Spatio-temporal Evolution and Optimization of Landscape Ecological Risk in Karst Mountainous Areas

Fangfang DENG[1,2], Zhongfa ZHOU[1,2*], Denghong HUANG[1,2], Yang ZHANG[1,3], Fuxianmei ZHANG[1,2], Shuanglong DU[1,2], Yue YANG[1,2]

1. School of Karst Science/School of Geography and Environmental Science, Guizhou Normal University, Guiyang 550001, China; 2. State Engineering Technology Institute for Karst Desertification Control, Guiyang 550001, China; 3. 117 Geology Brigade, Guizhou Bureau of Geology and Mineral Exploration and Development, Guiyang 550001, China

Abstract [**Objective**] The ecological vulnerability and landscape ecological risk of karst mountainous areas have increased as a result of enhanced disturbance of natural resources by human activities. This paper aimed to explore the characteristics of ecological risk evolution under different landscape patterns in the region, with a view to providing reference for land classification protection, sustainable use of resources and regional ecological risk optimization in karst mountainous areas. [**Method**] Taking Huangping County, a typical karst mountainous area, as an example, eight evaluation factors of natural and landscape patterns were selected to construct a landscape ecological risk evaluation model, to quantitatively explore the spatio-temporal evolution of landscape ecological risk and the trend of risk level transfer in the study area from 2010 – 2018, and to reveal the complex relationship between ecological risk and topography in karst mountainous areas. [**Result**] ① From 2010 to 2018, land use types changed to different degrees, with the most amount of woodland transferred out (1 627.37 hm^2) and the most amount of construction land transferred in (1 303.93 hm^2); a total of 3 552.31 hm^2 of land was transferred, with a change ratio of 2.13%, and there was a significant conversion between construction land, arable land, and woodland. ② From 2010 to 2018, the landscape ecological risk in the study area changed significantly, and the landscape ecological risk index decreased from 0.344 1 to 0.173 3, showing an upward and then downward trend; the landscape ecological risk of the whole region was dominated by low-risk and lower-risk zones, and the ecological risk level generally shifted from a high level to a low level, and the ecological environment was improved. ③ There was a negative correlation between ecological risk and topographic position, and high-risk zones were mainly distributed among low topographic zones; with the change of time, the advantage of risk level for the selection of topography was gradually weakened, and the influence of anthropogenic factors on the ecological risk of the landscape was becoming more and more prominent. [**Conclusion**] This paper can provide theoretical basis for land use optimization and ecological protection in karst mountainous areas.

Key words Karst mountainous area; Landscape pattern; Landscape ecological risk index; Terrain distribution index

DOI 10.19547/j.issn2152 – 3940.2024.01.004

Since the 21st century, driven by a series of factors such as rapid urbanization, global climate change, and national policies, ecological and environmental problems have become increasingly serious worldwide[1]. How to scientifically assess ecological risks is the key to promoting ecological restoration, which is of great significance for promoting regional sustainable development and optimizing management[2 – 4]. The assessment of ecological risks through land use change is a research hotspot based on landscape pattern evaluation methods[5 – 6]. In the current situation of rapid changes in global land use patterns, it has become important research contents to ensure the sustainable development of regional land resources by exploring potential ecological risks, optimizing the dynamic balance between different land use types, and scientifically managing land resources[7 – 9].

Received: December 10, 2023 Accepted: January 30, 2024

Supported by Region Project of the National Natural Science Foundation of China (41661088); Project for Guizhou Province "High-level Innovative Talent Training Program 'Hundred' Level Talents" (QKHPTRC [2016] 5674); Guizhou Science and Technology Plan Project (QKHZC [2023] GENERAL211).

* Corresponding author.

Landscape ecological risk refers to the adverse consequences that may arise from the interaction between landscape patterns and ecological processes under the influence of natural or human factors[10], and landscape ecological risk assessment is the basis for risk identification and prevention[11]. Since the end of the 20th century, foreign scholars have combined traditional ecological risk assessment with landscape ecology, and combined landscape ecology with watershed ecology, geography, and other disciplines to continuously develop into a wide-area landscape ecological risk assessment and form a comprehensive theoretical evaluation framework[12 – 13]. At present, scholars have relied on methods such as source sink method and landscape pattern index[14 – 15] to conduct extensive research on areas with intense human activities and ecologically sensitive vulnerability, such as watersheds[16 – 17], cities[3,18], mining areas[19 – 20], coastal zones[21 – 22], and nature reserves[23 – 25]. Compared with the source sink method, the landscape pattern index method can quantitatively express the structure and function of ecosystems, and has advantages in reflecting the structural composition and spatial configuration characteristics of landscapes[26 – 27]. At present, research mainly focuses on the calculation of landscape pattern indices based on types and levels. However, the representativeness of research on karst mountainous areas with complex surface environments, fragmented arable land resources, and strong spatial heterogeneity is limited. Karst mountainous areas have undulating terrain and fragmented landscapes. The implementation of ecological risk assessments in karst mountainous areas is beneficial for optimizing the landscape ecological risk assessment system and providing stronger guidance for regional social development[28]. Landscape ecological risk assessment combining the complex terrain and landforms of karst mountainous areas can provide theoretical basis for rational planning and utilization of land and optimization of regional ecological risks in the area.

In this paper, Huangping County in the karst mountainous area was taken as the research object. 8 evaluation factors from two dimensions of nature and landscape pattern were selected to construct a landscape ecological risk assessment model composed of landscape interference index and vulnerability index. At the same time, the terrain comprehensive index formed by elevation and slope was introduced to quantitatively explore the spatio-temporal evolution of landscape ecological risk and transfer trend of risk level in the study area from 2010 to 2018, and reveal the complex relationship between ecological risk and terrain in the karst mountainous area. The objective of this paper is to: ① analyze the land use transfer situation in the study area from 2010 to 2018; ② establish a landscape ecological risk index model based on the landscape pattern index, to explore the spatio-temporal evolution of landscape ecological risks and evolution trends of risk level; ③ explore the impact of karst terrain on landscape ecological risks.

1 Materials and methods

1.1 Overview of the research area Huangping County (107°35′40″ – 108°12′48″ E, 26°43′46″ – 27°14′30″ N) is located in the southeastern part of Guizhou Province, and the terrain gradually decreases from west to east and from northwest to southeast (Fig. 1). The northern mountainous area belongs to the Wuling Mountains, while the southern part belongs to the Miaoling Mountains, with hills and valley basins as the main landforms. There are a total of 32 rivers in Huangping, including the Chong'an River and the Wuyang River, with a length of over 10 km or a drainage area of over 20 km^2. These rivers belong to the Dongting Lake and the Wujiang River water systems in the Yangtze River basin. Huangping is located in a subtropical monsoon climate zone, with an average annual temperature of 15.1 ℃ and an average annual precipitation of 1 233.2 mm. The karst area of Huangping County is 998.67 km^2, accounting for 59.88% of the total land area of the county. The area of karst rocky desertification is 292.53 km^2, accounting for 17.54% of the total land area in the county. Huangping County has high mountains, deep valleys, and fragmented terrain, which poses ecological problems such as fragile ecological environment, soil erosion, and geological disasters. The serious desertification in this area has affected regional economic growth and threatened the survival of local residents. Unreasonable human activities have constrained the implementation of rural revitalization and sustainable development.

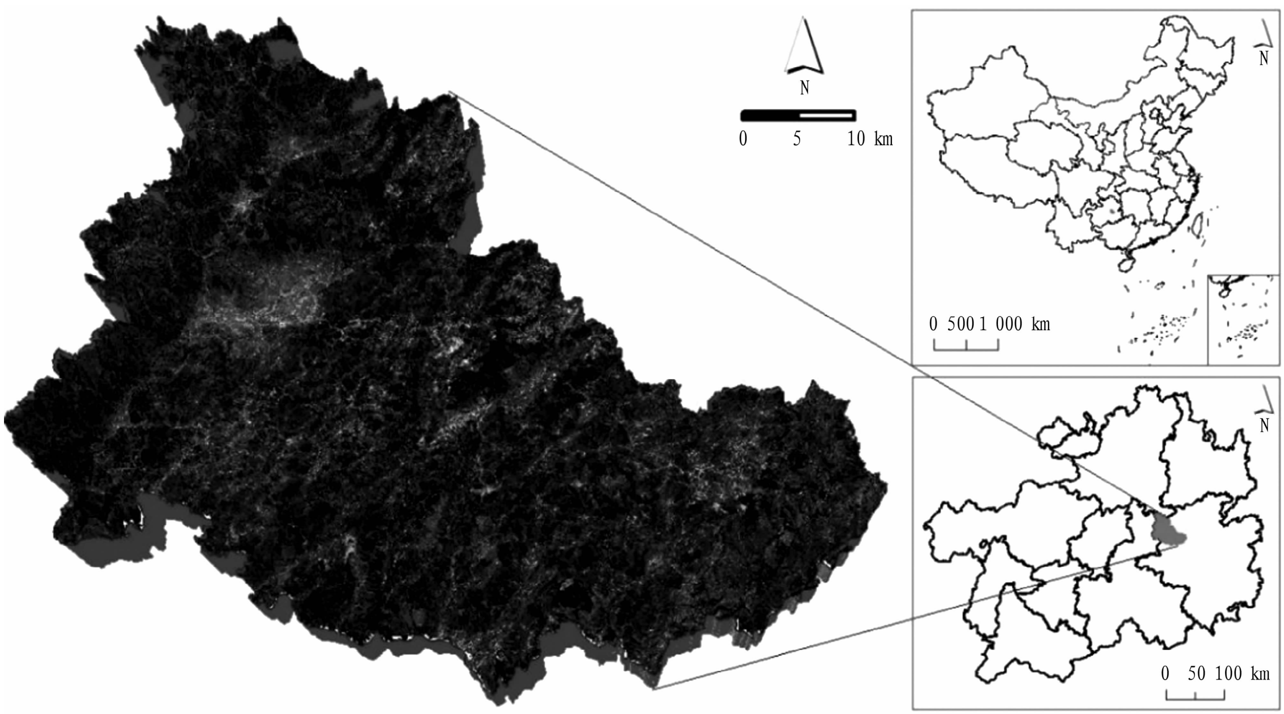


Fig. 1 Diagram of the study area

1.2 Data sources and processing The administrative boundary data of the research area and the land use data of four phases (2010, 2013, 2016, and 2018) were all from the Natural Resources Bureau of Huangping County. Referring to the *Classification of Land Use Status* (GB/T 21010 – 2017) of the second national land survey, ArcGIS 10.5 software was used to classify land use types into six categories: cultivated land, woodland, grassland, water area, construction land, and other land. The ground elevation DEM data came from ASTER GDEM (V3) dataset in the geospatial data cloud of the Computer Network Information Center of the Chinese Academy of Sciences (http://www.gscloud.cn), with a spatial resolution of 30 m × 30 m. Elevation and slope data were extracted in ArcGIS 10.5, and the obtained elevation and slope means were used for calculating terrain potential index. Using Fragstats 4.2 software, the number of patches and average patch area were obtained to calculate the landscape pattern index.

1.3 Research methods

1.3.1 Landscape ecological risk index. ① Division of evaluation units. Landscape ecology suggests that the area of patches should be 2 – 5 times of the average area of landscape patches[29]. Based on land use data in the study area, the average area of patches was obtained. Taking into account issues such as spatial scale in karst mountainous areas, the study area was divided into 18 500 grids of 300 m × 300 m. The ecological risk index for each unit was calculated, and the results were allocated to the central point of the evaluation unit. ② Construction of landscape ecological risk model. The ecological risk index (ERI) reflects the relationship between landscape pattern and ecological risk, and is constructed by the composition of different land use types and landscape pattern indices in each evaluation unit. The formula is as follows:

$$ERI = \sum_{i=1}^{n} \frac{A_{ki}}{A_k} R_i \quad (1)$$

where *ERI* is landscape ecological risk index of grid units within the sample area; A_{ki} shows the area of the i^{th} type of landscape in the k^{th} evaluation unit (hm^2); A_k shows the total landscape area of the k^{th} evaluation unit (hm^2); R_i shows the loss index of the i^{th} type of landscape[30]. Landscape pattern indices and their meanings in the study area was shown in Table 1.

Table 1 Landscape pattern indices and their meanings in the study area

Index name	Formula	Meaning
Landscape loss index (R_i)	$R_i = F_i \times S_i$	It indicates the degree of natural attribute loss after different landscape types are affected. F_i and S_i show landscape vulnerability and landscape disturbance index respectively. Referring to vulnerability ranking of landscape types in the landscape ecology[7,31 – 33], this paper assigned a value of 1 to construction land, 2 to woodland, 3 to grassland, 4 to cultivated land, 5 to water bodies, and 6 to other land types. The normalized non-zero processing for intensity of landscape vulnerability for each type was conducted, with values of 0.010, 0.208, 0.406, 0.604, 0.802, and 1.000, respectively.
Landscape disturbance index (S_i)	$S_i = aC_i + bN_i + cK_i$	It indicates the degree of interference from external activities on the landscape. Here, S_i shows landscape disturbance index; C_i, N_i and K_i show landscape fragmentation degree, landscape separation degree, and landscape dominance degree, respectively; a, b, and c are the weight of each landscape index, and the sum of the three is 1. Referring to previous studies[2 – 4], the values were assigned as $a = 0.5$, $b = 0.3$, and $c = 0.2$, respectively.
Landscape fragmentation index (C_i)	$C_i = \frac{n_i}{A_i}$	It indicates the degree of fragmentation of landscape types. The larger the value, the more complex and discontinuous the distribution of landscape patches, and the higher the ecological risk. Here, n_i is the number of patches in landscape type i; A_i is the area of landscape type i (hm^2).
Landscape separation index (N_i)	$N_i = \frac{1}{2}\sqrt{\frac{n_i}{A}} \times \frac{A}{A_i}$	It indicates the degree of dispersion of landscape patch distribution. The larger the value, the lower the stability of the ecosystem and the higher the ecological risk. Here, n_i is the number of patches in landscape type i; A_i is the total area of landscape type i (hm^2); A is total landscape area (hm^2).
Landscape dominance index (K_i)	$K_i = \frac{(B_i + L_i)}{4} + \frac{D_i}{2}$	It indicates the degree of control of a landscape over the entire ecosystem. Here, B_i is number of plots for landscape type i/total number of plots; L_i is number of patches in landscape i/total number of patches; D_i is distribution area of landscape type i (hm^2)/total sample area (hm^2).

1.3.2 Calculation of terrain niche index and terrain distribution index. Terrain is an important factor affecting land use types and landscape pattern distribution, especially in karst mountainous areas where complex terrain and landforms have a significant impact on local landscape ecological risks. A single elevation or slope cannot comprehensively reflect the process of terrain's impact on land use[5 – 6]. Therefore, terrain niche index and terrain distribution index were introduced to comprehensively and quantitatively analyze the relationship between terrain and landscape ecological risks in the study area.

(1) Terrain niche index. The higher the elevation and the steeper the slope, the higher the terrain niche index, and vice versa, the smaller it is[9]. The formula is as follows:

$$T = \log\left[\left(\frac{E}{\overline{E}} + 1\right] \times \left(\frac{S}{\overline{S}} + 1\right)\right] \quad (2)$$

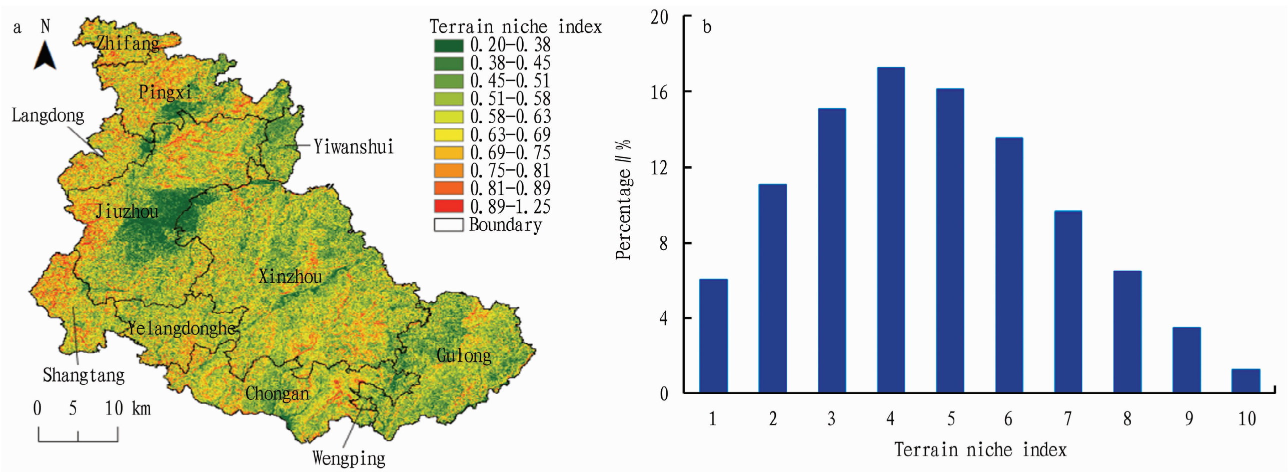
where T is terrain niche index; E and S show the elevation and slope values of any grid within the study area, respectively; $\overline{E}$ and $\overline{S}$ show the average elevation and average slope values of the entire research area, respectively[6].

(2) Terrain distribution index. The terrain distribution index represents the distribution frequency of landscape ecological risk levels within each terrain interval, which can effectively eliminate the interference of area on different terrain intervals and reflect the dominant distribution of ecological risks at different levels, represented by P. If $P > 1$, it indicates that ecological risk level area of the i^{th} type of landscape within the e terrain niche interval is a dominant distribution, and the larger the P value, the higher its dominance. If $P < 1$, it indicates that ecological risk level area of the i^{th} type of landscape within the e terrain niche interval is in a

disadvantaged distribution. If $P=1$, it indicates that the proportion of ecological risk level area of the i^{th} type of landscape within the e terrain niche interval is equal to the proportion of ecological risk level area of the i^{th} landscape within the entire study area. The formula is as follows:

$$P=\left(\frac{S_{ie}}{S_i}\right)/\left(\frac{S_e}{S}\right) \quad (3)$$

where S_{ie} shows the area of ecological risk level of the i^{th} type of landscape within the e terrain interval; S_i shows the total area of ecological risk level of the ith type of landscape; S shows total area of the research area; S_e shows the total area of e terrain niche[6]. To reflect the advantageous distribution intervals of ecological risk levels of each landscape, taking into account spatial heterogeneity in the study area, the natural breakpoint method was used to divide the terrain niche index into 10 gradients (Fig. 2): level 1, 0.20 – 0.38; level 2, 0.38 – 0.45; level 3, 0.45 – 0.51; level 4, 0.51 – 0.58; level 5, 0.58 – 0.63; level 6, 0.63 – 0.69; level 7, 0.69 – 0.75; level 8, 0.75 – 0.81; level 9, 0.81 – 0.89; level 10, 0.89 – 1.25.



Note: a. Spatial distribution of terrain niche index in the study area; b. Level statistics of terrain niche index in the study area.

Fig. 2 Terrain niche index of the study area

2 Results and analysis

2.1 Spatio-temporal characteristics of land use change The land use changes in Huangping County from 2010 to 2018 were shown in Table 2 and Fig. 3. Overall, woodland, grassland, and cultivated land are the main landscapes of Huangping County, covering the entire area. Other land use types are interlaced around or within it, and the three types of land account for more than 95% of the total area in the study zone. The area of woodland, grassland, and other land has decreased. Among them, the area of woodland decreased by 0.97%, which was the most, and 203.422 hm^2 of woodland disappeared every year; the grassland area has decreased by 0.41%, with an average annual decrease of 84.66 hm^2; the total area of other land has decreased by 1.9 hm^2, with an average annual decrease of 0.24 hm^2. According to the transfer matrix of various landscape types from 2010 to 2018, the total area of land use change was 3 552.31 hm^2, with a change ratio of 8.8%. Woodland was the main type of transfer out, with a transfer out area of 1 739.01 hm^2, accounting for 48.95% of the conversion area. It was mainly converted into arable land (1 382.61 hm^2), followed by construction land occupation. Farmland was the main type of transfer, with a total of 57.07% of other land use types converted to farmland during the study period, including 1 382.61 hm^2 of woodland, 620.13 hm^2 of grassland, 12.07 hm^2 of water, 10.76 hm^2 of construction land, and 1.74 hm^2 of other land transferred. According to the analysis of the transfer situation, the transfer among cultivated land, woodland, construction land, and grassland was the most obvious, accounting for 97.98% of the total transformed area.

Table 2 Area and proportion of land use type in 2010, 2013, 2016 and 2018 hm^2 (%)

Year	Construction land	Woodland	Grassland	Cultivated land	Water	Other land
2010	3 999.95	83 908.13	17 886.73	59 217.68	1 370.61	624.85
	2.40	50.24	10.71	35.46	0.82	0.37
2013	4 862.16	83 218.57	17 578.06	59 351.38	1 373.04	624.73
	2.91	49.83	10.53	35.54	0.82	0.37
2016	5 079.45	82 371.21	17 288.89	60 216.87	1 391.45	660.07
	3.04	49.32	10.35	36.06	0.83	0.40
2018	5 303.87	82 280.75	17 209.47	60 199.98	1 390.92	622.95
	3.18	49.27	10.30	36.05	0.83	0.37

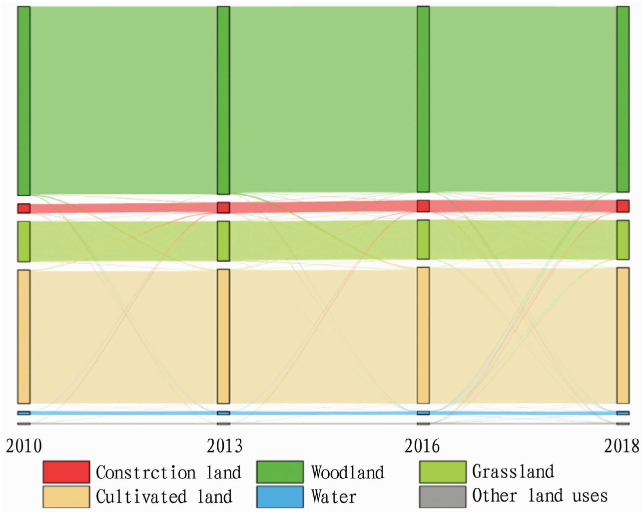
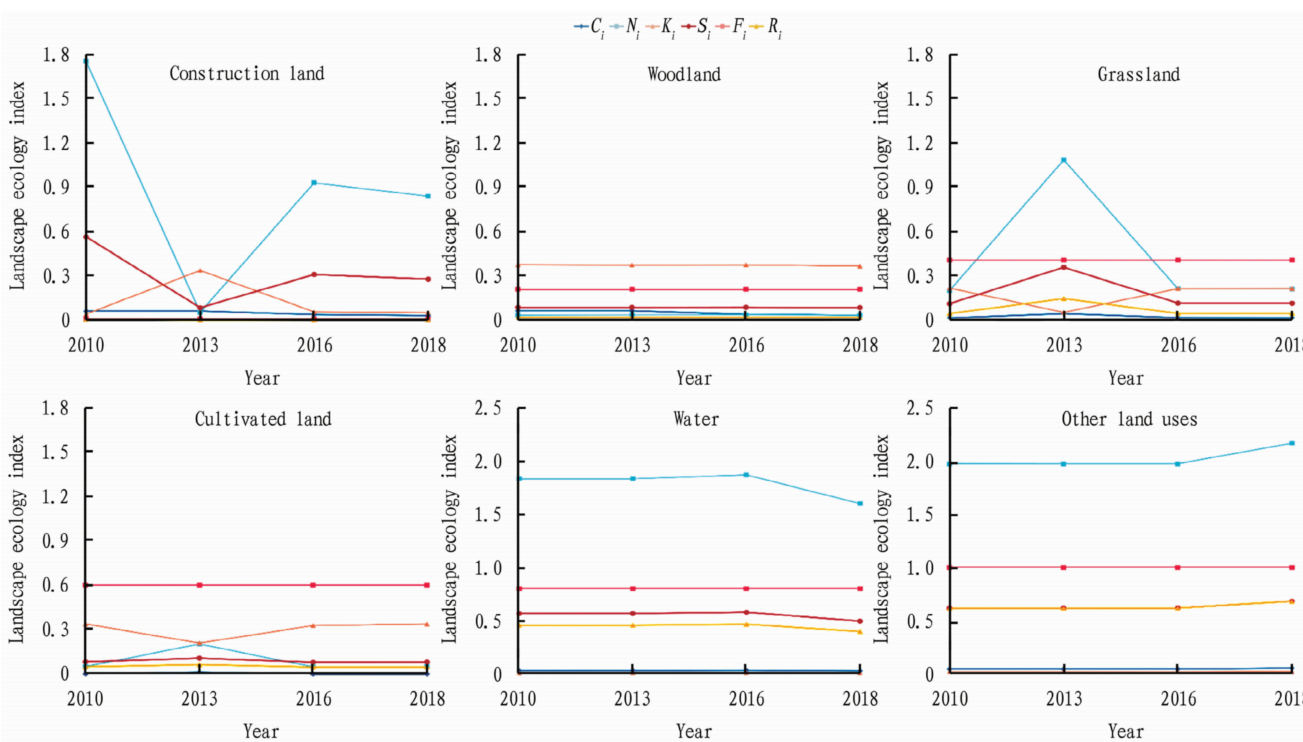


Fig. 3 Land use during 2010 – 2018

2.2 Characteristics of landscape pattern changes From 2010 to 2018, the area of woodland, grassland, and other land decreased (1 627.37, 677.26, and 1.9 hm^2), while the area of construction land, cultivated land, and water increased (1 303.93, 982.30, and 20.31 hm^2). R_i, S_i, and N_i of construction land, cultivated land, and water showed a decreasing trend, and the decrease of S_i and N_i of construction land and water was significant decrease (S_i: 0.287 and 0.072, N_i: 0.911 and 0.234). R_i, S_i, N_i, and C_i of other land use showed an upward trend, with a significant increase of 0.063 in R_i and S_i. In the landscape pattern data of land use types in four phases, there was a turning point in the landscape pattern index in 2013 and 2016. In terms of land use types, other land uses, water bodies, and construction land had higher N_i, while water bodies and other land use had higher C_i, S_i, and R_i. R_i of woodland, water, and other land showed small fluctuations in 2016, while R_i of construction land, grassland, and cultivated land showed significant fluctuations in 2013, and then recovered to the values of 2010. Among them, N_i and K_i of construction land tended to flatten from high-value fluctuation, indicating an increase in the clustering degree of construction land, as well as an increase in the quantity and density within local areas. Except for the fluctuations in 2013, the various landscape indices of cultivated land were almost at the same level. In terms of individual index, N_i fluctuated significantly, with a turning point in 2013 and 2016, and its performance was more pronounced in 2013. Next were K_i and S_i, with some fluctuations in 2013 and 2016; C_i, R_i, and F_i have not changed much. The fluctuation of the landscape pattern index of land use types from 2010 to 2018 was in descending order: $N_i > K_i > S_i > C_i > R_i > F_i$ (Fig. 4).



Note: C_i is landscape fragmentation index; N_i is landscape separation Index; K_i is landscape advantage index; S_i is landscape disturbance index; F_i is landscape vulnerability index; R_i is landscape loss index.

Fig. 4 Changes in landscape ecological indices of land use type

2.3 Spatio-temporal changes in landscape ecological risks Referring to the research results of previous scholars[34-35], the study area was divided into five levels using the natural breaks method: low ecological risk zone ($0 \leqslant ERI \leqslant 0.310\,0$), lower ecological risk zone ($0.310\,1 < ERI \leqslant 0.608\,1$), medium ecological risk zone ($0.608\,2 < ERI \leqslant 1.318\,8$), higher ecological risk zone ($1.318\,9 < ERI \leqslant 2.559\,0$), and high ecological risk zone ($2.559\,1 < ERI \leqslant 4.995\,0$).

2.3.1 Spatial distribution characteristics of landscape ecological risks. As a typical high-altitude mountainous county, the western part of Huangping County is an important ecological protection area. As an important ecological barrier for water source conservation and soil and water conservation in the Yangtze River basin of China, under the influence of various ecological protection policies, regional ecological risks have shifted towards low-level ecological risk areas. From Fig. 5, it can be seen that the average ecological risks in each period of the study area were 0.344 1, 0.485 2, 0.261 4, and 0.173 3, respectively, showing a fluctuating trend of first increasing and then decreasing, and the ecological risk was gradually shifting towards low-risk types. Except for the area of ecological risk zones in 2013, low ecological risk zone > lower ecological risk zone > medium ecological risk zone > higher ecological risk zone > high ecological risk zone. The low ecological risk zone decreased from 50.19% to 32.04%, and then increased to 69.74% and 71.31%; the area with lower ecological risk increased from 44.78% to 46.23%, and then decreased to 25.70% and 25.82%; the proportion of medium ecological risk zone was 3.99%, rising to 20.16%, and then decreasing to 3.53% and 2.19%; higher ecological risk zone increased from 0.71% to 1.21%, and then decreased to 0.70% and 0.50%; high ecological risk zone increased from 0.32% to 0.36%, and then decreased to 0.32% and 0.18%. A spatial structure with low ecological risk level as the widest distribution was formed within the region, and the risk levels had a trend of transitioning from high to low. The ecological risk has significantly decreased during the research period. Among them, the transformation from lower ecological risk zone to low ecological risk zone was the most obvious.

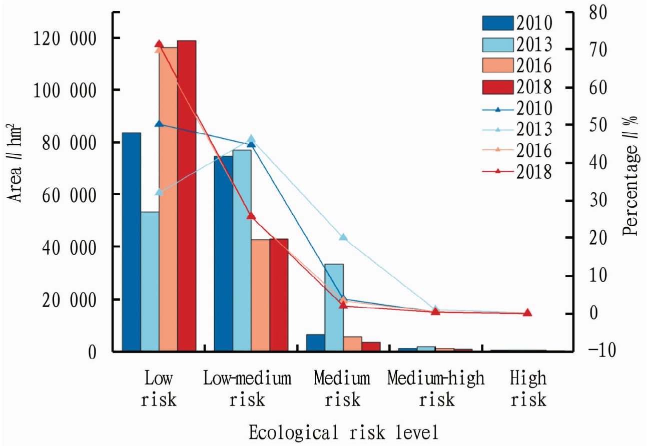
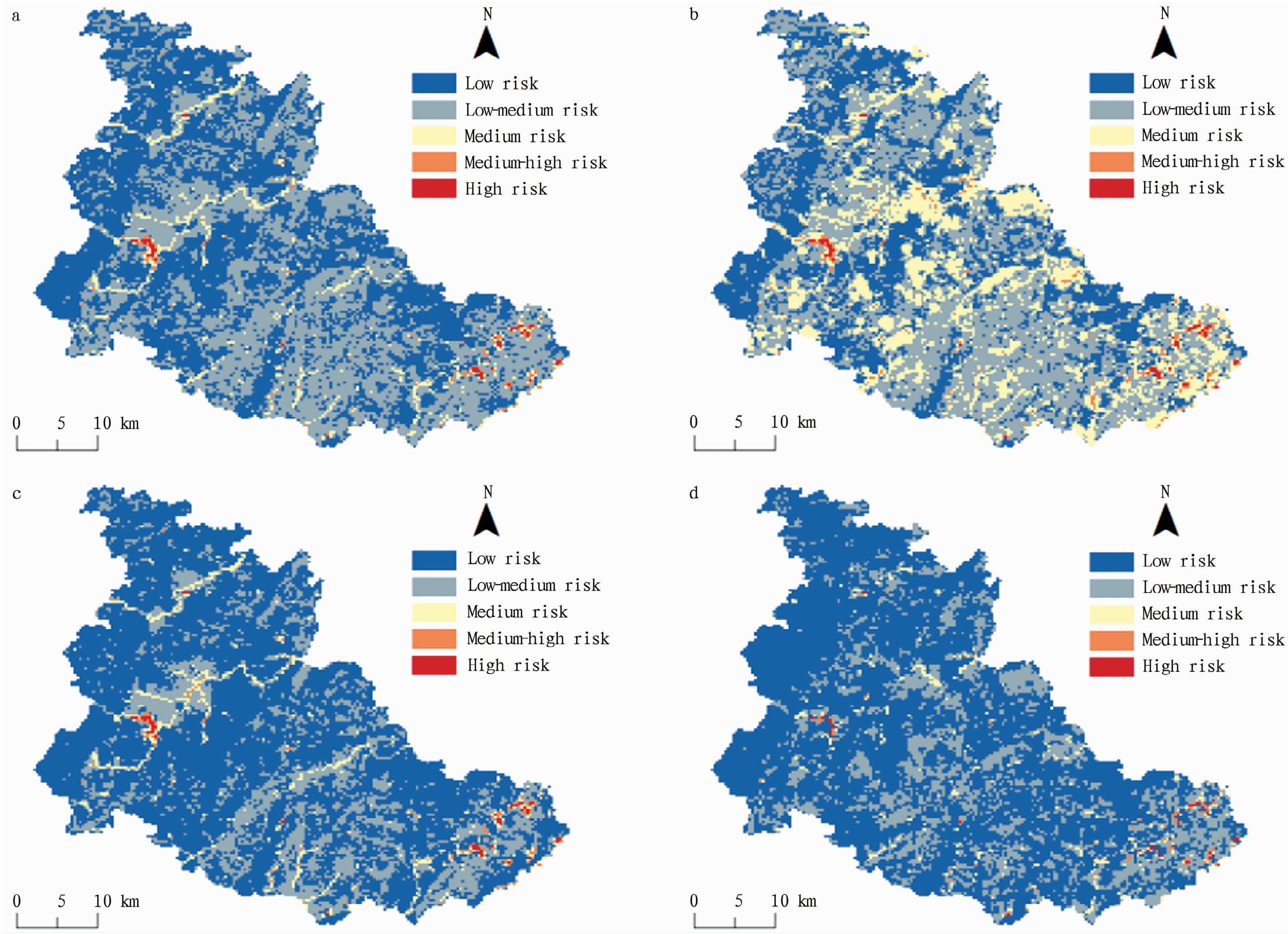


Fig. 5 **Area and percentage of landscape ecological risk at different levels**



Note: a. 2010; b. 2013; c. 2016; d. 2018.

Fig. 6 **Distribution of ecological risk levels across the landscape during 2010 – 2018**

In 2010, 2016, and 2018, the region was mainly characterized by lower ecological risk zone (50.19%, 69.74%, and 71.31%) and low ecological risk zone (44.78%, 25.70%, and 25.82%). In 2013, the entire region was dominated by lower ecological risk zone (32.04%), low ecological risk zone (46.23%), and medium ecological risk zone (20.16%). Seen from Fig. 6a, the entire region was mainly composed of lower risk zone and low risk zone in 2010, with higher risk zone and high risk zone mainly located in the northwest and southeast; the population distribution in high ecological risk zone was relatively high, and human activities have increased their interference with the landscape. However, the high ecological risk zone in 2013 remained relatively unchanged compared to 2010 (Fig. 6a – 6b). Without external intervention and regulation, it is difficult for natural ecosystems to achieve a virtuous cycle when landscape is severely damaged by human. In 2016, the zones with lower, medium, higher, and high ecological risks showed a decreasing trend (Fig. 6c), with reductions of 34 236, 27 729, 846, and 63 hm^2, respectively. This was reflected in the large-scale reduction of lower and medium ecological risk zones in the entire region, as well as the local weakening and contraction of higher and high ecological risk zones. In 2018 (Fig. 6d), the area of medium, higher, and high ecological risk zones in the study area further decreased by 2 232, 351, and 234 hm^2, respectively; the zones with low and lower ecological risks have further increased, with an additional area of 2 619 and 198 hm^2, respectively. From a distribution perspective, the scope of higher and high ecological risk zones has further narrowed, the risk level along the water system has decreased, and the lower ecological risk zone in the northwest dam area has transformed into low ecological risk zone.

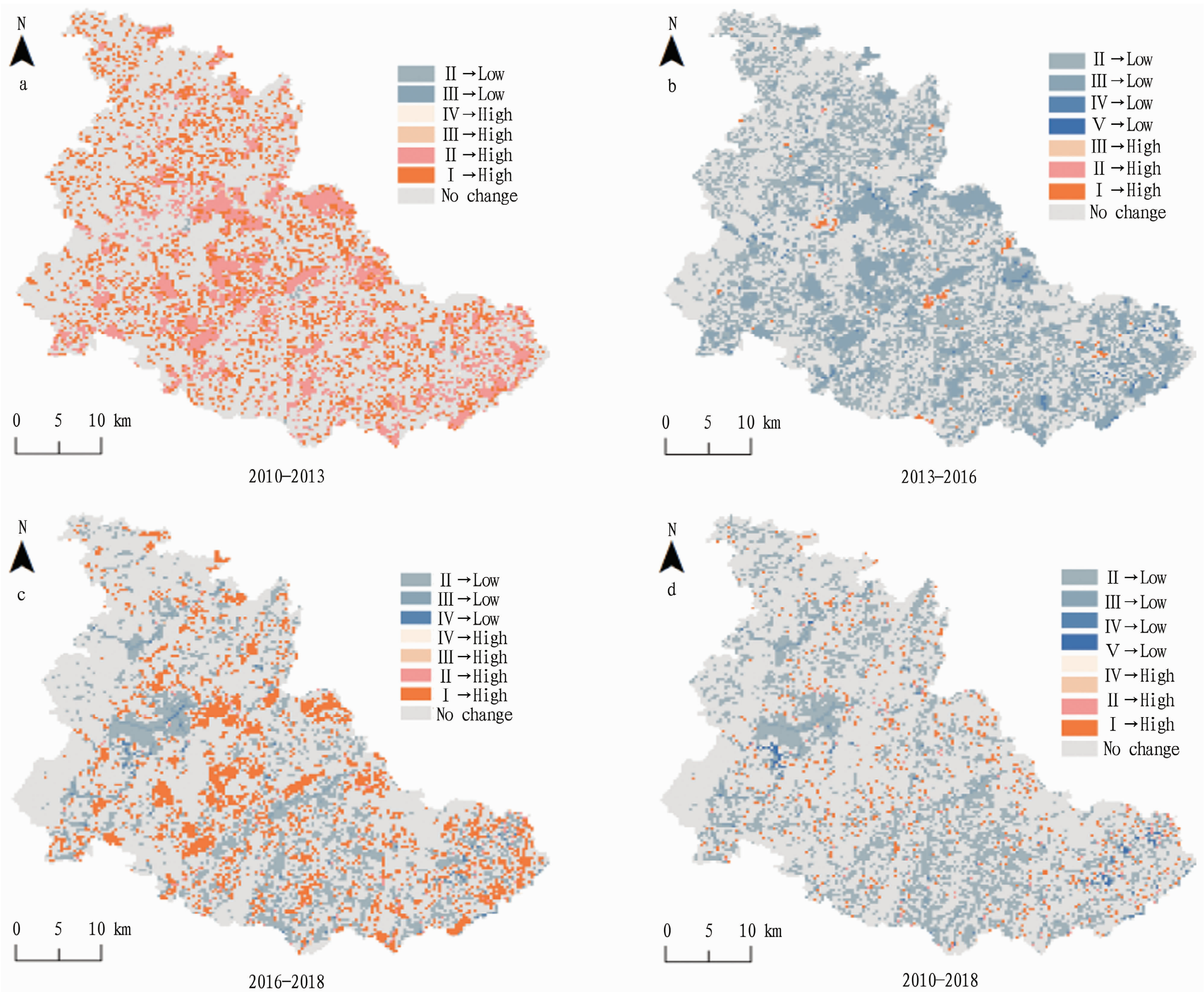
2.3.2 Spatio-temporal evolution of landscape ecological risks. Seen from Table 3, the entire region was mainly low and lower risk zones from 2010 to 2018, and risk level showed a trend of first increasing and then decreasing. The increase and decrease of risks were intertwined, with a total increase of 85 878 hm^2 and a total decrease of 105 462 hm^2. The overall ecological risk was showing a downward trend, and the ecological environment was developing well. The risk level showed a significant upward trend from 2010 to 2013. Except for the main areas of the Wuling Mountains and the Miaoling Mountains within the study area, the intensity of human interference within the region was high, leading to an increase in landscape ecological risk, with the rising areas covering the entire area. During the same period, the cultivated land in Huangping County changed from a global change to a local change. During 2013 – 2016, there was a significant decrease in the risk increasing type, only 1 494 hm^2, while the risk decreasing type during the same period was 75 321 hm^2, indicating a significant decrease in the risk level within the region. The main transfer targets for the decrease in risk level were lower and low risk. During 2016 – 2018, both increased and decreased risks occurred, and the landscape ecological risk reduction continued to be the main trend.

Table 3 Transfer matrix of landscape ecological risk zone at each level hm^2

Transfer type		2010 – 2013	2013 – 2016	2016 – 2018	Total
Risk increasing type	$V_1 \to V_2\ V_3\ V_4\ V_5$	30 609	1 296	26 136	58 041
	$V_2 \to V_3\ V_4\ V_5$	25 290	144	1 233	26 667
	$V_3 \to V_4\ V_5$	774	54	189	1 017
	$V_4 \to V_5$	63	0	90	153
	Total	56 736	1 494	27 648	85 878
Risk reduction type	$V_2 \to V_1$	342	45 774	25 317	71 433
	$V_3 \to V_2\ V_1$	18	28 521	3 762	32 301
	$V_4 \to V_3\ V_2\ V_1$	0	963	702	1 665
	$V_5 \to V_4\ V_3\ V_2\ V_1$	0	63	0	63
	Total	360	75 321	29 781	105 462
Risk invariant type	$V_1 \to V_1$	53 380	52 426	90 460	196 266
	$V_2 \to V_2$	49 068	31 185	16 650	96 903
	$V_3 \to V_3$	5 580	4 761	1 656	11 997
	$V_4 \to V_4$	1 125	1 062	387	2 574
	$V_5 \to V_5$	531	531	198	1 260
	Total	109 684	89 965	109 351	309 000

Note: V_1 is low ecological risk zone; V_2 is lower ecological risk zone; V_3 is medium ecological risk zone; V_4 is higher ecological risk zone; V_5 is high ecological risk zone.

The overall landscape pattern distribution from 2010 to 2013 was relatively uniform, mainly shifting from low ecological risk zone and lower ecological risk zone to other high-level risks (Fig. 7a). Among them, the patch of transferring from low ecological risk zone to high-level risk zone was more fragmented, distributed more evenly, and spread throughout the entire region; the transformation patch of lower ecological risk zones was more continuous and concentrated in the central and southern edge areas of Huangping County. From 2013 to 2016, the landscape pattern level shifted to a global change, with a focus on the transition from medium ecological risk zone and lower ecological risk zone to low-level risks (Fig. 7b). Among them, the patch of transferring from medium ecological risk zone to low-level risk zone was more fragmented and widely distributed, with a high degree of overlap with the transition from low ecological risk zone to high-level zone in Fig. 7a; the patch of transferring from lower ecological risk zone to low-level zone was more concentrated, with a high degree of overlap with the areas where low ecological risk increased from 2010 to 2013. From 2016 to 2018, the area of transition to higher and lower levels was generally consistent, and the distribution of the two was also more clustered. Among them, there was a high degree of overlap between low-risk to high-level transformation areas and medium-risk to low-level transformation areas; the transformation from lower ecological risk zone to low-level zone was more common in areas that have not undergone changes in the previous period.



Note: I is low ecological risk zone; II is lower ecological risk zone; III is medium ecological risk zone; IV is high ecological risk zone; V is higher ecological risk zone. Low is low level; High is high level.

Fig. 7 Changes of landscape ecological risk level during 2010 –2018

2.4 Terrain gradient analysis of landscape ecological risk

According to the formula (2), the terrain niche index of the study area was calculated using elevation and slope data. Seen from the definition of terrain niche index, the higher the elevation and slope, the higher the gradient of the terrain niche index. According to the formula (3), the terrain niche index of the study area was overlaid with the distribution map of landscape ecological risk level in each period, and the distribution index of each ecological risk level in the study area on different terrain niche gradients from 2010 to 2018 was calculated, in order to reveal the relationship between the distribution of each ecological risk level and terrain (Fig. 8).

As shown in Fig. 8, there was a negative correlation between ecological risk and terrain. Low risk zone had distribution advantages in the middle and high terrain intervals, but this advantage gradually decreased over time. From 2010 to 2018, the distribution advantage of lower risk zone in low terrain areas was greater, showing an overall downward trend, while the increasing trend tended to stabilize in 2018. The selection of terrain in medium and higher risk zones was obvious. The distribution advantage in the low terrain area decreased rapidly with the increase of terrain distribution index, and the optimal distribution appeared in low terrain. This advantage distribution was more obvious in 2016, while the distribution of higher risk zone in the terrain area was unstable in 2018, showing a rapid decrease followed by a rapid increase followed by a gradual decrease. It indicated a decrease in dominance over time. From 2010 to 2016, the high risk zone showed a slight increase followed by a significant decrease, while there was a continuous downward trend in 2018, indicating that the advantage of terrain selection in high risk zone weakened and tended to be distributed in the low terrain area. The distribution of each risk level zone on different terrain niche gradients indicated that low ecological risk zone tended to be distributed in the middle and high terrain intervals in the early stage of the research period, while medium risk zone, lower risk zone, higher risk zone, and high risk areas tended to be distributed in the middle and low terrain intervals. Over time, the selectivity of low risk zone towards terrain gradually weakened; the remaining risk areas gradually weakened with the increase of terrain distribution index, indicating that the impact of terrain on landscape ecological risk was gradually decreasing, and there was almost no impact on the ecology of medium and high terrain.

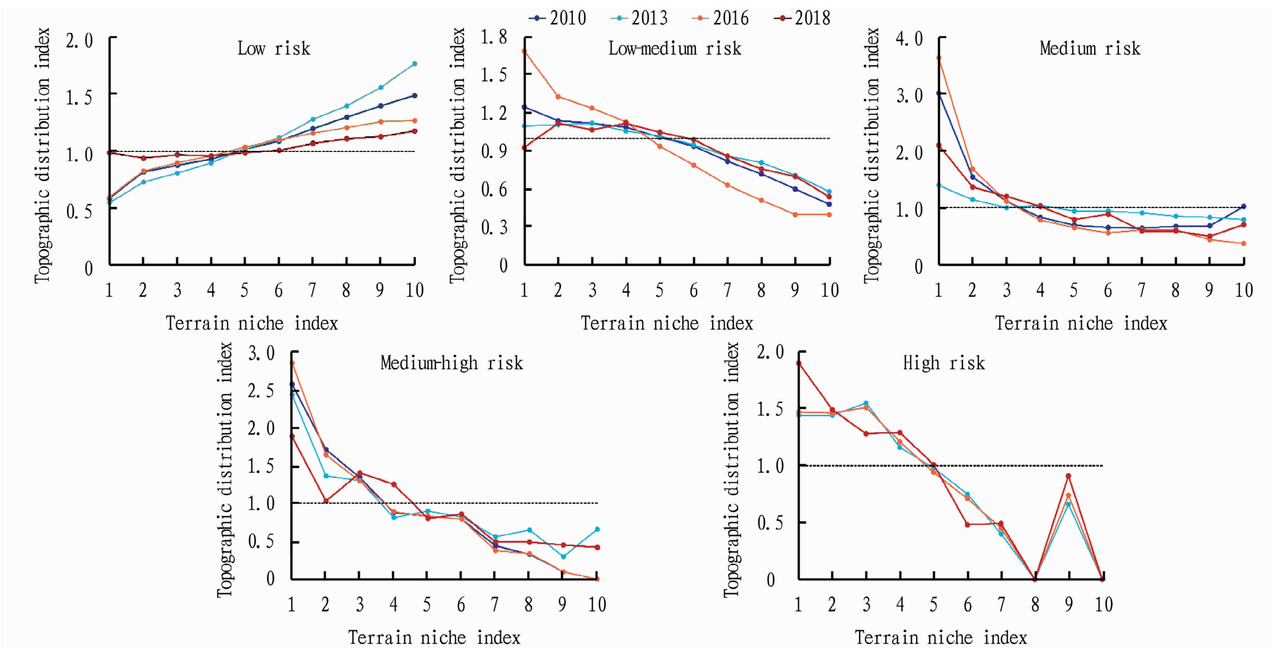


Fig. 8 Distribution index of ecological risk level zones on different terrain levels

3 Discussion

3.1 Ecological risk changes From 2010 to 2018, with the implementation of special plan of urbanization development in Guizhou Province during the "12th Five-year Plan" period and the *Several Opinions of the State Council on further Promoting Good and Fast Economic Development in Guizhou* in 2012, the transformation of land types was promoted. Especially from 2010 to 2013 and from 2013 to 2016, the planning and construction of "two vertical and three horizontal" and "one city and two districts" within the region resulted in the occupation of arable land for construction purposes, with the construction land area increasing from 3 999.95 hm^2 in 2010 to 5 303.87 hm^2 in 2018. At the same time, in order to ensure that the total amount of arable land resources remained relatively stable, and achieve a balance between occupation and compensation of arable land, woodland resources was developed into arable land, and the woodland decreased from 83 908.13 hm^2 in 2010 to 82 280.75 hm^2 in 2018. Human activities and urbanization have led to a series of transformations in land use patterns, disrupting the integrity of the original landscape and causing changes in landscape ecological risks. China has successively issued a series of land policies such as the *Regulations on the Conservation and Intensive Use of Land* and the *Opinions on Strengthening the Protection of Farmland and Improving the Balance of Occupation and Compensation*, which have improved the land use system from multiple aspects such as land use planning, farmland protection, and intensive land use. The adjustment range of land use types has decreased, and the risk level has shown a trend of transitioning from high to low, which was similar to other research results[9,36]. The implementation of national ecological protection and governance projects has played a crucial role in optimizing the landscape ecological risks in ecologically fragile areas.

3.2 Impact of terrain on the distribution of landscape ecological risks Terrain is one of the main driving factors for the spatial distribution trend of land use or vegetation structure[37-38]. The distribution of landscape ecological risks is closely related to land use changes. In this paper, terrain niche index was used to evaluate the relationship between terrain and landscape ecological risks, and to understand the distribution characteristics of ecological risks under different terrain gradients. In this paper, lower, medium, higher, and high ecological risk zones were all distributed in the middle and low terrain intervals. Karst areas have more mountains and less flat land. Due to the advantages of flat terrain and abundant water sources, the middle and low terrain intervals have become the main distribution areas for urban and rural settlements in the region. A large number of people and frequent human activities have deepened and increased the impacts on way and structure of land use, resulting in prominent multi-level ecological risks. On the contrary, low ecological risk zone was distributed in the middle and high terrain intervals. In middle and high terrain of the study area, the slope was large, the soil layer was thin, and soil erosion was severe, which was not conducive to agricultural production activities. Human activities had a relatively small impact on the ecological environment. With the promotion of policies such as "rocky desertification control" and "ecological migration and relocation" in recent years, as well as the promotion and popularization of the importance of ecological environment protection by local management departments, environmental protection awareness has been continuously enhanced. The research results of Wang Jinyu *et al.* [39] were consistent with this paper. Over time, the selection of terrain for different levels of risk zones gradually weakened, indicating that the impact of terrain on landscape ecological risk was weakening over time, and the impact of human factors on landscape ecological risk was becoming increasingly prominent.

3.3 Limitations and future research directions Referring to previous research[40-41], and dividing ecological risk zones, the landscape ecological risk index was calculated based on the landscape pattern index. When dividing evaluation units, issues such as terrain fragmentation and spatial heterogeneity in karst mountainous areas were considered based on the principles of landscape ecology. A smaller scale evaluation unit was used, and 18 500 grids were divided at the county level, which more accurately reflected the landscape ecological risk of the study area. Many scholars have explored the distribution characteristics of land use, landscape ecological risk, and terrain gradient separately, but research was mostly based on single natural factor analysis, and there were few studies that combined the three to discuss together. The landscape ecological risk was studied by introducing terrain gradients[1,39]. It can fully consider the impact of natural factors on risk in areas with complex terrain and landforms. The research results could provide a reference for land classification protection, sustainable resource utilization, and regional ecological risk optimization in karst mountainous areas to a certain extent. Due to data acquisition and indicator selection, this paper only analyzed data from four periods of 2010, 2013, 2016, and 2018, lacking long-term and multi-indicator analysis and prediction in future period. Subsequent research will focus on exploring the current shortcomings.

4 Conclusions

In this paper, Huangping County, a typical karst mountainous area, was taken as the research object. Eight evaluation factors were selected from the dimensions of nature and landscape pattern to construct a landscape ecological risk assessment model. It aimed to explore the spatio-temporal evolution of landscape ecological risk and the trend of risk level transformation from 2010 to 2018, as well as the relationship between the terrain and landscape ecological risks in karst mountainous areas.

(1) With the development of urbanization, the implementation of policies such as returning farmland to forest and grassland, land use types underwent varying degrees of changes from 2010 to 2018. Among them, woodland decreased the most, with a total decrease of 1 627.37 hm^2, and construction land increased the most, with a total increase of 1 303.93 hm^2. During the research period, a total of 3 552.31 hm^2 of land were transferred, with a change rate of 2.13%. According to the transfer situation, the transfer among cultivated land, woodland, construction land, and grassland was the most obvious, accounting for 97.98% of the total transformed area.

(2) The annual average values of landscape ecological risk index in 2010, 2013, 2016, and 2018 were 0.344 1, 0.485 2, 0.261 4, and 0.173 3, showing a trend of first increasing and then decreasing. The landscape ecological risk in the entire area was mainly low risk zone and lower risk zone, with an increase of 85 878 hm^2 in risk and a decrease of 105 462 hm^2 in risk. The overall ecological risk level has shifted from high to low, and the ecological environment of the study area has been gradually improved under external intervention.

(3) There was a negative correlation between ecological risk and terrain niche. From 2010 to 2018, only low ecological risk zone was distributed in the middle and high terrain intervals, while lower, low, medium, higher, and high risk zones were mainly distributed in the middle and low terrain intervals. Over time, the impact of terrain on landscape ecological risk gradually decreased, while the impact of human factors on landscape ecological risk became increasingly prominent.

References

[1] XUE L, ZHU B, WU Y, *et al.* Dynamic projection of ecological risk in the Manas River basin based on terrain gradients[J]. Sci. Total Environ., 2019, 653: 283-293.
[2] ZHANG H, ZHANG J, LV Z, *et al.* Spatio-temporal assessment of landscape ecological risk and associated drivers: A case study of the Yellow River basin in Inner Mongolia[J]. Land, 2023, 12: 1114.
[3] CHEN J, YANG Y, FENG Z, *et al.* Ecological risk assessment and prediction based on scale optimization: A case study of Nanning, a landscape garden city in China[J]. Remote Sens., 2023, 15: 1304.
[4] ZHANG J, ZHAO X, GUO J, *et al.* Spatio-temporal evolution and driving factors of landscape pattern in a typical hilly area in Southern China: A case study of Yujiang District, Jiangxi Province[J]. Forests, 2023, 14: 609.
[5] GAO YN, GAO JF, XU Y. Response of landscape ecological risk to land use change in level I aquatic eco-functional regions in Taihu Lake watershed[J]. Journal of Natural Resources, 2010, 25(7):1088-1096.
[6] CHEN XY, XIE GZ, ZHANG JP. Landscape ecological risk assessment of land use changes in the coastal area of Haikou City in the past 30 years [J]. Acta Ecologica Sinica, 2021, 41(3): 975-986.
[7] ZHANG B, LIU WB, ZHANG JH. Landscape ecological risk of the Sanjiang Plain based on land use change[J]. Territory & Natural Resources Study, 2021(2): 53-55.
[8] ZHANG YY, LV FT, MAI JK, *et al.* Analysis of landscape ecological risk evolution based on land use/cover change[J]. Geospatial Information, 2021, 19(9): 44-49, 157.
[9] WEI F, LIU J, XIA LH, *et al.* Landscape ecological risk assessment in Weibei dryland region of Shaanxi Province based on LUCC[J]. China En-

vironmental Science, 2022,42(4): 1963 – 1974.
[10] PENG J, DANG WX, LIU YX, *et al.* Review on landscape ecological risk assessment[J]. Acta Geographica Sinica, 2015, 70(4): 664 – 677.
[11] YANG F, JIN XB, LIU J, *et al.* Assessing landscape ecological risk in rapidly urbanized areas from the perspective of spatiotemporal dynamics [J]. Transactions of the Chinese Society of Agricultural Engineering, 2023, 39(18): 253 – 261.
[12] XU W, WANG J, ZHANG M, *et al.* Construction of landscape ecological network based on landscape ecological risk assessment in a large-scale opencast coal mine area[J]. Journal of Cleaner Production, 2021, 286: 125523.
[13] ZHANG Z, GONG J, PLAZA A, *et al.* Long-term assessment of ecological risk dynamics in Wuhan, China: Multi-perspective spatiotemporal variation analysis[J]. Environmental Impact Assessment Review, 2024, 105: 107372.
[14] WANG JL, CHEN CL, NI JP, *et al.* Resistance evaluation and "source – sink" risk spatial pattern of agricultural non-point source pollution in small catchment[J]. Transactions of the Chinese Society of Agricultural Engineering, 2018, 34(10): 216 – 224, 306.
[15] WANG X, SUN Y, LIU Q, *et al.* Construction and optimization of ecological network based on landscape ecological risk assessment: A case study in Jinan[J]. Land, 2023, 12: 743.
[16] LEUVEN RSEW, POUDEVIGNE I. Riverine landscape dynamics and ecological risk assessment: Riverine landscape dynamics[J]. Freshwater Biology, 2002, 47: 845 – 865.
[17] DU L, DONG C, KANG X, *et al.* Spatiotemporal evolution of land cover changes and landscape ecological risk assessment in the Yellow River basin, 2015 – 2020[J]. J. Environ. Manage., 2023, 332: 117149.
[18] LIANG T, DU P, YANG F, *et al.* Potential land-use conflicts in the urban center of Chongqing based on the "production – living – ecological space" perspective[J]. Land, 2022, 11: 1415.
[19] WU J, ZHU, Q, QIAO N, *et al.* Ecological risk assessment of coal mine area based on "source – sink" landscape theory: A case study of Pingshuo mining area[J]. J. Clean Prod., 2021, 295: 126371.
[20] CHEN XQ, DING ZY, YANG J, *et al.* Ecological risk assessment and driving force analysis of landscape in the compound mine-urban area of the northern Peixian County[J]. Chinese Journal of Ecology, 2022, 41 (9): 1796 – 1803.
[21] LI J, PU R, GONG H, *et al.* Evolution characteristics of landscape ecological risk patterns in coastal zones in Zhejiang Province, China[J]. Sustainability, 2017, 9: 584.
[22] YUAN BY, GAO JH, CHI Y, *et al.* Cross-scale spatiotemporal characteristics of landscape ecological conditions index in coastal zone of Jiangsu Province, China during 1990 – 2020[J]. Chinese Journal of Applied Ecology, 2022, 33(2): 489 – 499.
[23] ZHANG Y, ZHANG F, WANG J, *et al.* Analysis of the temporal and spatial dynamics of landscape patterns and hemeroby index of the Ebinur Lake Wetland Nature Reserve, Xinjiang over the last 40 years[J]. Acta Ecologica Sinica, 2017, 37(21): 7082 – 7097.
[24] WANG H, LIU X, ZHAO C, *et al.* Spatial-temporal pattern analysis of landscape ecological risk assessment based on land use/land cover change in Baishuijiang National Nature Reserve in Gansu Province, China[J]. Ecological Indicators, 2021, 124: 107454.
[25] ZHAO FF, SUN GL, JI XM, *et al.* Land landscape pattern and ecological risk analysis of Tianshan Grand Canyon National Forest Park[J]. Xinjiang Agricultural Sciences, 2022, 59(3): 735 – 743.
[26] LIU J, WANG M, YANG L. Assessing landscape ecological risk induced by land-use/cover change in a county in China: A GIS-and landscape-metric-based approach[J]. Sustainability, 2020, 12: 9037.
[27] HUANG J, HU Y, ZHENG F. Research on recognition and protection of ecological security patterns based on circuit theory: A case study of Jinan City[J]. Environ. Sci. Pollut. Res., 2020, 27: 12414 – 12427.
[28] WU L, ZHOU ZF, ZHANG L, *et al.* Response of landscape pattern change to habitat quality in karst area[J]. Environmental Science & Technology, 2023, 46(9): 206 – 217.
[29] LI C, ZHANG J, PHILBIN SP, *et al.* Evaluating the impact of highway construction projects on landscape ecological risks in high altitude plateaus[J]. Sci Rep, 2022, 12: 5170.
[30] JI Y, BAI Z, HUI J. Landscape ecological risk assessment based on LUCC: A case study of Chaoyang County, China[J]. Forests, 2021, 12: 1157.
[31] ZHANG XB, SHI PJ, LUO J, *et al.* The ecological risk assessment of arid inland river basin at the landscape scale: A case study on Shiyang River basin[J]. Journal of Natural Resources, 2014, 29(3): 410 – 419.
[32] JIN X, JIN Y, MAO X. Ecological risk assessment of cities on the Tibetan Plateau based on land use/land cover changes: Case study of Delingha City[J]. Ecological Indicators, 2019, 101: 185 – 191.
[33] ZHANG H, XUE L, WEI G, *et al.* Assessing vegetation dynamics and landscape ecological risk on the mainstream of Tarim River, China[J]. Water, 2020, 12: 2156.
[34] TAO C, ANMING B, HAO G, *et al.* Ecological vulnerability assessment for a transboundary basin in Central Asia and its spatiotemporal characteristics analysis: Taking Amu Darya River basin as an example[J]. Journal of Natural Resources, 2019, 34: 2643.
[35] ZHANG JC, GAO P, DONG XD, *et al.* Ecological vulnerability assessment of Qingdao coastal zone based on landscape pattern analysis[J]. Journal of Ecology and Rural Environment, 2021, 37(8): 1022 – 1030.
[36] XI SJ, CAI PL, AN YL. Spatio-temporal change and driving factors of integrated ecological risk of catchments in karst mountainous area of Guizhou Province from 2000 to 2018[J]. Journal of Ecology and Rural Environment, 2020, 36(9): 1106 – 1114.
[37] TONG X, WANG K, BRANDT M, *et al.* Assessing future vegetation trends and restoration prospects in the karst regions of southwest China [J]. Remote Sens., 2016, 8: 357.
[38] WANG X, WANG R. Terrain gradient effect of land use and its driving factors in the Qinghai – Tibet Plateau[J]. Pol. J. Environ. Stud., 2022, 31: 5299 – 5312.
[39] WANG JY, GUAN YH, WU XQ. Evolution of landscape ecological risk and its topographic differentiation in Karst Fault Basin[J]. Acta Ecologica Sinica, 2023, 43(19): 8167 – 8180.
[40] ZHANG XD, ZHAO ZP, ZHAO YX, *et al.* Landscape ecological risk assessment and ecological security pattern optimization construction in Yinchuan City[J]. Arid Land Geography, 2022, 45(5): 1626 – 1636.
[41] CHENG Y, GUAN YH, WU XQ. The spatial and temporal evolution of landscape pattern and landscape ecological security assessment in karst fault basin based on land use change[J]. Acta Ecologica Sinica, 2023, 43(22): 9471 – 9485.

(From page 15)

[10] HUANG YL, LIU C, ZENG KF, *et al.* Spatio-temporal distribution of $PM_{2.5}$ in Wuhan and its relationship with meteorological condition, 2013 – 2014[J]. Ecology and Environmental Sciences, 2015, 24 (8): 1330 – 1335.
[11] WU J, SUN ZB, ZHAI L, *et al.* Effects of different precipitation types on aerosol particles in Beijing[J]. China Environmental Science, 2018, 38(3): 812 – 821.
[12] ZHOU B, LIU DY, WEI JS, *et al.* A preliminary analysis on scavenging effect of precipitation on aerosol particles[J]. Resources and Environment in the Yangtze Basin, 2015, 24(Z1): 160 – 170.
[13] DUAN Y, WU ZP, ZHANG DH, *et al.* Wet scavenging effect of precipitation on $PM_{2.5}$ pollutant in Guiyang[J]. Meteorological Science and Technology, 2016, 44(3): 458 – 462.
[14] YU CX, DENG XL, SHI CE, *et al.* The scavenging effect of precipitation and wind on $PM_{2.5}$ and PM_{10}[J]. Acta Scientiae Circumstantiae, 2018, 38(12): 4620 – 4629.