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Landscape Ecological Risks to Rural Landscape and Planning Implications: A Case Spatio-Temporal Analysis in Xiangxi Autonomous Prefecture of SW China

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Abstract

Maintaining regional landscape ecological stability and enhancing rural landscape ecosystem services are critical research priorities. This study selected Xiangxi Autonomous Prefecture (XXAP), a representative mountainous region in Southwestern (SW) China, as the case study area. This study aims to construct a rural landscape ecological risk (RLER) evaluation index system based on five-period remote sensing data (2000–2020), analyze the spatio-temporal characteristics of RLER, and provide a scientific basis for landscape ecological management and rural spatial governance. The results show that the RLERI exhibited a balanced multi-ring development trend, decreasing slightly from 0.295 in 2000 to 0.282 in 2020, suggesting a slight alleviation of overall risk. Medium-risk areas of the RLERI consistently accounted for the largest proportion (over 37%). Notably, the share of high-risk areas remained relatively stable, fluctuating narrowly between 7.98% and 8.73%. Meanwhile, high-risk areas of the landscape disturbance degree (LDD) expanded markedly from 1.87% to 10.28%. Correspondingly, high-risk areas of the landscape fragility degree (LFD) also increased significantly, rising from 0.93% to 2.8%. Spatially, RLER displayed significantly positive spatial autocorrelation, with high–high (H-H) clusters concentrated in the central-southern part and low–low (L-L) clusters distributed in the northern and southern margins, indicating pronounced spatial differentiation. In conclusion, this study provides a transferable framework for ecological risk assessment in mountainous regions. Furthermore, it underscores the importance of optimizing landscape patterns in ecologically fragile areas, strengthening ecological risk management, and mitigating ecological risks in rural settings.

Keywords: rural human–land system; LDD; LFD; ecosystem service value; spatio-temporal heterogeneity; zonal management

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1. Introduction

Doxiadis first mentioned the concept of settlement and agglomeration in the 1950s [1]. The countryside, as the history of the extension of the farming civilization across the spatial carrier, contains a wealth of historical information and ecological attributes and embodies the interactive development process of human and natural systems [2,3]. Meanwhile, rural

areas reflect the wisdom of human survival and ecological pattern [4]. Rural systems constitute a transition zone between urban and village systems, primarily characterized by agricultural populations and economic activities [5]. They present multi-level settlement spaces of different grades, scales, and functions. Meanwhile, they depend on each other to be the spatial carriers of urban–rural integration and development [6]; they are an artificial system that interacts with natural systems. Rural areas refer to a geographical system of human–land interactions composed of counties, townships, villages, and their administrative jurisdictions. Rural landscapes are highly dynamic system in which human and natural systems interact [7].

Landscape ecological risk (LER) is an important branch of ecological risk [8]. Ecological risk refers to potential ecosystem damage caused by unpredictable natural changes and human activities, reflecting a system's inability to resist or adapt to external pressures [9]. LER is a result of the risk generated by the interaction of landscape patterns and ecological processes under the role of anthropogenic activities or other multiple elements, which is not only an expression of the heterogeneity but also refers to the risk coercion factor on the possible loss caused by the specific regional landscape components, structure, function, and process [10]. Overseas research is mainly based on the ecological environment management policy, ecosystem services, and other research perspectives. For example, Dearfield put forward the U.S. ecological environment development management policy as the goal of the study area to carry out LER assessment [11]; Stritih argued that mountain forest ecosystem services are at risk due to natural disturbances, providing empirical evidence from the Swiss Alps, which shows that disturbances have spatially heterogeneous impacts on ecosystem services [12]; Ayre proposed the application of a Bayesian network model in ecological risk based on the empirical study of northeastern Oregon [13]; Angeliki argued that the socio-ecological system decoupling of landscapes leads to rural degradation and makes traditional settlements vulnerable to fire [14].

The new urbanization in China has widened the urban–rural gap while causing rural issues like water pollution, farmland fragmentation, and idle construction land [15]. The ensuing multiple disturbances, such as high-intensity disturbance of anthropogenic construction activities [16], village abandonment [17], and climate change [18], have resulted in a huge waste of land resources and over-exploitation of land, which seriously threaten the fragmentation of rural landscapes or alter the biodiversity and bring a series of potential ecological threats to the development [19]. Sun et al. have evaluated the impacts of land-use change on climate systems, demonstrating a significant quantitative increase in ecosystem services provision [20].

From a research perspective, rural development has led to the emergence of various ecological risks, including changes in cropland use intensity, alterations in ecological vulnerability, and landscape fragmentation. From the analysis of research scales, the LER evaluation has been studied basically on islands [21], administrative units at all levels [22], different natural geographic units such as calcareous landscapes [23], coastal cities [24], river [25], forest park [26], areas of human interference [27], typical ecologically fragile zones such as mountainous areas [28], and other macro-scales [29], whereas in-depth investigations of LER and their impacts at the township scales have been carried out. The ecological risk of landscape and its spatio-temporal changes at rural scales have been less studied.

In China, maintaining regional landscape ecological stability and enhancing rural landscape ecosystem services are critical research priorities, driven by national strategies such as Ecological Civilization, the Rural Revitalization Strategy, and Ecological Redline Protection. While micro-basins and ecological mosaics are effective for analyzing hydrological or biological processes, they often fail to align with administrative boundaries for

implementing targeted governance. Consequently, existing studies often lack empirical assessments at the administrative rural unit in Xiangxi Autonomous Prefecture (XXAP), limiting targeted governance for this unique mountainous region. To bridge this gap, this study shifts the analytical scale to the administrative rural unit to better capture human–land conflict and improves the model by integrating ecosystem services tailored to local environmental characteristics.

As such, measuring RLER's response to land use expansion is particularly important for maintaining the stability of ecosystem structure and service functions and for safeguarding the harmony of human–land relations in rural areas. XXAP is located in a typical ecologically fragile zone, which is an important water conservation and ecological security barrier area in the Wuling Mountain Area. The long-term ecological problems faced by rural areas mainly include soil erosion, land degradation such as landslides, coal mining areas [30], and mountain disasters [31]. Each risk-causing factor is dangerous to the ecology and living space [32] and can destroy their non-renewable historical and cultural heritage, as well as lead to problems such as tourism overdevelopment [33] and poverty alleviation pressures and seriously impede the process of rural revitalization [34]. In view of this, this paper constructs a RLER evaluation index system based on five periods of relevant data during 2000–2020, analyzes the spatio-temporal characteristics of RLER, and provides a transferable framework for global karst regions facing similar human–land conflicts, thereby providing a basis for decision-making on the construction or management of landscape ecology.

2. Materials and Methods

2.1. Study Area

XXAP is situated on the eastern margin of the Yunnan-Guizhou Karst Plateau in northwestern Hunan Province; the terrain slopes from higher elevations in the northwest to lower elevations in the southeast, covering Jishou City and the counties of Longshan, Yongshun, Baojing, Huayuan, Guzhang, Fenghuang, and Luxi. Influenced by the tectonic activity associated with the Eurasian and Indian Plates, the region is characterized by a well-developed typical karst landform [35] (Figure 1). The base map was generated by ArcGIS 10.3 software (Data source: http://www.gscloud.cn; http://www.ngcc.cn. 2017). The area has an annual average temperature ranging from 15.8 to 19.5 °C and a multi-year average rainfall of 1400 mm. The area exhibits a typical subtropical monsoon humid climate. Its total water resources reach 21.37 billion m^3. The area is richly endowed with forest resources, with a forest area of approximately 10,415 km^2. It serves as a crucial water conservation and ecological security barrier zone within the Yangtze River Basin.

To accurately match the scale of human activity with ecological processes, this study selects the administrative villages as the basic evaluation unit. The 109 sampled villages cover the full gradient of topographic and socio-economic variations, serving as representative socio-ecological units for risk assessment.

However, rural development poses a significant threat to the regional landscape ecological foundation due to the constraints of natural resource carrying capacity and diverse cultural dynamics. Furthermore, the region is subject to long-standing ecological challenges, primarily including soil erosion, landslides, and other forms of land degradation and mountain hazards [36]. Consequently, conducting coordinated research on landscape ecosystem protection in this region holds significant ecological importance and practical urgency.

2.2. Data Sources

This study evaluated the RLER using the administrative village as the basic research unit, focusing on five temporal nodes: 2000, 2005, 2010, 2015, and 2020. Administrative

boundary data were obtained from the National Geomatics Center of China (http://www.ngcc.cn). The list of rural settlements was extracted from the Xiangxi Statistical Yearbook 2021, and administrative boundary data for rural settlements were acquired from the BIGEMAP map downloader (2023). Digital elevation model (DEM) data were obtained from the Geospatial Data Cloud platform (http://www.gscloud.cn) to ensure temporal consistency in elevation analysis. Based on existing relevant studies and a revised analysis of Classification of Land Use Status Quo (GB/T 21010-2017) [37] issued by the Standardization Administration of China and the Ministry of Natural Resources, as well as the Technical Regulations for Land Use Dynamic Remote Sensing Monitoring (TD/T1010-2015) [38] issued by the former Ministry of Natural Resources of the People's Republic of China. Land use types in the XXAP were categorized into six types: forest land, cultivated land, grassland, construction land, water bodies, and unused land. The overall accuracy was 94.4%, and the kappa coefficient was 0.88, indicating that the classification meets the requirement for subsequent landscape ecological risk assessment. Annual mean temperature, precipitation, and wind speed data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.geodata.cn); NPP data were derived from the MOD17A3 Version 6.1 dataset (USGS, United States Geological Survey) with a 500 m spatial resolution; NDVI data were acquired from the Geospatial Data Cloud platform with a 500 m spatial resolution; soil data were sourced from the National Earth System Science Data Center with a 1 km spatial resolution; water conservation capacity data were obtained from the National Earth System Science Data Center with a 500 m spatial resolution.

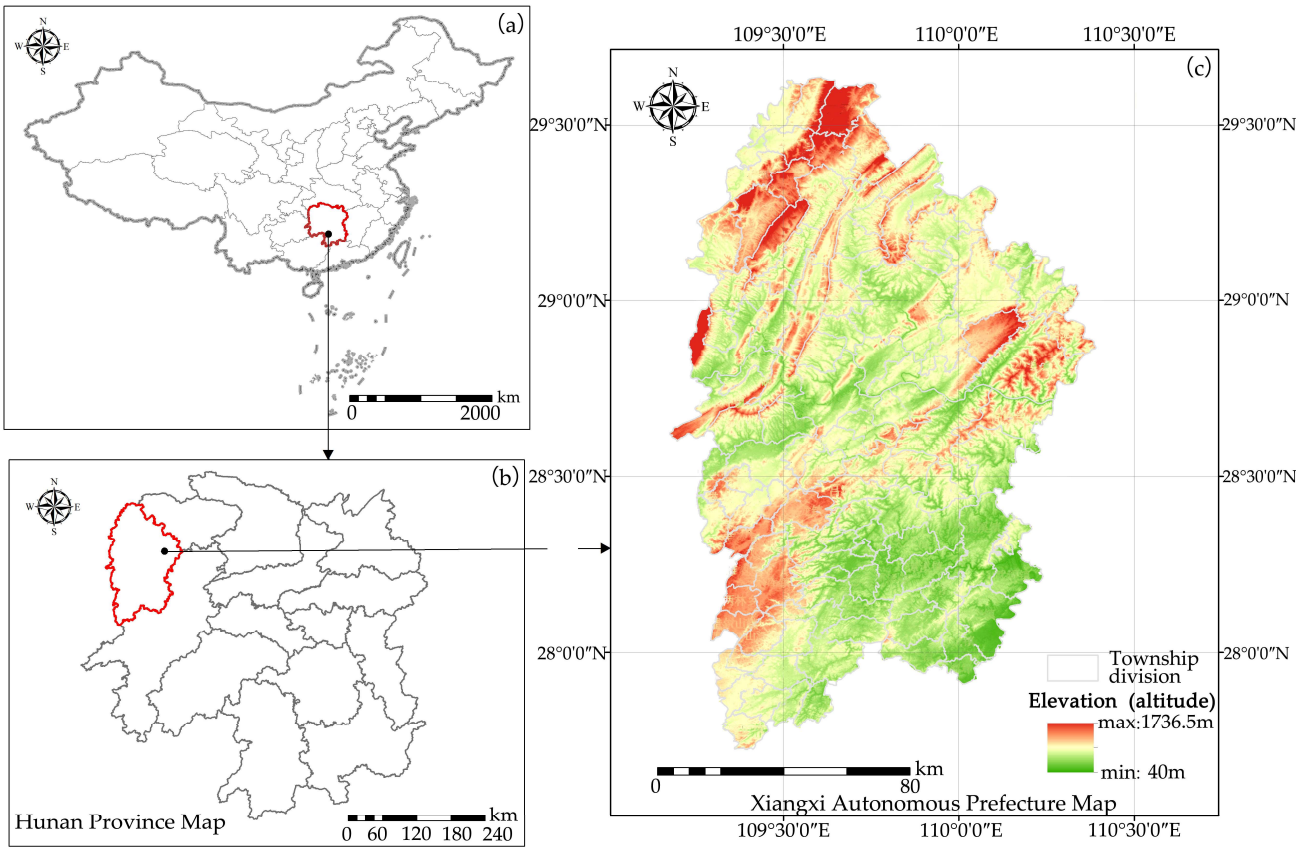

Figure 1. Geographical location of the study area (**a**), administrative division of Hunan Province (**b**) and topographic map of XXAP (**c**).

2.3. Methods

2.3.1. Overall Research Framework

This study was structured around a three-stage analytical rationale: data collection and processing, followed by model construction, and concluding with interpretation analysis. As illustrated in Figure 2, the overall research framework consists of three main phases: (1) data collection and processing; (2) construction of the improved RLER assessment model; (3) and interpretable results analysis.

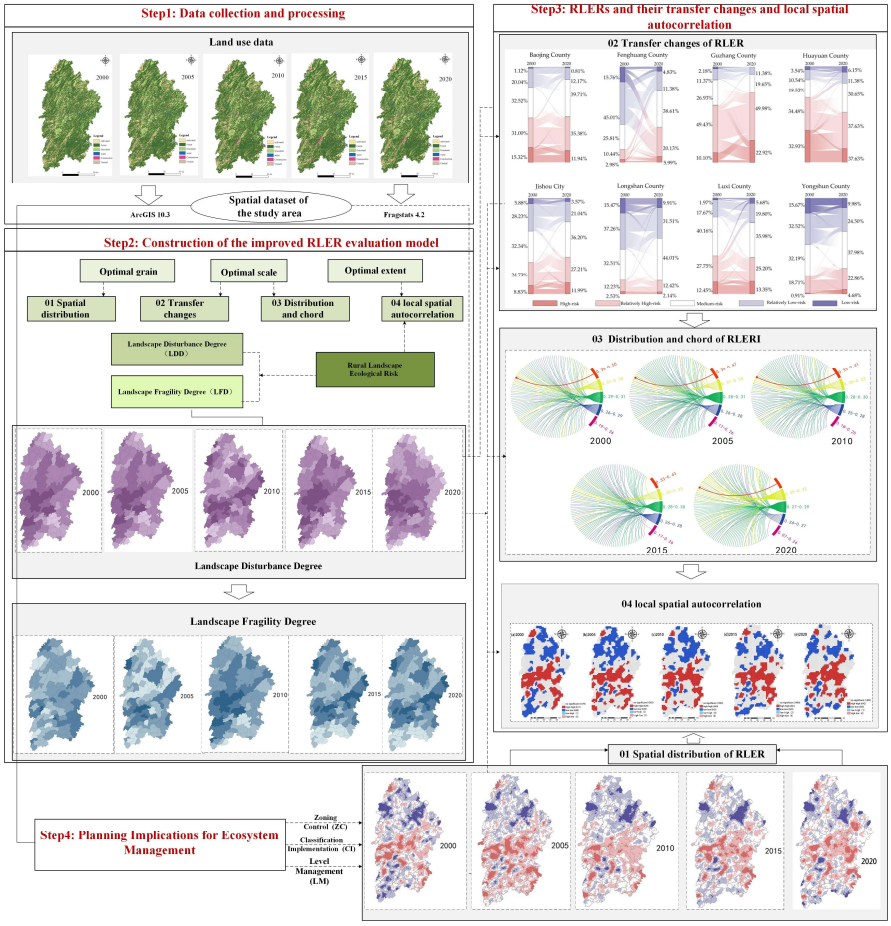

Figure 2. Research framework diagram.

2.3.2. Landscape Disturbance Degree (LDD)

The measurement process primarily comprises the following two steps. First, land-use type classification images were converted into GRID format, and landscape pattern indices were quantitatively calculated using the Fragstats 4.2 software. Indicator selection integrated the literature frequency method with a fixed, theory-driven framework widely recognized in landscape ecological risk assessments. Second, the entropy method was applied to derive vulnerability index values for different landscape types. The calculation is presented as Table 1.

LDD is defined as the ecological stability of different landscape types and the buffering and regulating capacity of ecosystems. A higher value signifies a greater level of disturbance from human activities on the ecosystem and consequently a more negative impact on biodiversity or viability. It is calculated as follows [39]:

$$S_i = aC_i + bN_i + cD_i \quad (1)$$

Table 1. LDD and LFD: Assessment Index System and Ecological Significance.

Criteria Layer	Index Layer	Ecological Significance	Calculation Formula
Landscape Interference Degree (Si)	Ci	Ci is used to determine the degree of fragmentation in the landscape ecological system.	$C_i = \frac{Y_i}{X_i}$ (2) where Y_i is the number of patches of landscape type i; X_i is the total area of landscape type i.
	Ni	Ni is used to assess the degree of separation among landscape patches.	$N_i = \frac{X}{X_i} * P_i$ (3) where X is the total area of the regional landscape; X_i is the total area of landscape type i; P_i is the area of patch i/total area of the sample.
	Di	Di is used to determine the dominance of different landscape patches within the structure	$D_i = \frac{Q_i+M_i}{4} + \frac{P_i}{2}$ (4) where D_i is the number of grids in which patch i occurs/total number of grids; Q_i is the number of patches i/total number of patches; and M_i is the area of patch i/total area of the sample.

The weights in the formula are between a + b + c = 1, based on the empirical values of existing references and the characteristics of the regional landscape changes; a, b, and c are assigned the values of 0.5, 0.3, and 0.2, respectively.

2.3.3. Landscape Fragility Degree (LFD)

The spatio-temporal heterogeneity of landscape ecosystem services can reflect the ultimate outcomes of landscape patterns and ecological processes. The landscape vulnerability index is evaluated using ecosystem service values that are based on the equivalent value factor per unit area. Adopting the spatio-temporal factor adjustment method, the national ecosystem service values are corrected to the spatiotemporal scope of the study area. Soil conservation capacity is calculated using the RUSLE model. The calculation formulas are as follows [40,41]:

$$VZ_i = VC_i + VS_i + VW_i + VH_i \quad (5)$$

$$V_i = \frac{\max(VZ_i) - VZ_i}{\max(VZ_i) - \min(VZ_i)} \quad (6)$$

$$VC_i = NPP * \left(1 - VC_{npp}\right) \quad (7)$$

$$VW_i = NPP \times (1 - VCnpp) \times Asic \times Apre \times (1 - Aslo) \quad (8)$$

$$VH_i = NPP \times (1 - VCnpp) \times Apre \times Atem \times D \quad (9)$$

VZ_i is the ecosystem service value of risk assessment unit i; VC_i is the vegetation carbon fixation of risk assessment unit i; VS_i is the soil conservation capacity of risk assessment unit i; NPP is the net primary productivity of vegetation; VC_{npp} is the annual stability factor of NPP; A_{sic} is the soil infiltration energy force factor; A_{pre} is the annual average precipitation factor. VHi provides the amount of habitat for risk assessment unit k; A_{tem} is the annual average temperature factor; D is the surface roughness factor.

2.3.4. Improvement of RLERI Evaluation Model

Unlike resilience or ecosystem service framework that prioritize adaptive capacity and provisioning benefits, the landscape type structure (LTS) and ecosystem service function (LSF) framework specifically couples landscape disturbance with inherent fragility to quantify degradation risk. RLERI for the k-th evaluation unit is calculated using Equation (1) [42]:

$$RLERI_k = \sum_i^n \left(S_{k,i} * \frac{A_{k,i}}{A_k} \right) * V_k \quad (10)$$

where i represents the landscape type, n is the total number of landscape types, $A_{k,i}$ is the area of landscape type I within unit k, and A_k is the total area of unit k. V_k denotes the landscape fragility degree (LFD) of unit k.

$S_{k,i}$, which is the landscape disturbance degree (LDD) of landscape type I within unit k, was directly derived using the moving window method in Fragstats 4.2 software. This method quantifies the spatial heterogeneity of landscape types by calculating various landscape metrics within a specified neighborhood for each cell [43].

To preliminarily test the robustness of the RLERI, we conducted a simple sensitivity analysis by adjusting the LDD weights (a, b, c) to two alternative combinations: (0.4, 0.3, 0.3) and (0.6, 0.2, 0.2), while keeping a + b + c = 1. The resulting RLERI rankings across all evaluation units remained highly consistent (Spearman's rank correlation coefficient > 0.9), indicating that the index is not overly sensitive to moderate changes in weight assignments.

2.4. Exploratory Spatial Data Analysis (ESDA)

ESDA examines the spatial distribution pattern of variables by integrating geographic locations and attribute characteristics. Global spatial autocorrelation is calculated as follows [44]:

$$\text{Global Moran's I} = \frac{n\sum_{i=1}^n \sum_{j\neq 1}^n w_{ij}\left(A_i - \overline{A}\right)\left(A_j - \overline{A}\right)}{B^2 \sum_{i=1}^n \sum_{j\neq 1}^n w_{ij}} \quad (11)$$

$$B^2 = \frac{1}{n}\sum_j \left(A - \overline{A}\right)^2 \quad (12)$$

$$\overline{A} = \frac{1}{n}\sum_{i=1}^n A_i \quad (13)$$

A_i and A_j represent the observed values of the variable in spatial units i and j; $W_{i,j}$ is an element of the spatial weight matrix, representing the spatial adjacency relationship between landscape ecological risk units; n is the number of landscape ecological risk units; $\overline{A}$ is the mean value of A.

Local spatial autocorrelation analysis evaluates the spatial clustering patterns of geographic units by measuring correlations among spatial attribute values. In this study, we employed GeoDA to quantify spatial autocorrelation values of landscape ecological risks using the following formula:

$$\text{Local Moran's I} = \frac{\left(A_i - \overline{A}\right)}{B^2}\sum_j W_{ij}\left(A_j - \overline{A}\right) \quad (14)$$

This value captures the heterogeneity of spatial attributes. When the ecological risk attribute value of a unit is relatively high or low and exhibits a strong negative spatial correlation with its neighbors, it signifies a spatial outlier. The calculation formula is as follows [45]:

$$Z = 1 - \frac{E(I)}{\sqrt{VAR(I)}} \quad (15)$$

VAR represents the variance, and E(I) denotes the expected value of Moran's I under the null hypothesis. If $|Z| > 1.96$, it indicates a significant spatial autocorrelation of RLERI at the 0.05 significance level.

The multidimensional landscape index integration method was applied to analyze LTS-LSF, thereby quantifying their associated risks [46]. Building upon existing research indices [47] and considering the ecological characteristics of XXAP's rural areas, we selected

ten indices based on three principles: target dominance, locality, and data accessibility. These indices collectively capture landscape heterogeneity while maintaining clear ecological relevance, enabling comprehensive quantitative assessment.

3. Results

3.1. Characteristics of Spatio-Temporal Changes of Landscape Disturbance Degree (LDD)

LDD in the study period is less than 0.35; the types VI (relatively high risk) and V (high-risk) show a continuous and stable increase; the rate of the rise and fall is basically the same; until 2020, and some rural areas of LDD demonstrate a significant change. The rate of X8 in Baojing County increased from 0.111 to 0.24, X3 in Jishou City from 0.06 to 0.23, and X17 in Yongshun County from 0.09 to 0.23 (Figure 3).

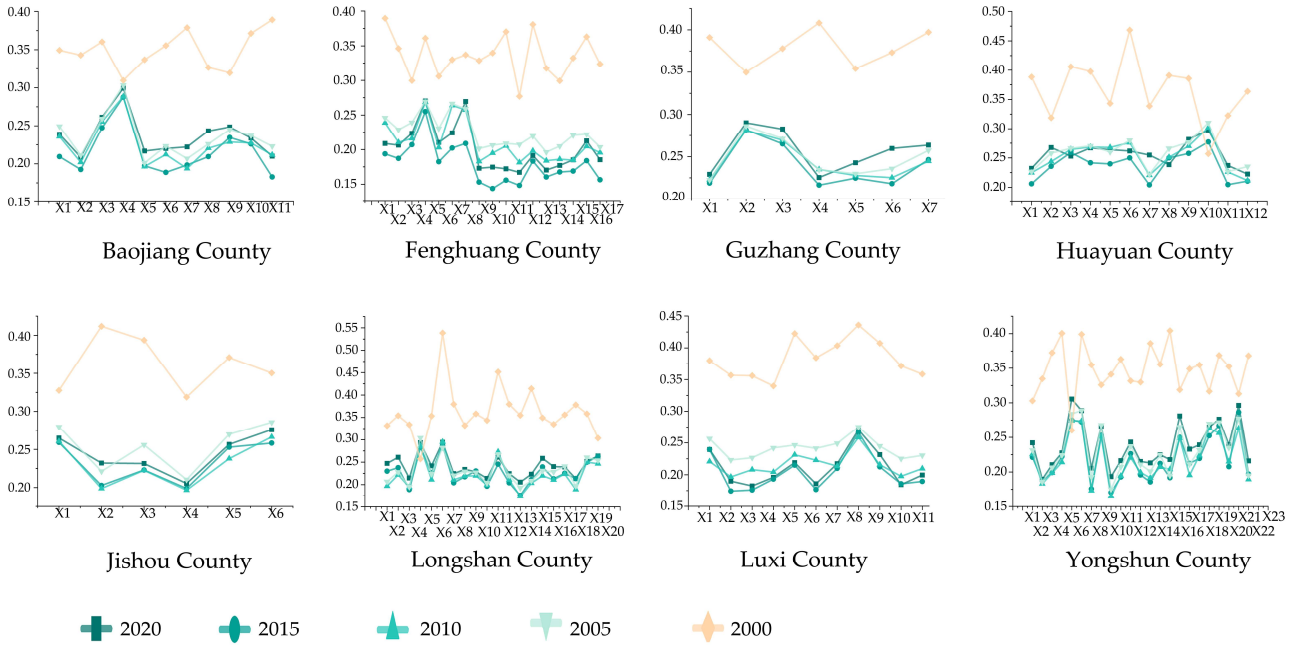

Figure 3. Distribution of temporal change in LDD.

The LDD displayed a nonlinear upward trajectory throughout the study period, showing sustained growth after 2010 and peaking in 2020. These findings suggest the necessity of implementing mitigation measures in land-use planning and human activities to prevent continued linear escalation of ecological disturbance.

The trend of spatial distribution of LDD grades basically remained stable, though the difference between grades was significant (Figure 4). The types VI and V predominantly clustered in the middle and south, sporadic distribution in the south and the top of the north; The types I (low-risk) and II (relatively low-risk) were mainly concentrated along the central part of XXAP to the north and south of the region; the mean values of LDD exhibited an increasing tendency. Until 2020, the typical rural areas with increased LDD were X10 in Huayuan County, where the rate of LDD increased from 0.22 to 0.29 in 2015, and X2 in Baojing County, where the value of LDD increased from 0.18 to 0.21 in 2015. Therefore, future measures should be formulated to control the rise of potential RLER.

3.2. Characteristics of Spatio-Temporal Changes in Landscape Fragility Degree (LFD)

The LFD values remained below 0.4, and the mean value increased from 0.22 to 0.31 between 2000 and 2015, trending toward fluctuation with a slow upward trajectory, though no abrupt changes occurred (Figure 5). Some areas showed higher and lower changes from year to year, with significant temporal differences, indicating that the development

is highly likely to lead to a downward trend in landscape ecosystem service capacity and weaken the ability to resist interference in the surrounding landscape.

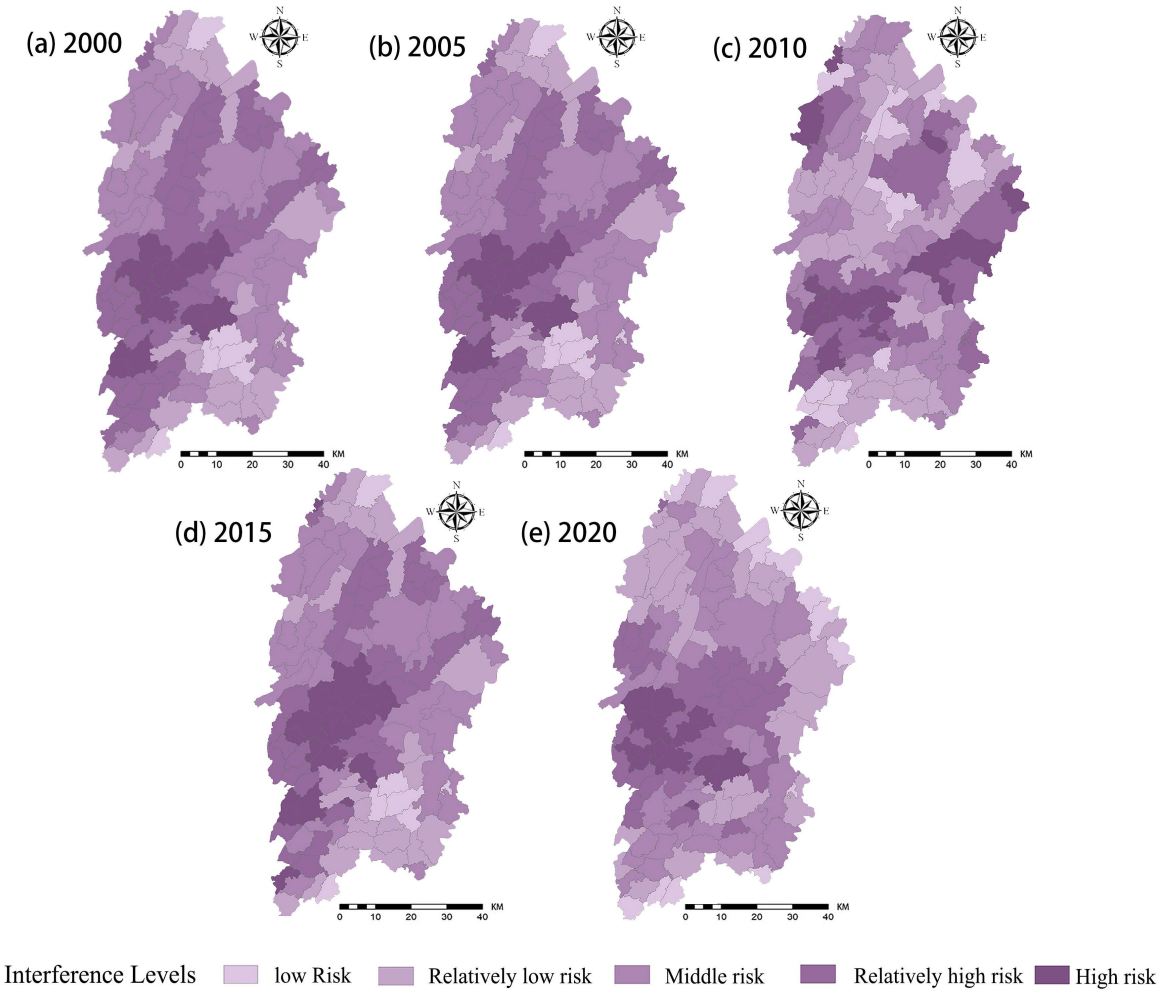

Figure 4. Spatial distribution of LDD.

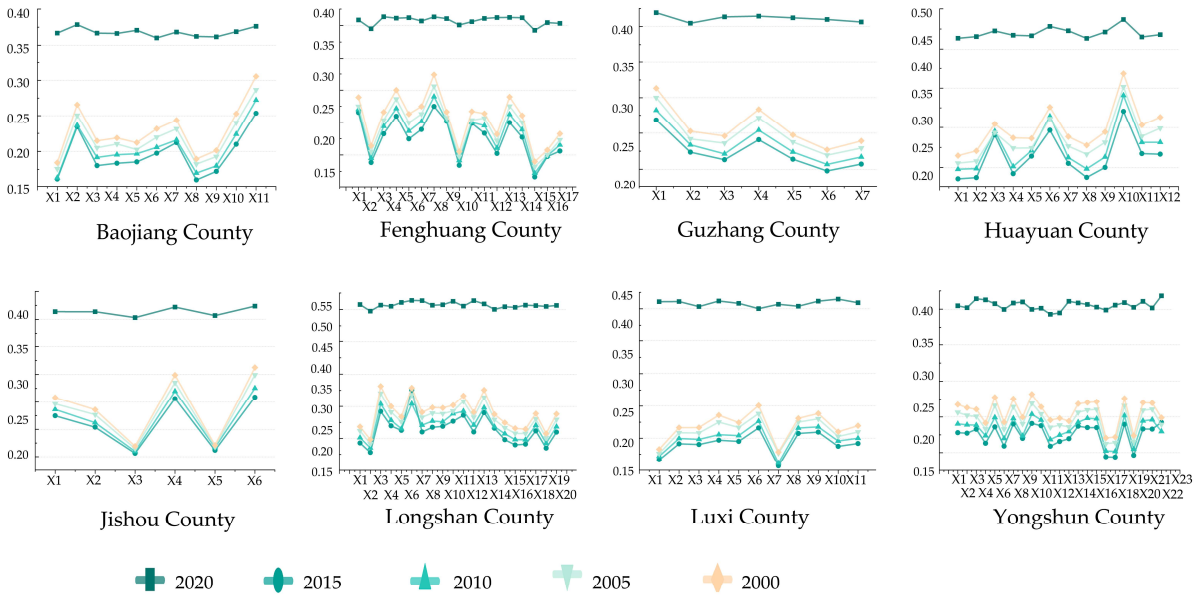

Figure 5. Temporal variation distribution of LFD.

From 2000 to 2005, LFD showed a significant decreasing trend. Typical representatives include X1 in Longshan County, which decreased from 0.33 to 0.21; X11 in Huayuan County, which decreased from 0.32 to 0.23; X2 in Guzhang County, which decreased from 0.35 to 0.29; and X8 in Luxi County, which decreased from 0.44 to 0.28.

Between 2005 and 2010, LFD showed a trend of stable change. Notable examples include X5 in Yongshun County, which decreased from 0.28 to 0.27; X11 in Baojing County, which decreased from 0.22 to 0.21; and X12 in Fenghuang County, which decreased from 0.2 to 0.19.

From 2010 to 2015, LFD showed a trend of stable change. X4 in Guzhang County decreased from 0.24 to 0.22, X2 in Jishou City increased from 0.19 to 0.20, and X13 in Longshan County decreased from 0.19 to 0.17. Until 2020, the trend of LFD exhibited an upward trend. Typical representatives include X4 in Baojing County, which increased from 0.13 to 0.32; X2 in Jishou City, which increased from 0.20 to 0.31; and X5 in Yongshun County, which increased from 0.28 to 0.31.

The V areas of LFD were mainly distributed in X8, X7, and X5 in Luxi County in the southeastern part, with values of 0.44, 0.40, and 0.42; in the middle and western parts of X2, X6, and X3 in Huayuan County, with values of 0.41, 0.47 and 0.41; and the I areas were mainly distributed in the southern part, with values of 0.28 and 0.30 (Figure 6).

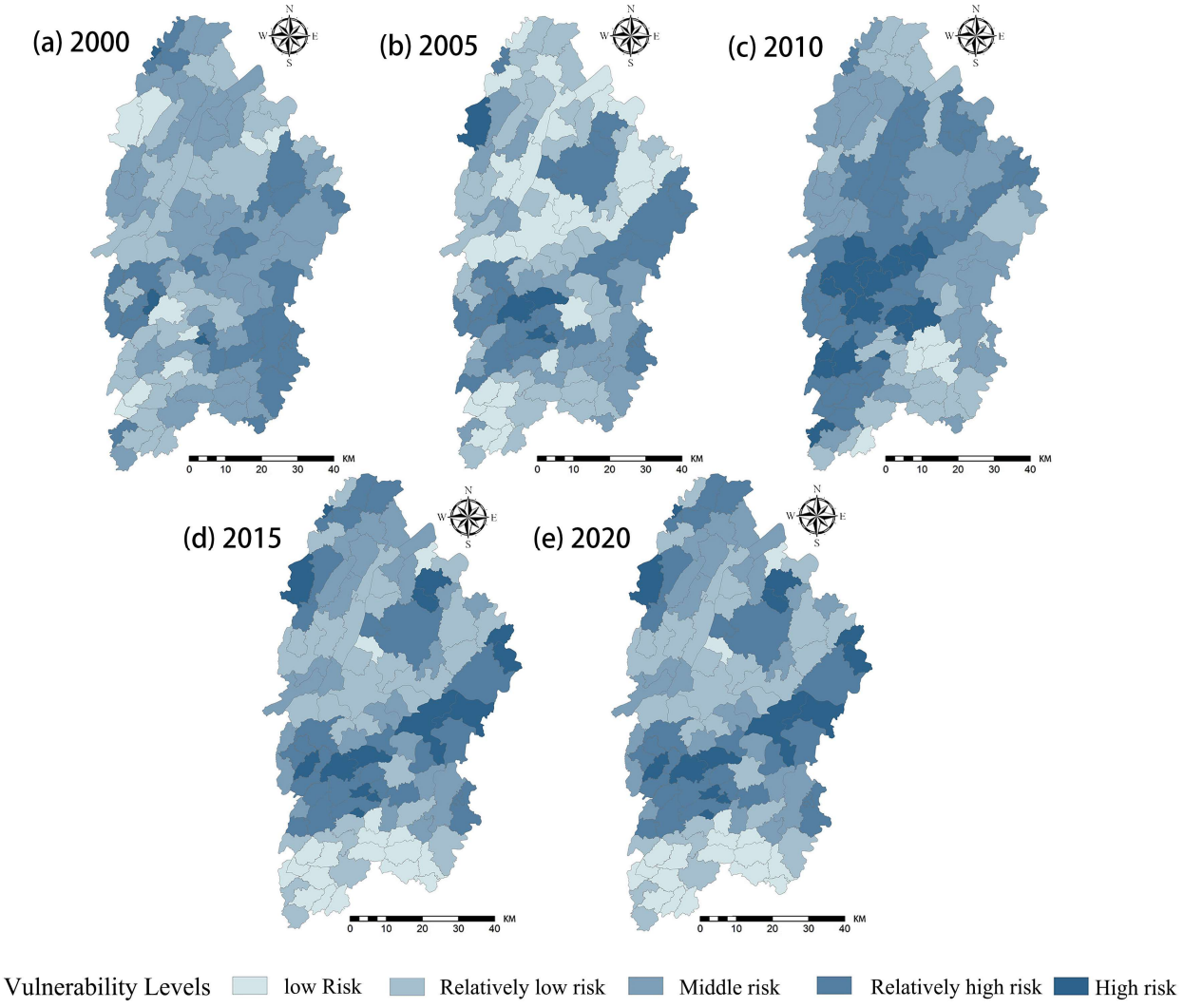

Figure 6. Spatial distribution of LFD.

3.3. Spatial Variation Characteristics of the RLERI

As shown in Figure 7, the fluctuation amplitude of RLERI changes in rural areas is small; the average values of RLERI are 0.29, 0.29, 0.28, 0.28, 0.28, and among these, some areas are still persisting in the high ecological risk zone, and even still show the trend of growth. X10 in Huayuan County, X6 in Jishou, and X4 in Fenghuang County are above 0.3. The highest value of RLER was X10 in Huayuan County, with the values of 0.35, 0.34, 0.33, 0.33, 0.32. RLERI shows unbalanced fluctuation. Therefore, it is necessary to strengthen the early warning research on RLERI in the future.

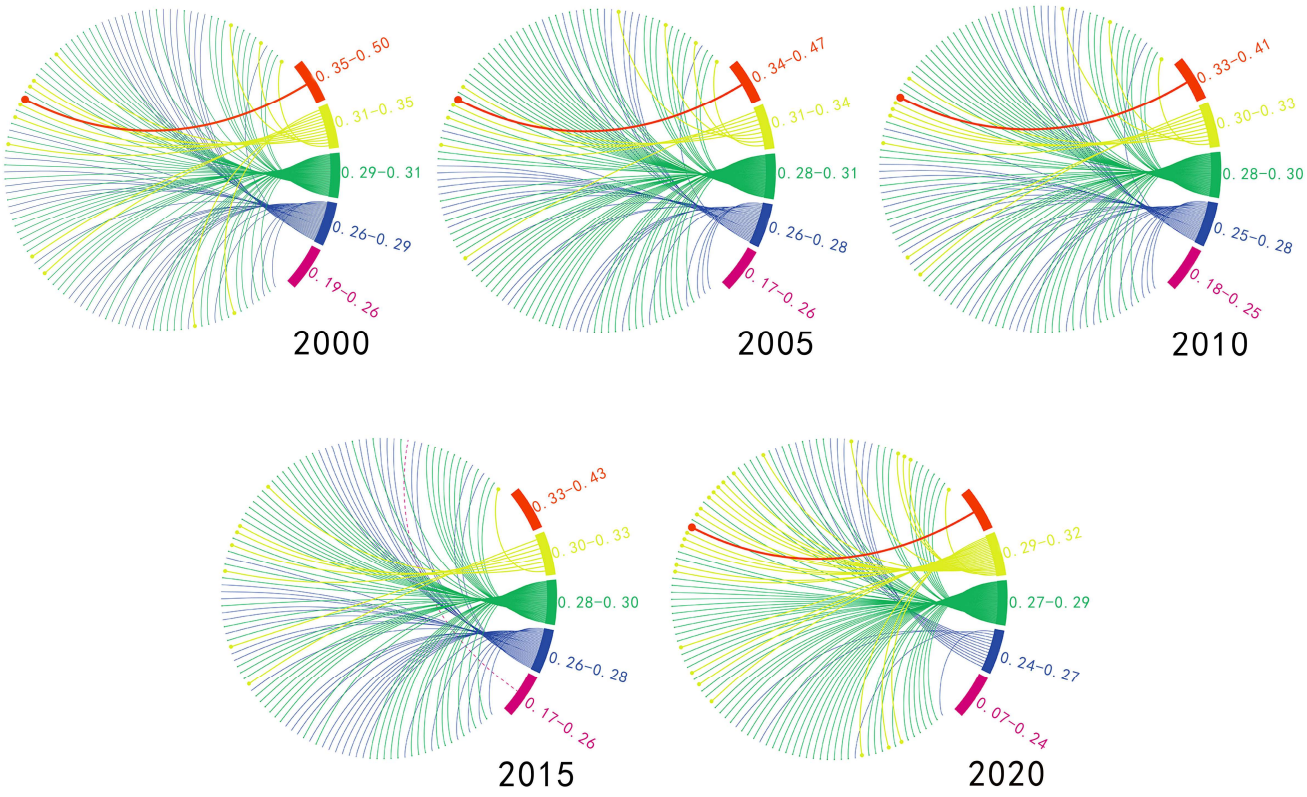

Figure 7. Distribution and chord of RLERI.

Through the statistics of different grades, we can further obtain the trend of the temporal changes in order to provide a more scientific decision-making basis for the next regulation counter measures of the land-use expansion and adaptation. RLERI varies significantly in different grades, and RLERI is relatively stable during the study period, basically maintaining a fluctuating trend with no sudden upward or downward changes, which is closely related to the good ecological substrate of the local area and the implementation of the construction of ecological civilization. Therefore, in the future, relevant risk management measures should be established according to this trend of change to achieve sustainable development in the region.

3.4. The Characteristics of Spatial Variation

To more intuitively compare and analyze the spatial differentiation characteristics of RLERI in each period, RLERI values were further divided into equal spacing with the help of the creation of fishing net analysis function, and ordinary kriging was employed for spatial interpolation. Finally, RLERI in each year was equally spaced into five classes using the natural breakpoint method to obtain the spatial visualization distribution maps of RLERI.

Figure 8 shows that the assignment intervals vary somewhat from year to year because of the different values of RLERI. Moreover, it will definitely lead to an increase in the pressure on land, ecology, and other environments. There is a trend to reduce the transfer of the very low concentration area in the south during 2015, with the distribution of the V areas. Therefore, how to coordinate the sustainable development of human activities in rural areas, landscape, and ecological environmental protection will become an important issue of concern for the future spatial development of rural areas.

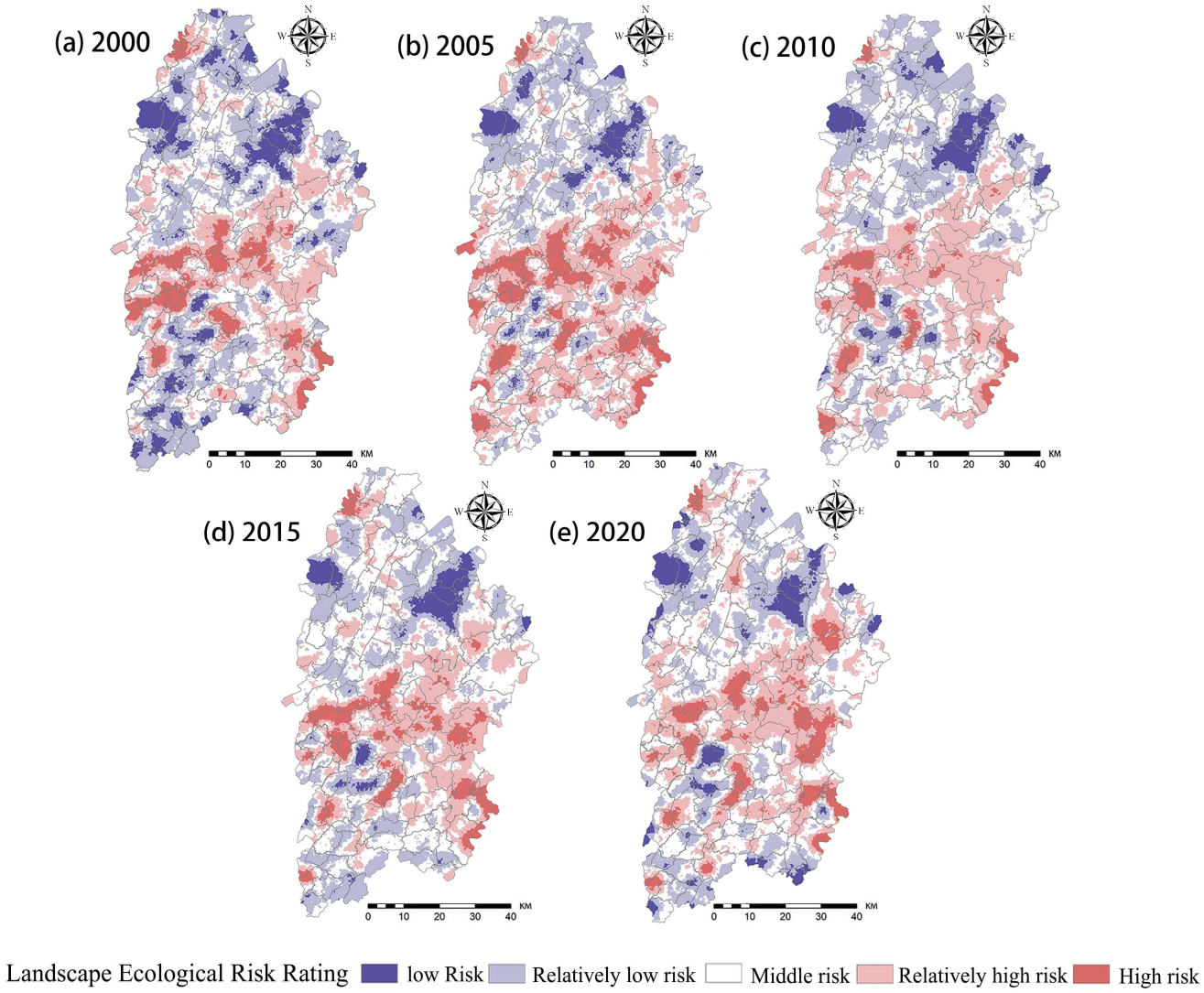

Figure 8. Spatial distribution of RLERI.

3.5. Transfer Characteristics of RLERI Ranks

Due to the large number of rural areas, the county level was used for comparative analysis of rank transfer. Figure 9 shows that Baojing County was in the III and V levels in 2000, accounting for 32.58% and 30.97%, followed by I and VI levels, accounting for 20% and 15.33%; but until 2020, it was mainly in the III and V intervals, accounting for 39.67% and 35.46%. The villages with a relatively high proportion of the III level and above areas include X1, where the III areas account for 65.73%, and X11, where the V areas account for 73.47%.

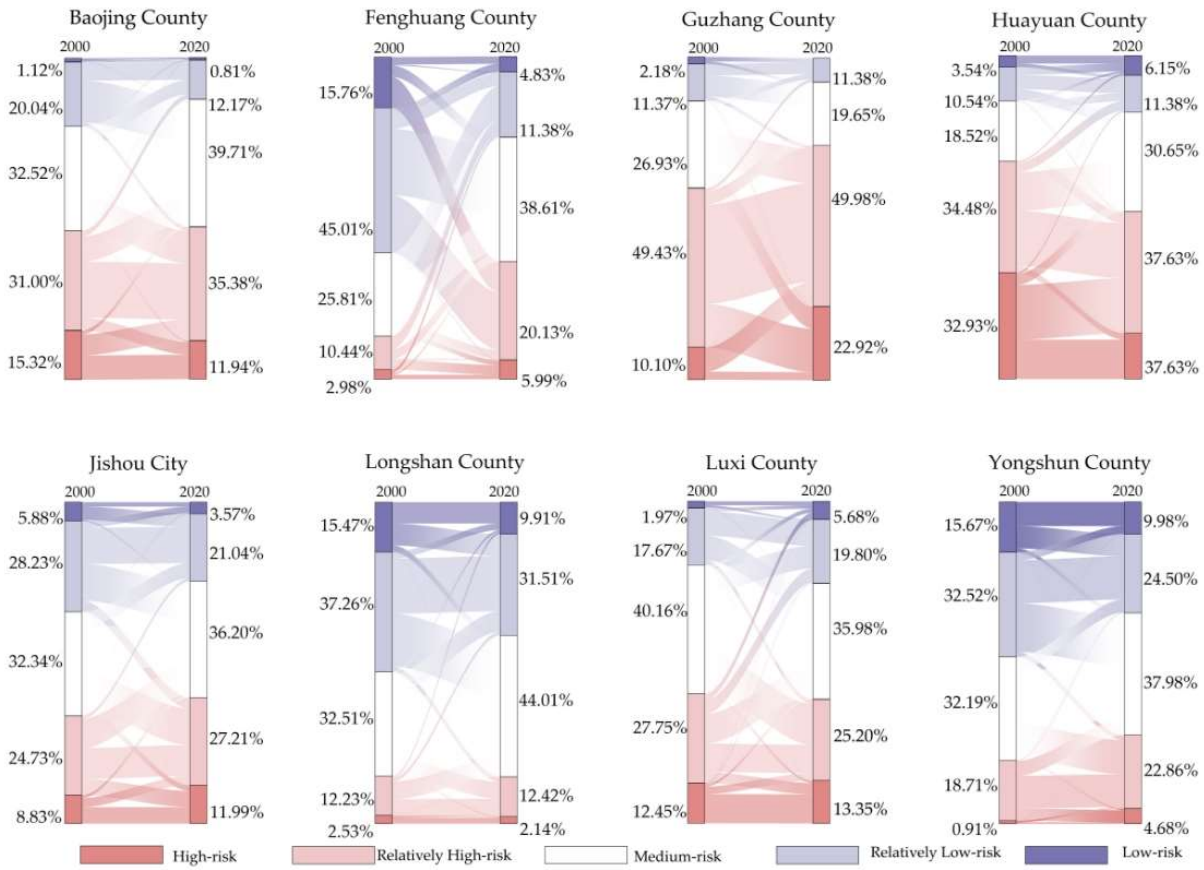

Figure 9. Transfer changes of RLERI.

RLERI level transfer is mainly manifested as a trend of I or II transitions to the III or VI areas. RLERI level area change is mostly transitions between neighboring levels, with few cross-rank leaps, which indicates that the area of RLERI undergoing abrupt changes is relatively small.

3.6. Global Spatial Autocorrelation Analysis

In order to further determine the specific location and spatial distribution patterns, the global spatial autocorrelation can be clearly expressed by using Moran scatter plot [48]. The global Moran's I index value shows that the RLER shows a stable trend of rise and fall, which is manifested in 2010 as the transitional year, with the highest Moran's I index value of 0.87. The overall decline before 2010 showed a state of 'weakening, strengthening, weakening', which indicated that RLER agglomeration gradually weakened, and the degree of spatial autocorrelation and spatial heterogeneity began to gradually reduce.

Figure 10 shows that RLER grid basically falls into the first and third quadrants centrally, with no trend of abrupt change, indicating that the distribution shows an obvious trend of high–high (H-H) or low–low (L-L) agglomeration distribution, and the clustering intensity of the grid itself or the neighboring grids is significant. There are interactions between neighboring spatial cells, which are not randomly distributed. The global Moran's I value in 2010 was 0.866, with the strongest spatial clustering. The global Moran's I value in 2020 was 0.84, which was the lowest value, indicating that the spatial autocorrelation and spatial heterogeneity tended to decline slowly. Meanwhile, it showed that the study area began to show a declining trend of agglomeration.

It can be seen that the spatial dependence is strong, showing obvious spatial agglomeration distribution. After 2010, the trend of declining agglomeration began to appear, indicating the emergence of a small scattering characteristic.

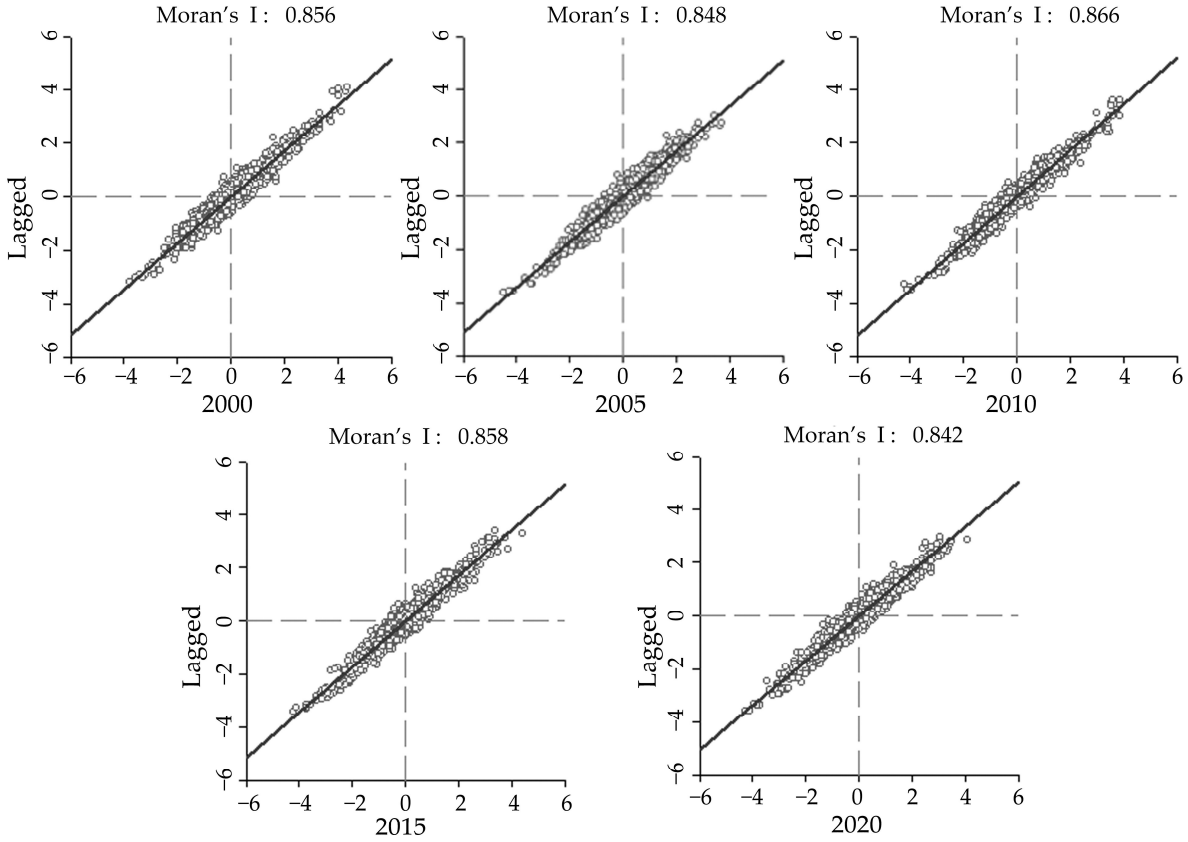

Figure 10. Moran Scatter Plot of RLERI.

3.7. Local Spatial Autocorrelation Analysis

The LISA distribution map expresses the local spatial relationship of attribute values in the grid and its surrounding grids, which is obtained to further analyze the local spatial clustering characteristics of RLER in XXAP at the grid scale. RLER spatial units are specifically classified into five categories. The LISA agglomeration map shows that the spatial agglomeration distribution is overall more stable, and the spatial distribution patterns are all dominated by the high–high (H-H) and low–low (L-L) agglomeration modes (Figure 11).

(1) High–high (H-H) agglomeration area: the RLERI is high and the RLERI of neighboring units is also high. The distribution of agglomeration is more obvious, mainly distributed in the core area of the south-central part, with sporadic distribution in the north and the southern tip and more obvious distribution in Huayuan County, Luxi County and Jishou City. Specifically, the type showed a fluctuating upward trend, reaching a grid maximum of 649 in 2010 and a rising trend of 642 grids in 2020. It indicated a volatile trend in the spatial autocorrelation.

(2) Low–low (L-L) agglomeration area: the RLERI is low and the RLERI of neighboring units is also low. This type of area shows a pattern of north–south agglomeration distribution, mainly distributed in the northern and southern parts in the hilly and low-mountainous areas, which are located in Longshan County, Yongshun County, and the southern part of Fenghuang County as the main areas of concentrated distribution. Combined with the distribution of landscape types, this result can be attributed to the fact that this area is a concentration of woodland and other landscape types, with high vegetation cover and stable landscape ecosystems. Specifically, from 2000 to 2020, the type shows a continuous decreasing trend, from 699 grids in 2000 to 554 in 2020.

(3) High–low (H-L) agglomeration area: the RLERI is low while the neighboring cells have higher RLER. This type of area has only a small distribution and is basically at zero. Data analysis showed a small grid distribution in the northeast corner of Baojing County in 2005, which was attributed to the radiative influence of high-risk areas on low-risk areas.

(4) Low–high (L-H) agglomeration area: the RLERI is low while the neighboring cells have higher RLERI. The above data analysis shows that this type has a small grid distribution mainly around the high RLERI in Luxi County. It is attributed to the result of the interaction between neighboring cells.

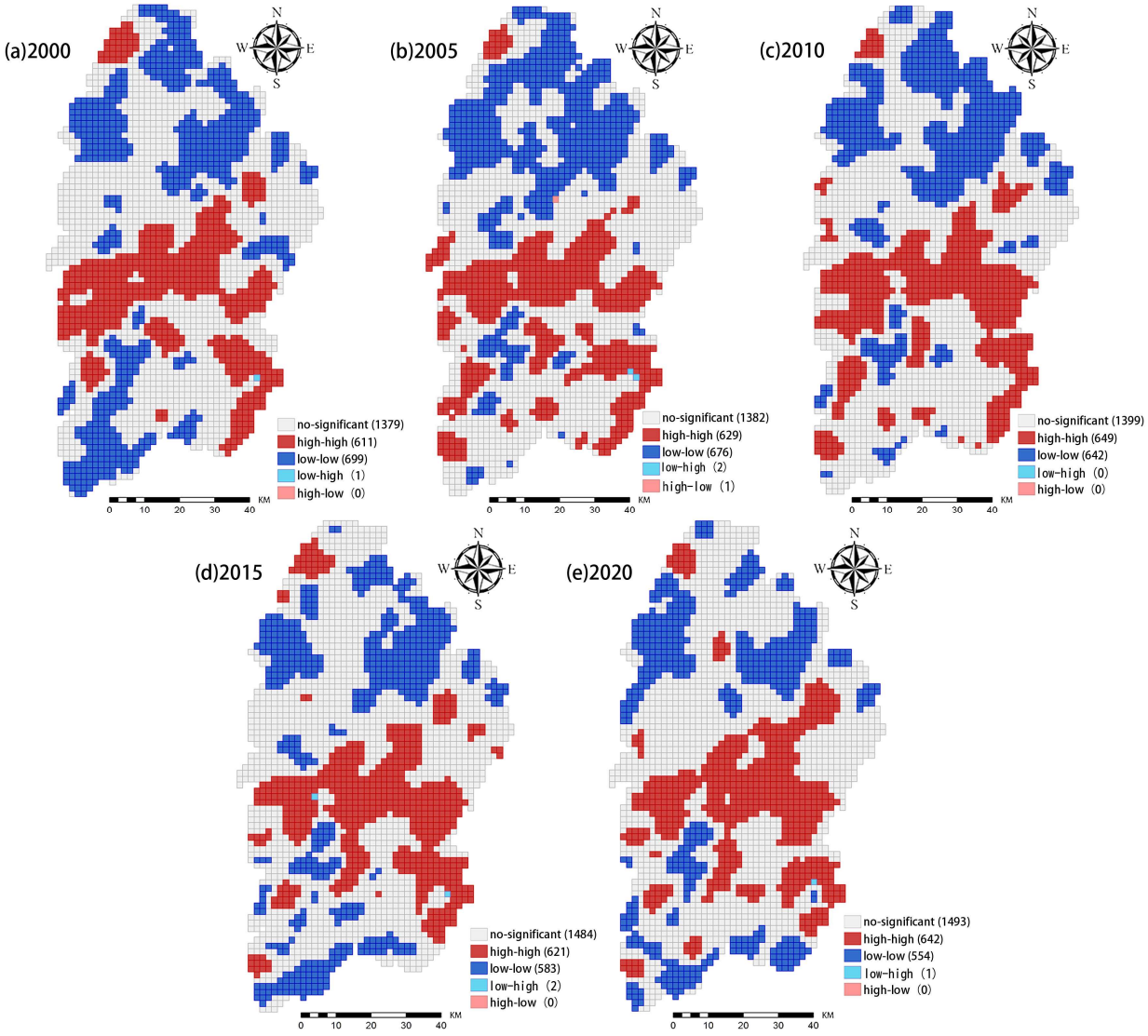

Figure 11. A clustering of RLER.

4. Discussion

4.1. Implications of the Characteristics of Dynamic Changes in RLER

The LTS-LST framework complements—rather than competes with—resilience or ecosystem service (ES) assessment by diagnosing 'risk hotspots' where structural disturbance and ecological sensitivity intersect, offering a targeted tool for spatial governance. This study proposes a new evaluation index system incorporating ecosystem service indicators, which aligns with the view of Zhao et al. that using landscape pattern indices for ecological risk assessment has certain limitations [49]. The spatio-temporal heterogeneity of

rural risk levels stems from the coupled effects of landscape disturbance degree (LDD) and landscape fragility degree (LFD). However, this study reveals the characteristics of spatio-temporal mismatches across the 109 county-level units. Overall, extensive vegetation cover in mountainous terrain contributes to high ecological service capacity [50], maintaining LFD at moderate-to-low levels. Despite relatively limited human impacts in these areas, LDD shows incremental intensification due to combined natural and anthropogenic factors. Consequently, priority should be given to adopting targeted risk mitigation strategies in mountainous regions to reduce the probability of landscape ecological risk occurrence. This finding is consistent with the result of many scholars showing nonlinear relationships between RLER and LDD/LFD dimensions [51,52]. This non-linear response is not unique to China; similar patterns have been observed in mountainous regions of the European Alps. Thus, this study also provides a conceptual framework applicable to other mountain rural areas globally [53].

As a significant component of land use, RLER plays a vital role in ecosystem services. XXAP is a predominantly mountainous region, which serves as an ecological barrier, underpinning both socio-economic development and ecological security in the Wuling Mountain Area. If the structure of its mountain ecosystems begins to disintegrate and ecological functions deteriorate, the diverse ecosystem services supporting human survival in these areas will face collapse risks [54], potentially triggering severe socio-economic losses [55].

Rational utilization of mountain resources to maintain ecosystem stability is a key goal for both ecological risk assessment and land managers in mountainous regions [56]. Therefore, analyzing the dynamic changes in RLER is essential for comprehensively understanding rural evolution. This study not only improves the reliability of risk mapping but also assists decision-makers in holistically managing the spatio-temporal evolution of risks in mountainous rural areas.

4.2. The Distribution of RLER

From 2000 to 2020, RLER in XXAP exhibited a stable fluctuation trend, suggesting strong spatial aggregation of RLER but significant regional disparities. Spatially, the LERI distribution followed a general pattern of higher values in the south and lower values in the north. High-risk areas were primarily clustered in the central-southern region, whereas those in the northern part displayed a more scattered distribution.

Such a spatial variation can be attributed to several factors. In the central-southern region, the relatively flat terrain and high transportation accessibility have intensified landscape disturbances [57]. Additionally, certain topographically complex rural areas experienced heightened landscape vulnerability due to natural disasters, collectively increasing ecological risks. In contrast, the northern area's higher elevation supports dominant landscape types, primarily woodlands and grasslands, which are less prone to human disturbance and maintain favorable natural vegetation conditions. Future efforts should focus on establishing rural resilience planning mechanisms through constructing landscape ecological networks between fragmented inter-patch corridors and habitats [58]. This north–south dichotomy mirrors findings from rural areas in the Japanese Archipelago, where depopulated high-altitude villages experience risk reduction, while peri-urban lowlands face escalating ecological stress. This consistency underscores that topography mediates human–environment interactions [59].

Risk-level transition analysis demonstrates dynamic changes across all risk levels, particularly showing progression from low-risk to medium- and high-risk categories. The highest-risk and relatively high-risk areas exhibited an initial decrease followed by subsequent expansion. Specific rural clusters display sustained increases in landscape

ecological risk, suggesting the presence of latent ecological threats within the study area's landscape ecosystem. This finding aligns with Zhao et al. regarding latent risk accumulation in transitional zones [60].

The dominance of H-H and L-L clustering patterns, combined with the limited but ecologically significant H-L and L-H transition zones, provides a robust empirical basis for formulating differentiated spatial governance strategies. Specifically, the persistence and expansion of H-H clusters (particularly in the central-southern region) signal urgent intervention needs, while the shrinkage of L-L clusters indicates progressive ecological degradation in previously stable areas.

4.3. Lessons of XXAP

Globally, mountainous rural regions are undergoing profound socio-ecological transitions, facing common pressures from urbanization, land abandonment, and climate variability [61]. By analyzing the spatio-temporal characteristics of RLER in XXAP, this study has elucidated the complex evolutionary dynamics of rural human–environment systems in mountainous regions. The research proposes a forward-looking resilience-oriented planning framework for RLER mitigation in mountainous rural areas, based on distinct 2020 landscape ecological risk levels, and develops differentiated spatial governance strategies for rural territories.

This study establishes a comprehensive regulatory framework characterized by 'Zoning Control (ZC)-Classification Implementation (CI)-Level Management (LM)'. The framework includes a four-tiered system comprising planning interventions tailored to different ecological risk probability zones; dynamic land-use expansion strategies with adaptive capacity; identification of rural settlement expansion patterns through differentiated outcome analysis; and corresponding landscape ecological control measures. The proposed approach aims to enhance villages' endogenous development capacity and ecological self-restoration potential, ultimately promoting optimal territorial resource utilization and orderly spatial expansion in rural areas.

Zoning Control (ZC): based on the four LISA types, ZC establishes a four-tier zoning system: H-H zones require ecological restoration, strict development restrictions, and habitat connectivity enhancement; L-L zones maintain preventive conservation, encourage low impact activities, and prohibit large-scale land conversion; H-L zones need targeted precision interventions to reduce local disturbance and fragment high-risk patches; L-H zones demand intensive monitoring, adaptive interventions, and buffer strips to prevent risk spillover.

Spatial zoning constitutes a core element of planning, aiming to delineate functional positioning of priority regulation areas based on probability zones of landscape ecological risks, thereby achieving scientific hierarchical demarcation and refined zonal management of regulated areas [62,63]. This zoning logic resonates with similar practices reported in European mountain regions [64] and East Asian rural landscapes [65].

Classification Implementation (CI): CI differentiates industrial pathways: H-H zones prohibit new development; L-L zones permit ecological agriculture and low-impact tourism; H-L zones require moratorium until risk mitigation; L-H zones allow strictly regulated tourism with offset requirements.

This approach requires a tiered objective-driven refinement guided by the distinctive industrial characteristics of agriculture [66] and tourism [67]. Building upon differentiated regulatory zones, it aims to establish targeted land-use spatial development models and specific landscape ecological control strategies.

The CI framework thus not only provides a pragmatic tool for reconciling production and conservation objectives in the XXAP context but also contributes a replicable analytical

protocol for comparative studies across different mountainous rural contexts worldwide, where comprehensive modeling approaches are often infeasible due to data constraints [68].

Level Management (LM): This tiered governance approach addresses varying probability levels of landscape ecological risks while complying with ecological conservation requirements [69]. It aims to maintain mutually beneficial synergies between rural ecological and economic systems; it formulates both ecological engineering specifications and adaptive land-use expansion pathways. By clarifying the differences and interrelationships among spatial regulation models, LM enhances the integration of the aforementioned three control measures (ZC, CI, LM), accentuating the dominant functional advantages and enhancing functional complementarity to facilitate high-quality rural development. This approach ultimately strengthens the implementability and scientific rigor of evidence-based regulatory strategies.

The ZC-CL-LM regulatory framework offers a transferable template for comparative studies across different socio-ecological contexts, combining ecological risk zoning, industrial typology differentiation, and multi-level governance coordination to inform evidence-based territorial strategies.

4.4. Limitations and Recommendations for Future Research

This study contributes to a better understanding of the development of land use and ecological risks. Although RLER assessment has considered many different dimensions, few studies have been conducted from the perspective of two dimensions (LDD and LFD) in rural areas. The landscape pattern is significantly affected by natural factors, human activities, topographic factors, and so on, which have a direct impact on the eco-environment. Ecosystem service functions have been incorporated into the assessment system. While ecosystem service functions have been incorporated; however, as the development of rural tourism substantially increases the change in land structure, it remains difficult to reveal the microstate structural changes of the landscape. Therefore, uncertainty quantification of the RLER assessment in mountainous rural areas should be considered.

Additionally, the factors that cause RLER in rural areas can be divided into internal and external factors. Human activities are the main external factors that cause RLER changes with topography. In order to satisfy the needs of life and production in the region, human beings have made great changes in land-use patterns, which has induced the change in the native landscape type of the region and the corresponding ecological risk. Therefore, the robustness and accuracy of landscape ecological indicators should be verified from multiple dimensions in the future. In future research, a systematic differentiated landscape ecological indicator system should be established to identify potential risks in landscape ecosystems through scientific methods, such as climate change, biodiversity loss, habitat destruction, pollution, etc. Future studies should utilize remote sensing technology, geographic information systems (GIS), and Internet of Things tools to monitor changes in ecosystems in real-time and detect potential threats in a timely manner. Thus, future research could expand to incorporate additional ecosystem function and structure indicators (e.g., tourism disturbance [70], anthropogenic activities [71], and economic factors [72]) with the aim of developing differentiated rural spatial governance strategies through enhanced case studies on mountainous rural landscape ecological risks across diverse environmental contexts.

The quantitative measurement of RLER, though limited as an assessment method to characterize the ecological condition of a small-scale region, is intended to provide evidence-based policymaking tools for land and resource managers. The quantitative analysis of RLER influencing factors in this study still needs to be improved. In addition, although using counties as ecological risk units can objectively reflect RLER patterns at small scales,

this approach fails to fully account for spatial heterogeneity. Such scale limitations may sever natural physiographic linkages; therefore, further research is needed to holistically characterize and analyze landscape patterns. A natural approach could be adopted in the future to address rural sustainability issues. This solution can serve as an applied extension of the aforementioned RLER research, reconciling the conflict between landscape patterns and sustainable development through an ecology-oriented methodology [73].

Future research should continuously integrate cutting-edge international literature and expand comparative case studies across diverse socio-ecological contexts to further validate the universality of the proposed framework. We acknowledge methodological limitations affecting RLERI robustness. First, the study is subject to the modifiable areal unit problem (MAUP); we did not conduct exhaustive sensitivity analyses for alternative grid sizes, weight sensitivity analyses, systematic cross-validation, or formal uncertainty quantification. Second, temporal robustness was constrained by the availability of only five time points. These limitations are common in regional-scale studies where data constraints preclude comprehensive validation. Future work should incorporate cross-validation, multi-scale uncertainty analysis, and temporal stability tests. Despite these constraints, our findings provide a replicable framework for similar mountainous regions.

5. Conclusions

This study assesses the spatio-temporal heterogeneity characteristics of RLER using an improved RLER evaluation model and remote sensing data. The RLER evaluation index system was established based on the 'LTS-LSF' framework with the support of ArcGIS 10.3 software, Fragstats 4.2 software, and GeoDA 1.2 software, which provided reliable data for subsequent ecological analysis. The key findings are as follows:

(1) LDD shows a pattern of slow fluctuations. Between 2000 and 2020, its spatial distribution remained largely stable. Risk levels VI and V were primarily concentrated in the south-central region, with sporadic distribution in the far south and northern areas. Levels I and II were mainly distributed along a central north–south belt. Conversely, LFD exhibited a gradual increase followed by a declining trend. Levels VI and V of LFD are chiefly distributed along an east-west belt in the central region. A slight rise in the extent of levels VI and V was observed, reflecting an urgency to enhance ecological resilience.

(2) The RLERI demonstrated an unbalanced trend yet without abrupt changes. Spatially, RLERI was generally higher in the south and lower in the north. Significant transfers occurred from lower to higher risk levels. This continuous growth trend underscores potential hidden risks in RLER, reinforcing the need for persistent ecological monitoring and proactive management.

(3) RLERI exhibited significant spatial heterogeneity. The spatial distribution in the study area was dominated by high–high (H-H) and low–low (L-L) clustering patterns. H-H clusters were mainly concentrated in the central and southern regions, while L-L clusters were scattered sporadically in the north and south. Few high–low (H-L) or low–high (L-H) aggregation phenomena were present. Therefore, ecological conservation must be prioritized in planning to align development activities with the carrying capacity of natural ecosystems.

(4) Based on the four LISA-based zoning types, we propose a differentiated governance framework: H-H zones require ecological restoration and strict restrictions; L-L zones maintain preventive conservation and low-impact activities; H-L zones need targeted interventions; L-H zones require early-warning systems to prevent spillover. This four-tier zoning framework enhances the practical applicability of our findings for territorial spatial planning. Policy actions include enforcing Ecological Redlines in

H-H clusters, linking the four-tier zoning to Territorial Spatial Planning, and aligning these strategies with the Rural Revitalization Strategy.

(5) Based on these findings, future initiatives should develop ecological restoration plans aligned with regional ecological baselines by analyzing the spatio-temporal aggregation patterns of landscape ecological risk. Approaches such as near-natural restoration should be implemented to facilitate sustainable rural development.

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Abbreviations

The following abbreviations are used in this manuscript:

XXAP	Xiangxi Autonomous Prefecture
LDD	Landscape Disturbance Degree
LFD	Landscape Fragility Degree
RLERI	Rural Landscape Ecological Risk Index
RLER	Rural Landscape Ecological Risk
LTS	Landscape Type Structure
LSF	Landscape Service Function

Jishou X1: Aizhai; X2: Danqing; X3: Hexi; X4: Majing'ao; X5: Taiping; X6: Ji Lue.

Baojing X1: Bier; X2: Fuxing; X3: Hulu; X4: Ludongshan; X5: Maogouxi; X6: Purong; X7: Qianling; X8: Qingshuiping; X9: Wanmipo; X10: Yangchao; X11: Changtanhe.

Fenghuang X1: Alaying; X2: Chatian; X3: Gangziping; X4: Heku; X5: Jixin; X6: Larshan; X7: Lianglin; X8: Liaojiaqiao; X9: Linfeng; X10: Luochaojing; X11: Tuojiang; X12: Xinchang.

Longshan X1: Ciyantang; X2: Da'an; X3: Dianfang; X4: Guitang; X5: Hongyanxi; X6: Huatang; X7: Liye; X8: Luota; X9: Maoping; X10: Miao'er Beach; X11: Min'an; X12: Neixi; X13: Longche; X14: Shigao; X15: Shipai; X16: Shuitianba; X17: Xichehe; X18: Xiluo; X19: Zanguo; X20: Zhaoshi.

Huayuan X1: biancheng; X2: Buchou; X3: Huayuan; X4: Jiwei; X5: Longtan; X6: Malichang; X7: Mao'er; X8: Minle; X9: Shilan; X10: Shuanglong; X11: Yayou; X12: Changle.

Yongshun X1: Cheping; X2: Duishan; X3: Furong; X4: Guitang; X5: Kesha; X6: Langxi; X7: Liangcha; X8: Lingxi; X9: Maoba; X10:Qingping; X11:Runya; X12: Shaba; X13: Shidi; X14: Shouche; X15: Songbai; X16: Tawo; X17: Wanmin; X18: Wangping; X19: Xiqi; X20: Xiaoxi; X21: Yanjiang; X22: Yongmao; X23: Zejia.

Luxi X1: Baiyangxi; X2: Dalan; X3: Heshui; X4: Jiefangyan; X5: Pushi; X6: Shiliuping; X7: Tanxi; X8: Wuxi; X9: Xixi; X10: Xiaozhang; X11: Xinglongchang.

Guzhang X1: Duanlongshan; X2: Gaofeng; X3: Guyang; X4: Hongshilin; X5: Morong; X6: Pingba; X7: Yantouzhai.

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