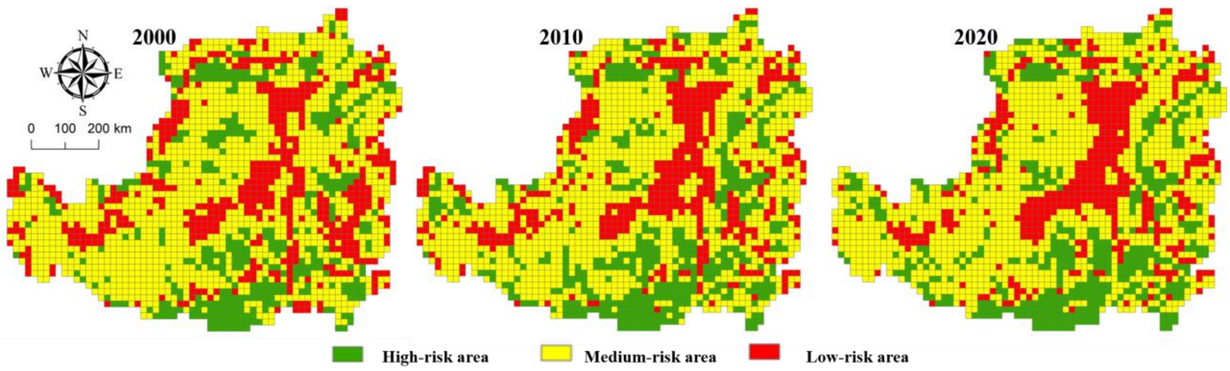

Figure 4. Landscape ecological risk classification in the Loess Plateau region.

4. Recommendations for High-Quality Development on the Loess Plateau

Ecological risk control in the Loess Plateau region has made preliminary progress, which is closely related to ecological restoration projects such as soil and water conservation, small watershed management, natural forest protection, reforestation (grassland), and terraced land improvement [28]. A series of ecological restoration projects have to some extent adjusted the land use structure and improved the ecological conditions for social production [29]. However, localized ecological degradation issues still persist in certain areas of the region. With the accelerated process of urbanization, there has been a rapid expansion in the demand for construction land, and human activities have intensified land fragmentation and occupation of cropland [30].

Currently, a fully functional and well-circulated regional ecosystem, characterized by efficient cycling processes, has not yet been fully established in the Loess Plateau region. To achieve high-quality ecological development in this area, there is a need to strengthen ecological governance and consolidate the ecological foundation. In accordance with the specific characteristics of the Loess Plateau and its regional development objectives, it is imperative to comprehensively implement differentiated ecological governance measures that encompass a comprehensive range of governance elements and are scientifically sound in their allocation. It is recommended to pragmatically advance engineering projects such as silt retention dams, slope terracing, and gully treatment and land reclamation based on local conditions. Building upon the principles of natural laws and available resources, it is essential to implement appropriate afforestation, efficient irrigation practices, suitable grassland management, and appropriate land fallow policies. Furthermore, scientific land improvement, the establishment of high-standard farmlands, conservation, and restoration of forest vegetation should be conducted. A coordinated approach that integrates high-quality governance and ecological engineering projects for mountains, rivers, forests, croplands, lakes, grasslands, sand, and soil would facilitate the restoration of ecosystem functions, comprehensively optimize the ecological environment of the Loess Plateau, and solidify the foundation for the sustainable operation of the ecosystem.

The coordination and harmonization of ecological risk governance with the high-quality development of the economy and society require a regional approach that takes into account the ecological risks and resource endowments, guiding the construction of green ecological industry clusters in the Loess Plateau region. In areas with high ecological risks, there should be a shift towards stock renewal and intensive and efficient utilization of construction land and cropland, while comprehensively protecting ecological land such as forests, grasslands, and water area. In areas with moderate ecological risks, the leading role of spatial planning should be fully utilized to balance the distribution of different types of land, integrate and match natural endowments with production factors, reduce the negative impacts of economic development on the environment, and maintain or even improve the current level of ecological risk. In areas with low ecological risks, it is necessary to strategically plan green industry clusters, strengthen infrastructure construction, leverage the comparative advantages of green ecological industries, and establish intensive and high-value green agricultural industry clusters focused on crops (such as millet, barley), fruits (such as apples, dates), edible fungi, and specialty plants (such as Chinese wolfberry, sea buckthorn, hops). Additionally, it is important to establish agro-pastoral industry clusters primarily focused on feed, meat production (such as beef and mutton), dairy industry, and cashmere production, as well as protecting grassland agricultural industry clusters. Simultaneously, it is essential to promote the integration of regional industrial development with soil and water conservation, agricultural water conservancy construction, and circular economy projects, while supporting the development of new technologies, new formats, and new models that are environmentally friendly.

5. Conclusions

The dominant land types in the Loess Plateau region are grassland and cropland. From 2000 to 2020, the areas of forest, grassland, water area, and impervious area increased by 139.46×10^4, 62.46×10^4, 7.09×10^4, and 87.17×10^4 ha, respectively, while the area of cropland decreased by 182.23×10^4 ha. Currently, there is rapid urbanization and a significant expansion in construction land demand, with the area increasing from 97.71×10^4 ha in 2000 to 184.88×10^4 ha in 2020. During the same period, areas of 46.14×10^4, 494.73×10^4, and 89.12×10^4 ha converted from cropland to forest, grassland, and impervious area, respectively. The overall fragmentation of the ecological landscape in the Loess Plateau region has decreased, and there is an increasing diversity of landscape types. The fragmentation of cropland, forest, and grassland has also reduced, leading to a concentration of landscape patches. High-risk areas of landscape ecological risk show a tendency to aggregate, altering the spatial distribution of high-risk areas. Currently, the high-risk areas of landscape ecology in the Loess Plateau region are mainly concentrated in northern Shaanxi and along the Yellow River, including Yulin, Yan'an, and Ordos. In the future, continuous coordination of high-quality governance of mountains, rivers, forests, cropland, lakes, grasslands, and sand, along with ecological engineering construction, is crucial for improving the ecological environment of the Loess Plateau, laying a solid foundation for regional production, and leading the high-quality development of green ecological industrial clusters in the region.

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