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EVOLUTION CHARACTERISTICS OF LANDSCAPE ECOLOGICAL RISK PATTERNS IN SHANGLUO CITY IN THE QINLING MOUNTAINS, CHINA

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Highlights:
- in the case of a healthy ecological environment, the conditions in the mountainous area are still at the middle landscape ecological risk;
- during the development of mountainous cities, the increase in landscape ecological risk brought about by urbanization can be reduced by strengthening the protection of the environment;
- the analysis of regional landscape ecological risks based on both, administrative regions and watersheds, is more comprehensive for future urban planning.

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Abstract. Landscape ecological risk assessment (LERA) is the basis of regional landscape pattern optimization, and a tool that can help achieve a win-win situation between regional development and ecological protection. The landscape ecological risk (LER) of the southern end of the Qinling Mountains, China exhibited an increasing trend after the year 2000, but the degree of increase and the spatial and temporal dynamics were not clear, limiting the formulation and implementation of landscape optimization measures in the area. Here, we constructed a landscape pattern risk index ERI by combining data on landscape disturbance and landscape vulnerability from land use information for Shangluo City for years 2000, 2005, 2010, 2015, and 2020; then, we calculated a LER level and its spatial and temporal dynamics for Shangluo City for years 2000 to 2020. Moran's I and LISA indices were used to characterize the spatial correlation of ERI in Shangluo City. We found that Shangluo had a large proportion of medium-risk areas, and its LER shifted from medium-high, high in year 2000 to medium risk, medium-low and low risk in year 2020, and LER of Shangluo was clustered in space but the degree of clustering decreased in the past 20 years. We conclude that the development strategy of Shangluo should depend on providing a sustainably-developed environment.

Keywords: LERA, ERI index, spatial autocorrelation analysis, Shangluo, Qinling Mountains.

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1. Introduction

The landscape ecological risk (LER) describes the degree of the interaction between landscape patterns and ecological processes that may result in adverse consequences (Cao et al., 2019; Ran et al., 2022). Landscape ecological risk assessment (LERA) analyzes the impacts of internal risks and external disturbances on various landscape factors from the perspective of landscape patterns and ecological processes to reduce ecological pressures and risks (Kapustka et al., 2001; Leuven & Poudevigne, 2002; Liu et al., 2018). Advancement in urbanization increased the interference of human activities with nature and changed the distribution pattern of the urban landscape. However, increasing environmental awareness led to an increase in the number of urban green space patches reducing urban landscape fragmentation and improving landscape connectivity (Mondal et al., 2021). The often-conflicting needs of rapid urbanization and environmental protection need to be optimized; this can be achieved by analyzing urban LER changes and providing a scientific basis for optimization schemes of landscape patterns that promote urban development and ecological protection (Lin et al., 2021).

LERA often addresses a specific aspect of the environment. For example, Keshavarzi and Kumar (2020) conducted a potential LERA of heavy metals in agricultural soils in northeastern Iran (Keshavarzi & Kumar, 2020); Islam et al. (2017) based a LER on trace element pollution in river sediments in a mangrove forest in Bangladesh (Islam et al., 2017). The focus of pollutant LER is to reduce the concentration of pollutants, but the adverse consequences of land use activities associated with pollutant reduction may be far more severe than pollution; therefore, addressing LER requires the incorporation of landscape characteristics into the environmental management process (Kapustka et al., 2001).

Recent LER analyses involved more comprehensive evaluations with landscape knowledge. For example, Khoroshev (2020) proposed a LER evaluation framework that considered geographical characteristics, material flow, and dynamic processes in coniferous forest watersheds in Europe and Russia (Khoroshev, 2020); Peng et al. (2015) used risk probability and potential ecological loss in 58 watersheds in Liaoyuan, China to study potential ecological risks in mining cities (Peng et al., 2015); Zhang et al. (2020) used a landscape index to analyze the impact of urbanization on the ecosystems of 48 coastal cities in China from 1990 to 2015 (Zhang et al., 2020). LERA has a tendency to change from small-scale environmental assessment to larger and more complex scale analyses, making it more effective as an environmental management tool (Hope, 2006).

In large and more complex LERA studies, the spatiotemporal dynamics of land use and cover change (LUCC) are closely related to landscape processes and dynamic changes (Mohajane et al., 2018; Darvishi et al., 2020; Jin et al., 2021; Wang et al., 2021). Based on LUCC data, the landscape index method uses Geographic Information Systems (GIS) to calculate a regional LER index at a spatiotemporal scale and perform hierarchical quantification (Chan & Vu, 2017; Darvishi et al., 2020). This method can calculate the direct and cumulative effects of various risk factors in the landscape based on the structure and composition of the landscape pattern (Liu et al., 2020). The establishment of LER based on the landscape index method calculated from LUCC data can be based solely on the landscape pattern index (Zhang et al., 2020). Further, this method, used with environmentally-sensitive areas, can provide theoretical basis for promoting regional sustainable development and formulating environmental restoration policies (Leuven & Poudevigne, 2002). Because of its comprehensive approach, LERA is currently one of the most commonly used methods, especially for urban development (Qu et al.,2021; Zhang et al., 2022; Zhu et al., 2022).

The Qinling Mountains divide northern and southern parts of China and are an important ecological barrier regulating climate, maintaining soil and water, conserving water sources, and maintaining biodiversity (Wang et al., 2020). Shangluo is a representative city in southern Qinling Mountains, located in the southeastern part of Shaanxi Province, and Dan River in Shangluo is the main water source of the middle route of China's South-to-North Water Diversion (SNWD) Project (Zhou & Cao, 2020). Research showed that the LER was extremely high based on images of Landsat TM from 1984 to 2014 in the southeastern part of the Qinling Mountains, and with a tendency to increase (Cui et al., 2018). Also, the epicenter of LER in the Hanjiang River Basin and Daba Mountains in Shaanxi Province moved to the southeast during 1980 to 2017 (Liu et al., 2020). However, the change in LER in each basin of Shangluo City is not clear, and it is not clear whether LER in Shangluo City improved following a series of ecological protection efforts. Shangluo City is a growing urban area where ecological security may be at risk; however, Shangluo City is also a key pilot demonstration area for China's environmental construction, and the level of ecological civilization construction is gradually increasing due to the impact on resources and the environment (Yu et al., 2022). Therefore, understanding the spatiotemporal dynamics of LER in Shangluo City from 2000 to 2020 will provide data support for ecological security and sustainable development in the Qinling Mountains.

To address this need, we analyzed the temporal and spatial distribution of the LER in Shangluo based on LUCC data from 2000, 2005, 2010, 2015, 2020. We characterized spatial autocorrelation with the Moran's index of spatial autocorrelation (Moran's I) and the local spatial autocorrelation index for local indicators of spatial association (LISA). The objectives of this study were to 1) analyze the spatiotemporal dynamics of LUCC change in Shangluo from 2000 to 2020, 2) analyze the LER pattern of Shangluo, and 3) evaluate the dynamic LER through spatial autocorrelation analysis.

2. Materials and methods

2.1. Study area

Shangluo (108°34′-11101′E and 33°02′-34°24′N) is located in the southeastern Shaanxi Province at the southern edge of the Qinling Mountains (Figure 1). Shangluo is divided into six counties, including Zhashui, Zhenan, Shanyang, Luonan, Danfeng, and Shangnan, and the Shangzhou District. Shangluo spans the Yangtze and the Yellow Rivers, and is divided into six subwatersheds of the Xun, Qianyou, Jinqian, Tianqiao, Dan, and Luo Rivers. Shangluo City is the main water source of the Middle Route of SNWD in China (Zhou & Cao, 2020). In order to ensure the stability of water quality with the implementation of the Middle Route Project of SNWD after 2000, Shangluo City embarked upon extensive water pollution prevention and control, small watershed construction, terrace construction, and returning farmland to forest (Zhang et al., 2017). Recently, the demand for water has been increasing, and there is a risk of insufficient water production (Chen et al., 2022). To address the water supply versus demand dynamics, we analyzed the spatial differences in LER in different watersheds under the influence of environmental policies and whether the decrease in river water is related to the change in LER.

The climate of Shangluo is mainly a continental monsoon climate zone, with the transition from the warm temperate zone in the north to the subtropical zone in the souths; the average annual precipitation is 710–930 mm and the annual average temperature is 7.8–13.9 °C; the total length of sunshine ranges from 1860 to 2130 hours, and the frost-free period is 210 days (Bin, 2012). Shangluo

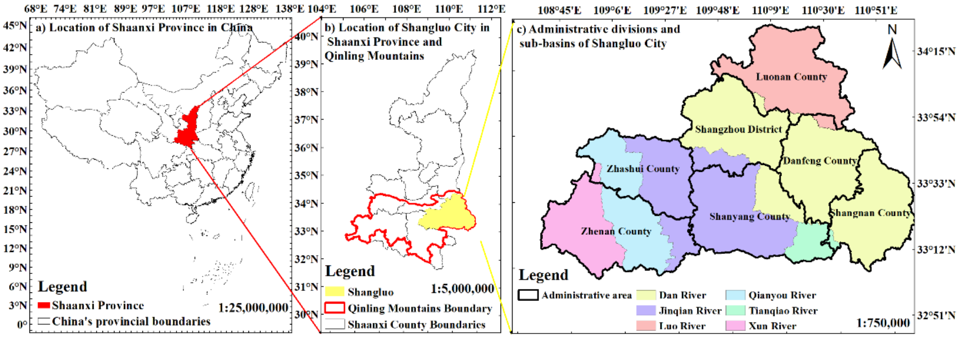

Figure 1. Location of Shangluo with its administrative divisions and subwatersheds

is a key forest area in Shaanxi Province, with forests in river valleys and basins composed mainly of *Populus tomentosa* Carr, and in the mountains of aerially-seeded *Pinus tabuliformis* Carr. Natural forests are broad-leaved and various pine forests; the production forests include mainly walnuts and chestnuts. Soils are mainly cinnamon, brown earth, and yellow brown earth (Yu et al., 2022).

2.2. Data sources

LUCC was interpreted from Landsat ETM (30-m resolution) remote sensing images for years 2000, 2005, 2010, and from OIL (30-m resolution) remote sensing images for years 2015, 2020. The data were acquired between June to September, covering the vegetation growing season, and with the smallest cloud cover <2%. We first performed radiometric calibration and FLAASH atmospheric correction of remote sensing data with ENVI 5.3 software (Environmental Sciences Research Institute, 2012). Then, we classified LUCC of Shangluo with the most commonly-used unsupervised method ISODATA. The overall interpretation accuracy of the field survey and a random sampling check of >90% was conducted by the Data Center of the Chinese Academy of Sciences (CAS) for the five periods. LUCC was classified into six categories: cropland, woodland, grassland, water, residential land, and unused land.

2.3. Data Analysis

2.3.1. Dynamics of LUCC change

LUCC changes in Shangluo were analyzed for years 2000, 2005, 2010, 2015, and 2020. The land-use data for different periods were used to determine the amount of change for each land-use. Also, for 2000 and 2020 of land-use data, overlay algebraic calculation was used to form land-use transfer matrices for Shangluo City to analyze the overall area change for different LUCC types in the past 20 years.

2.3.2. LER index

To determine heterogeneity of LER across the region (Zhang et al., 2020), the study area was divided into 3138 units of 2.5 km^2, which was sufficient to calculate changes in LER index and ensure the appropriate amount of calculation. We chose the commonly-used LER index (ERI), which takes into account the intensity of external disturbances and the internal vulnerability of each landscape type, and we combined this with data from the literature and landscape characteristics of the study area to calculate the landscape pattern risk dynamics in Shangluo City (Hunsaker et al., 1990; Li et al., 2017; Hua et al., 2018; Liu et al., 2020; Zhang et al., 2020). The higher the ERI value, the higher the LER.

The purpose of LER analysis is to assess the possibility of an ecosystem being adversely affected by human disturbance, and the risk probability depends on the resistance and the ability of the system to recover to an equilibrium state (Leuven & Poudevigne, 2002). Thus, we chose a landscape disturbance index (E_i) and a landscape vulnerability index (F_i) to construct ERI (Cui et al., 2018). The calculation Equation (1) is:

$$\mathrm{ERI} = \sum_{i=1}^{n} \frac{S_{ki}}{S_k} \sqrt{E_i \times F_i}, \tag{1}$$

where k is a basin unit; i is landscape type; n is the total number of landscape use types; S_{ki} is the area of landscape i in the k unit; S_k is the total area of unit k; E_i is the landscape disturbance index of landscape type i; and F_i is the landscape vulnerability index.

The construction of a landscape disturbance index (E_i) is based on the pattern analysis method in landscape ecology (Hua et al., 2018). The landscape fragmentation index (C_i), landscape separation index (N_i), and landscape fractal dimension index (D_i) were selected to measure the disturbance degree of the ecosystem represented by different landscapes, using the Equation (2):

$$E_i = aC_i + bNi + cD_i, \tag{2}$$

where a, b, c are the weights of C_i, N_i, D_i. We gave a, b, and c the weights of 0.5, 0.3, and 0.2, respectively, based on previous studies (Li et al., 2017). Detailed equations and descriptions of C_i, N_i, and D_i are shown in Table 1.

Based on the results of previous research, we calculated the landscape vulnerability index (F_i) according to the conditions of each landscape component in our study area. We assigned six vulnerability values to landscape types: unused land 6, water of 5, cropland of 4, grassland 3, woodland 2, and residential land 1 (Zhang et al., 2020).

Table 1. Calculation of the landscape index and its ecological meaning

Index	Symbol	Equation	Ecological meaning of index
Landscape fragmentation	C_i	$C_i = n_i / A_i$	Indicates the process of landscape types from a single continuous whole to complex discontinuous patches; the smaller the value, the higher the stability of the landscape (Li et al., 2022)
Landscape separation	N_i	$N_i = \frac{A}{2A_i}\sqrt{\frac{n_i}{A_i}}$	Represents the degree of separation between different patches in a landscape type; the larger the value, the higher the separation of landscape types (Liu et al., 2018)
Landscape fractal dimension	D_i	$D_i = \frac{2\ln(P_i / 4)}{\ln A_i}$	Value ranges from 1–2. The smaller the value, the simpler the shape of the landscape patch (Qu et al., 2021)

Note: In the equation, n_i is the number of patches of landscape type *i*; A_i is the area of landscape type *i*; *A* is the total area of landscape type; P_i is the perimeter of landscape type *i*.

In each unit, ERI was calculated and the value was assigned to the central pixel of the unit area. Then, spatial distribution of ERI in Shangluo was calculated by Kriging interpolation which is less disturbed by spatial elements compared with IDW interpolation.

We used the natural-breaks method (Xie et al., 2021) to divide ERI into five levels, including low risk (ERI < 0.150), medium low risk (0.150 ≤ ERI < 0.167), medium risk (0.167 ≤ ERI < 0.179), medium high risk (0.179 ≤ ERI < 0.188), and high risk (ERI ≥ 0.188). Finally, the ERI and its level were calculated for Shangluo, Shangluo's administrative districts, and Shangluo's subwatersheds at different times to analyze spatiotemporal dynamics of LER in Shangluo City.

2.3.3. The spatial autocorrelation method

Spatial autocorrelation reflects the degree of spatial correlation among risk variables (Liu et al., 2020). In this study, Moran's I index and LISA index were used to characterize the spatial relationships among ERI of the individual units.

Of these, Moran's I index characterizes the LER of the entire study area. The value of Moran's I index is [–1, 1], with Moran's I < 0 indicating a negative correlation and that the LER is discrete in space. Moran's I > 0 indicates a positive correlation and that the LER is clustered in space. When Moran's I = 0, there is no correlation, indicating that the LER is randomly distributed in space. The autocorrelation is stronger as the absolute value approaches 1. The LISA index defines the distribution of LER levels and helps with identification of spatial aggregation patterns of risk cold and hot spots.

Moran's I and LISA indices were calculated using the GeoDa software available at https://www.geoda.uiuc.edu/. The Equation (3) for Moran's I and Equation (4) for LISA (Li et al., 2022) are as follows:

$$\mathrm{I} = \frac{n \times \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij} \times (X_i - \bar{X})(X_j - \bar{X})}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij} \times \sum_{i=1}^{n}(X_i - \bar{X})^2}; \quad (3)$$

$$\mathrm{LISA} = \frac{n \times (X_i - \bar{X})}{\sum_i (X_i - \bar{X})^2} \sum_i W_{ij}(X_j - \bar{X}), \quad (4)$$

where W_{ij} represents the spatial connection matrix between spatial unit *i* and *j* with $i \neq j$; *n* is the total number of spatial units; X_i is the attribute value of the spatial unit *i*; X_j is the attribute value of spatial unit *j*; and $\bar{X}$ is the attribute average value of all spatial units.

3. Results

3.1. LUCC changes

The main LUCC type in Shangluo was grassland, which accounted for 40% of the area; the proportion of grassland did not change significantly in the past 20 years (Figure 2 and Figure 3). The proportion of woodland was about 35%, and it ranged from 35.68% in 2000 to 35.89% in 2010 and back to 35.75% in 2020. The proportion of cropland was more than 22%, and it exhibited a decreasing trend in the past 20 years. The proportion of residential land was <1%, with an increasing trend in the past 20 years. The proportion of the area of water was constant at 0.22% from 2000 to 2015, and increased to 0.25% in 2020. The area occupied by unused land was <0.05% during the period of study.

Except for cropland, the area of other LUCC types increased from 2000 to 2020 (Table 2). In that time period, 94.45% of the grassland area remained unchanged, although the total area of grassland increased by 22.2 km^2 and the increase was mainly from cropland (3.64%). Residential land increased by 43.68 km^2, and 32.19% of cropland and less than 5% of woodland and grassland were converted to residential land. However, residential land was also converted into grassland and woodland, accounting for 2.74% and 6.82%, respectively. The area of cropland decreased by 108.66 km^2, and it was mainly converted into grassland (6.46%) and woodland (3.84%). The area of the woodland increased by 34.22 km^2 which was mainly converted from grassland (2.44%) and cropland (2.28%). The water area increased by 6.43 km^2, and the increase was mainly contributed by grassland (5.78%) and cropland (15.56%). Unused land did not change significantly, and there was a conversion of <1 km^2 between residential land and grassland.

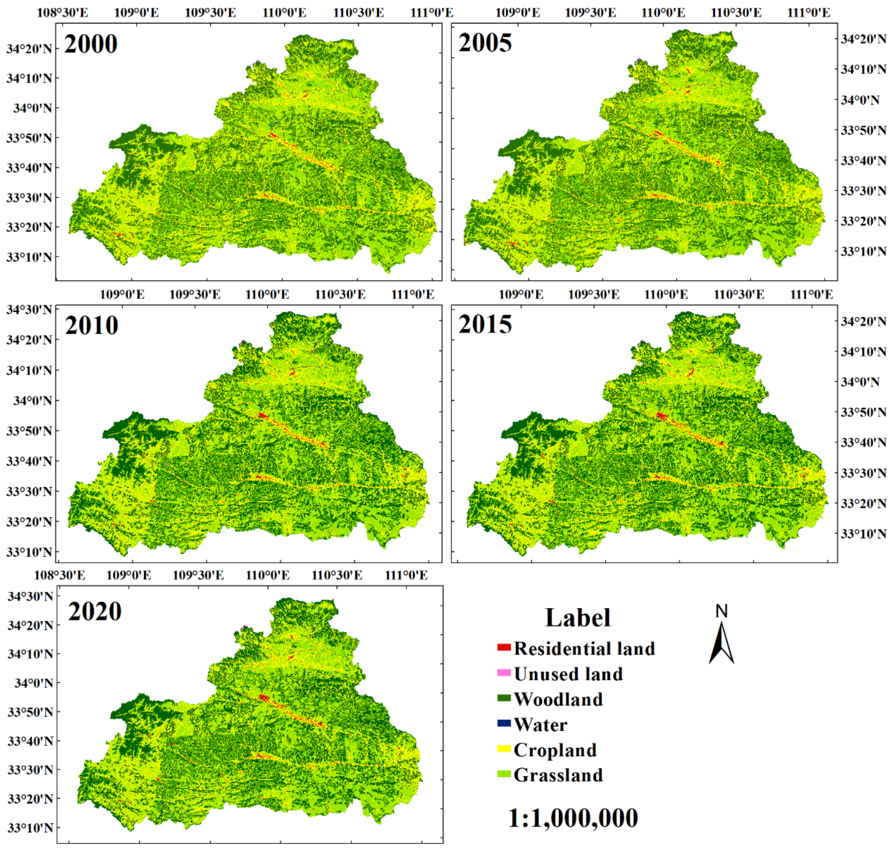

Figure 2. LUCC in Shangluo from 2000 to 2020

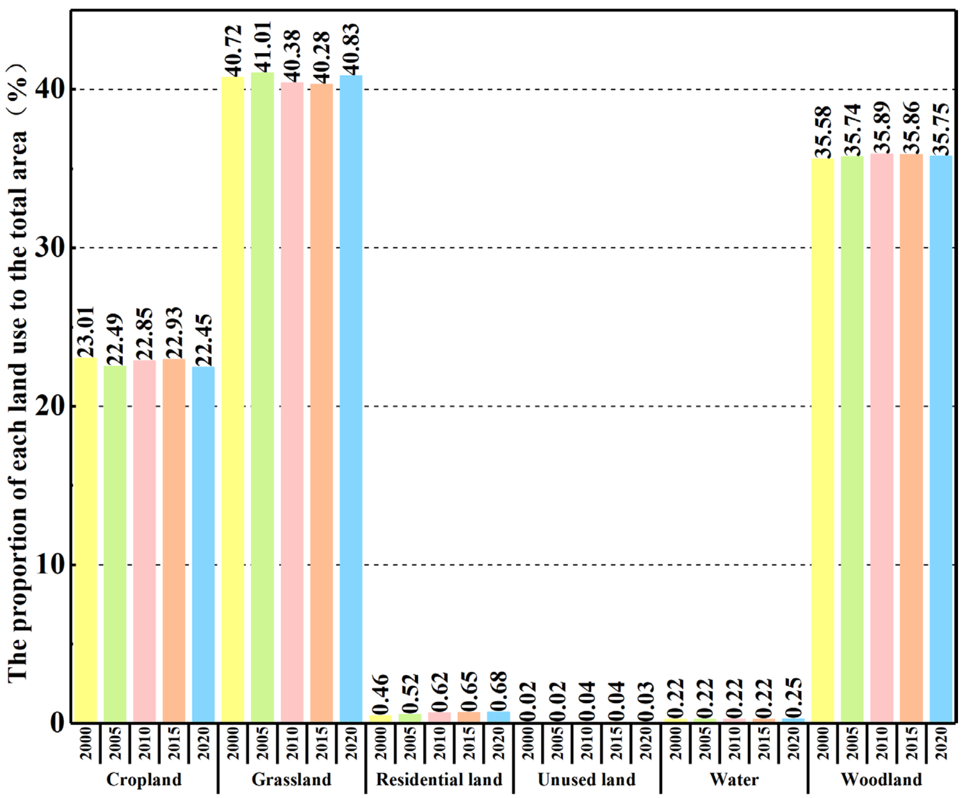

Figure 3. The area proportion of land types in Shangluo from 2000 to 2020

Table 2. LUCC transfer matrix for Shangluo from 2000–2020

LUCC types		Area of LUCC type in 2000/km^2						2020 total area
		Grassland	Cropland	Woodland	Residential land	Water	Unused land	
Area of LUCC type in 2020/km^2	Grassland	7532.90	290.93	170.09	1.88	1.96	0.01	7997.77
	Cropland	242.59	3990.73	159.08	2.48	2.45	0.01	4397.34
	Woodland	190.45	173.15	6632.20	6.17	0.63	0.12	7002.72
	Residential land	5.85	43.18	5.12	79.9	0.05	0.05	134.15
	Water	2.83	7.62	1.08	0.03	37.39	0.01	48.96
	Unused land	0.92	0.39	0.93	0.01	0.05	3.51	5.81
2000 total area		7975.54	4506.00	6968.50	90.47	42.53	3.71	

3.2. Spatiotemporal dynamics in LER

The LERA map of Shangluo was shown in Figure 4.

Low and medium low risk areas were mainly distributed along urban fringes, and low risk areas were close to medium low risk areas. The medium risk area was the most widely distributed, with its highest concentration in the east and the center of the area. The medium high risk areas were mainly in the northwest and southwest of the city. The high risk areas were mainly concentrated in the north (Luonan County, Shangzhou District), southwest (Zhen'an County) and southeast (Shanyang County) of the city, and the distribution in other parts was more scattered.

From the perspective of administrative divisions and subwatershed, the LER changes in Shangluo from 2000 to 2020 were shown in Table 3 and Table 4.

Areas with a higher average LER (exceeding 0.18) over the past 20 years were Luonan County, Shangzhou District, and Zhen'an County, while area with the lowest LER was Zhashui County. Low risk areas in Danfeng County, Shanyang County, and Shangzhou District accounted for less than 3% in each area, and 7.66% Zhashui County; in the past 20 years. The medium low risk areas in Shangzhou District were <3%, while in Zhashui County they were >14%. The medium risk areas in all regions exceeded 20%, reaching 54.31% in Danfeng

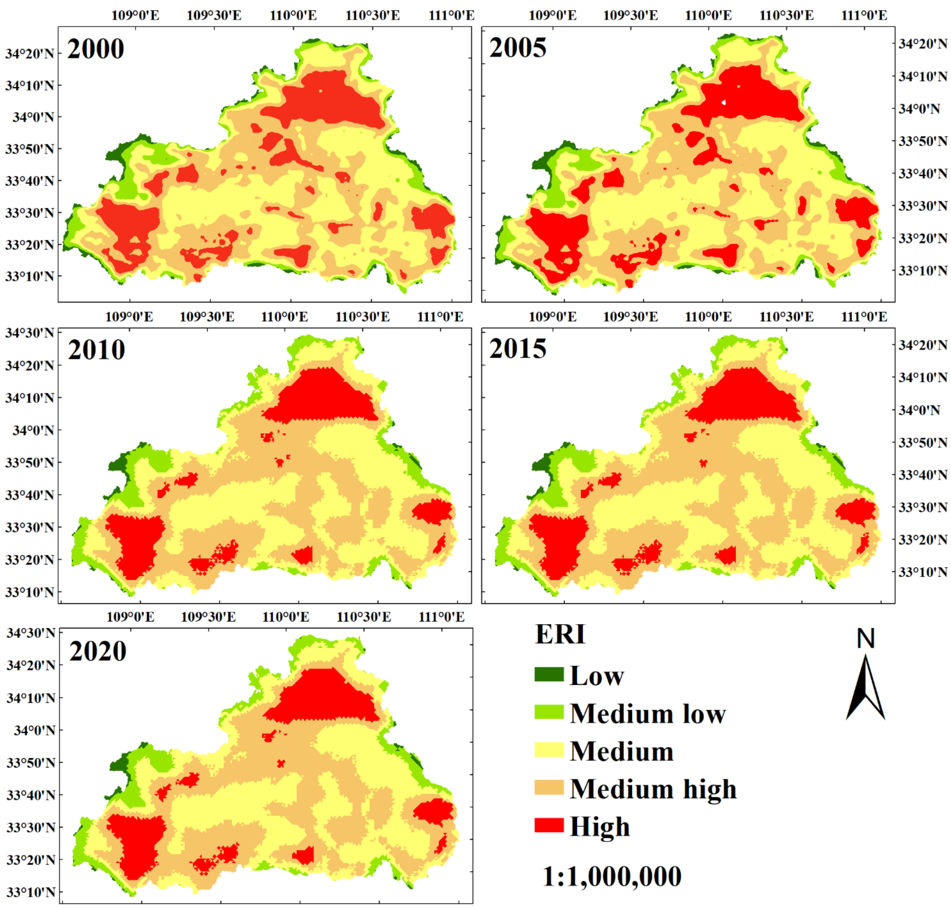

Figure 4. Changes in LER in Shangluo from 2000 to 2020

Table 3. Average ERI changes in different administrative districts of Shangluo from 2000 to 2020

Administrative division	2000	2005	2010	2015	2020	Average	Standard Deviation
Shangzhou District	0.1819	0.1812	0.1808	0.1807	0.1808	0.1811	0.0004
Zhashui County	0.1738	0.1737	0.1736	0.1737	0.1737	0.1737	0.0001
Zhenan County	0.1807	0.1808	0.1809	0.1809	0.1809	0.1808	0.0001
Shanyang County	0.1785	0.1784	0.1785	0.1785	0.1785	0.1785	0
Luonan County	0.1826	0.1826	0.1828	0.1829	0.1827	0.1827	0.0001
Danfeng County	0.1767	0.1766	0.1764	0.1765	0.1764	0.1765	0.0001
Shangnan County	0.179	0.1788	0.1786	0.1787	0.1788	0.1788	0.0001

Table 4. Average ERI changes in different subwatersheds in Shangluo from 2000 to 2020

Subwatershed	2000	2005	2010	2015	2020	Average	Standard Deviation
Xun River	0.1769	0.177	0.1773	0.1773	0.1772	0.1771	0.0002
Qianyou River	0.1774	0.1775	0.1773	0.1773	0.1776	0.1774	0.0001
Jinqian River	0.1789	0.1787	0.1788	0.1789	0.1788	0.1788	0.0001
Tianqiao River	0.1748	0.1749	0.1747	0.1747	0.1747	0.1748	0.0001
Dan River	0.1797	0.1794	0.1791	0.1792	0.1792	0.1793	0.0002
Luo River	0.1823	0.1822	0.1824	0.1825	0.1823	0.1823	0.0001

County. The medium high risk areas were <20% in Luonan County, and >40% in Shangzhou District. The high risk areas were <20% in Danfeng County, Zhashui County, and Shanyang County, and >45% in Luonan County. The high risk areas in Shangzhou District reached 24%.

The Luo River exhibited the highest ERI, exceeding 0.18, while the Tianqiao River Basin had the lowest. The proportion of low risk areas in each river basin did not change significantly, and that in Xun River was the largest at about 11%. Xun River had the largest area of medium low risk areas, accounting for about 12%. The Xun River area exhibited < 20% of the medium risk area while the Jinqian River had about 44%. Only Dan River exhibited > 30% of the medium high risk areas. The high risk areas in Luo River accounted for 46%, while those in Xun River, which accounted for 39%.

The changes of average risk and the percent distribution of different risk levels were shown in Figure 5. The average change in the LER index in Shangluo City was very small, at 0.01. This indicated a downward trend from 2000 to 2010, slightly increasing in 2015, and a return in 2020 to the LER level of 2010.

In general, the proportion of low and medium low risk areas in Shangluo was relatively low, at 5 and 7%, respectively; the proportion of medium risk areas was the highest at around 34%, and the medium high and high risk areas were about 27%. The area of low risk increased by 0.13% between 2000 and 2015, but it decreased by 0.06% in 2020. The medium lower risk zone increased by 0.25% between 2000 and 2010, decreased by 0.03% in 2015, and increased by 0.03% in 2020. The medium risk zone increased from 33.59% in 2000 to 34.29% in 2010, and decreased to 34.10% in 2020. The medium high risk area decreased from 27.95% in 2000 to 27.44% in 2010, but increased by 0.03% and 0.41% in 2015 and 2020, respectively. The proportion of high risk areas exhibited a decreasing trend, especially from 2000 to 2002, when it decreased by 0.57%, but it increased by 0.13% in 2015, and decreased by 0.32% in 2020.

Overall from 2000 to 2020, the proportion of low and medium low risk areas in Shangluo increased by 0.32%, and that of medium risk areas increased by 0.51%. Medium high risk and high risk areas decreased by 0.83%. Although the overall LER in Shangluo was decreasing, the degree and the rate of decrease were very slow.

According to Table 3, Table 4, Appendix (Table A1, Table A2), the ERI changes of different administrative regions and sub-basins were obtained.

The LER decreased significantly in Shangzhou District between 2000 and 2010, and it stabilized after 2010. In the past 20 years, low risk areas in Shangzhou District have increased the most. The medium low risk areas have been increasing from 2000 to 2020 in Zhashui. The medium risk areas increased significantly in Shangzhou District to about 5%. The medium high risk areas decreased by about 1% in the past 20 years in Shangzhou District. The high risk areas increased about 2% from 2000 to 2020 in Luonan County. The high risk areas in Shangzhou District decreased about 5% in 20 years. The proportion of low risk areas in each river basin did not change significantly. The proportion of medium low risk areas did not change significantly. The medium high risk area in Luo River declined by 1%. The high risk areas in Luo River increased by nearly 2% in the past 20 years, while those in Xun River increased in 20 years by about 1%. The high risk areas in Dan River Basin decreased by about 2%.

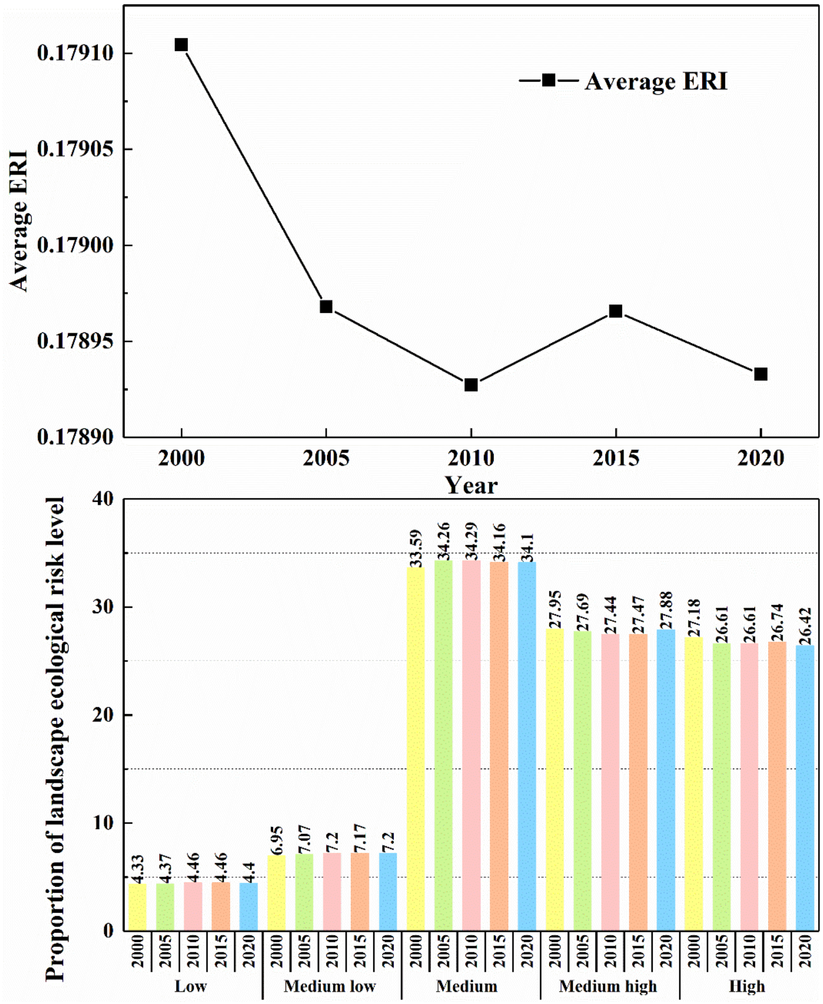

Figure 5. Change in the average value of LER and the proportion of LER level in Shangluo from 2000 to 2020

3.3. Spatial autocorrelation analysis

Moran's I of LER in Shangluo for 2000, 2005, 2010, 2015, and 2020 was 0.377, 0.374, 0.371, 0.369, and 0.368, respectively. Based on 999 random permutations, the expected value of Moran's I in all years was E(I) = – 0.0003. The Z value in 2000, 2005, 2010, 2015, and 2020 was 40.332, 40.114, 39.647, 39.558 and 39.242, respectively.

During the entire study period, Moran's I values were positives, and p-value were <0.001, indicating that the LER index for Shangluo exhibited significant positive spatial correlation. That is, LER in Shangluo affected each other in space. Moran's I index exhibited a downward trend over the 20 years. This indicated that, with changes in LUCC, the spatial aggregation of LER and the spatial differentiation were continuously decreasing.

The LISA aggregation map of LER in Shangluo is shown in Figure 6 and the result was significant at p-value≤0.05 level. The high-risk areas are mainly concentrated in the High-High level, that is, the LER level of these areas is high, and the LER level of adjacent areas is also high, indicating a strong spatial correlation. The low-risk and medium-low-risk areas are mainly concentrated in the Low-Low level, that is, the regional LER intensity is low, and the LER intensity of adjacent areas is also low, showing a spatial aggregation pattern. The medium risk area is located in the transition area between high-low and low-high level of LUCC changes. The Low-High level is scattered in the interior and at the edge of the High-High grade, indicating that there is a possibility of a further increase in LER in the high-risk area. The High-Low grade is sporadically distributed around the Low-Low grade, which means that low-risk areas and medium-low-risk areas may also undergo a further reduction in LER. During the study period, the area of High-High and Low-High grades decreased, and the spatial agglomeration decreased significantly. The number of high-low and low-high level changed steadily in the past 20 years.

4. Discussion

4.1. Characteristics of the LER

The one district and six counties in Shangluo that constituted the study area are located in the ecological protection planning zone for the water sources in the middle

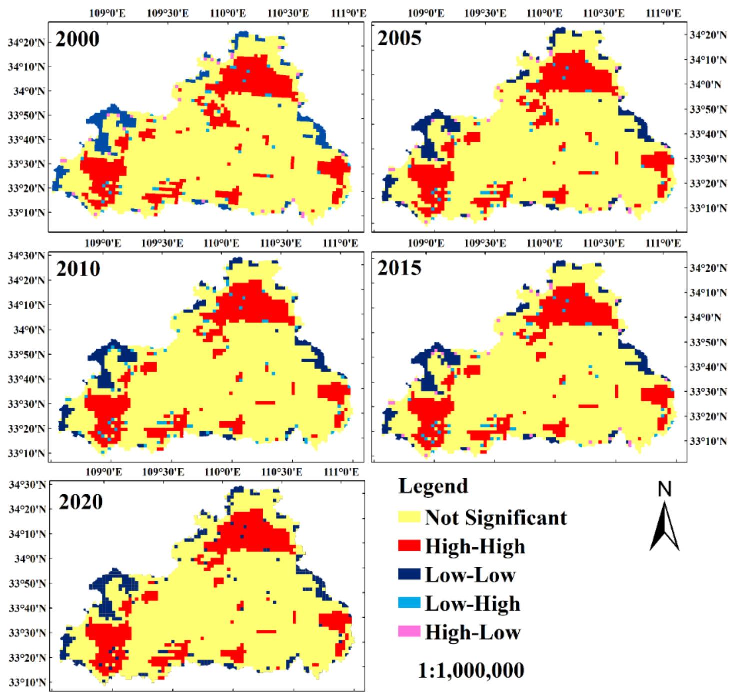

Figure 6. LISA aggregation map of LER in Shangluo from 2000 to 2020

route of the SNWD Project in China (Sun et al., 2012). Shangluo's level of urbanization, investment in land development, and the level of economic development are lowest among 10 cities in Shaanxi Province (Zhao et al., 2013). Thus, LUCC in Shangluo is mainly grassland and forest land. Urban construction land are at high risk, while forest and grass areas are at low risk (Xu et al., 2021). Yet ecological sensitivity of mountain areas is relatively high, with ecological resilience also high due to the high cover of vegetation; these characteristics result in low to medium levels of overall ecological vulnerability of mountain areas (Peng et al., 2015). Although Shangluo has a small population and slow economic development, its location in a mountainous area (Bin, 2012) raises its overall LER to a medium level.

LER assessment is an important means to characterize landscape ecological security; the higher the LER, the greater the vulnerability of and interference among important landscape units, the smaller the future benefits, and the smaller the threat to the sustainability of the landscape (Peng et al., 2015). For cities with weak economic foundation and urgent need for development, it is very important to balance protection of the ecological environment and development of economy (Li et al., 2017). Based on remote sensing and geographic information, it is feasible to evaluate the risk to an urban landscape pattern by using land use change data. Our research showed that the landscape ecological risks of mountain cities are not necessarily at a low level. Although vegetation cover in mountainous areas may be higher than that in the plains, the natural and semi-natural landscapes in the mountains may also form a high LER area (Liu et al., 2012). The hydrogeological environment in mountain areas such as the Shangzhou District is prone to natural disasters such as landslides, leading to high LER (Chen et al., 2016b). Shangluo's land area with incidence of soil erosion accounts for 66% of the total (Chen et al., 2022); therefore, understanding the changes in LER is a high priority for sustainable urban development.

4.2. Dynamics of the LER

Shangluo has slow economic growth and little impact on the environment (Bin, 2012); the rate of urbanization in Shangluo lagged behind the national average and the average level of Shaanxi Province in years 2016 to 2018 (Zhou & Cao, 2020). Shangluo has a high forest cover, with some forests protected under a forest protection policy; the managed and protected forest land totaled more than 1,600,000 hectares in 2006–2010 (Zhang, 2002), with little change in forest area between 2000 and 2019 (Wei et al., 2022). The slow change in LUCC led to a slow change in LER in Shangluo City. This is consistent with the findings for LER in Shaanxi Province which decreased by 0.78% between 1980 and 2017; the rate of change in LER in mountainous areas in Shaanxi Province was small (Liu et al., 2020).

Shangluo City's LER showed a slow downward trend. The process of urbanization increases the risk of disturbance to the ecosystem (Li et al., 2021); correspondingly, the high-risk areas of the region, such as the Shangzhou District, expanded. In the process of urban development, residential, agricultural, and roads types are also the main sources of high LER (Hayes & Landis, 2004). Species habitat is destroyed leading to a decrease in biodiversity and an increase in urban LER (Liu et al., 2018). Highway construction causes the destruction of vegetation and aggravates fragmentation of landscape (Li et al., 2022). Agglomeration of traffic lines resulting from urban expansion also increases the LER (Mann et al., 2021). At the same time, cultivated land occupied by construction land in the urban built-up area of Shangluo City has gradually evolved into a more stable large-scale landscape matrix, and the increase in vegetation cover in the built-up area increased the stability of the regional landscape and reduced the risk of landscape disturbance (Cui et al., 2021).

The increasing emphasis on environmental protection and ecological remediation helped increase the quality of the environment in Shangluo. The area of forested landscapes increased, and Shangluo City exhibited a tendency to a gradual decrease in landscape separation (Liu et al., 2013). In 2015–2020, the level of ecological construction increased in Shangluo City due to the influence of the resources and environmental levels (Chen et al., 2022). Further, during the conversion of farmland to forest, a large amount of cultivated and unused land was converted into grassland, greatly enhancing grassland patches and surrounding stable habitats, supporting restoration of regional habitats and effectively reducing LER (Zhang et al., 2016; Sun et al., 2012; Pan et al., 2019). Transfer of cultivated land to woodland and grassland enhances the stability of the ecosystem (Ji et al., 2021). Resource utilization efficiency of Shangluo showed an upward trend between 2015 and 2019 (Yu et al., 2022) but, due, to open-pit mining prior to 2005, forest resources were destroyed and landscape vulnerability increased; since 2005, the environment in the mining area improved and LER was slightly reduced (Cui et al., 2018). Based on the Bayesian network model, the LER assessment of forests in northeastern Oregon indicated that the most likely deterrence of LER change was the policy of forest management (Ayre & Landis, 2012). The protection and management of land can promote the protection of ecosystems and biodiversity (Cui et al., 2018).

In addition, in the past 20 years, Shangluo municipal government has carried out sufficient water source protection and water quality improvement project construction (Zhang et al., 2017). Water conservation capacity calculated by InVEST multi-year average water conservation model of Shangluo rivers follows the order of Xun > Qianyou > Jinqian > Dan > Luo rivers (Tianqiao River Basin in Shangluo is small in area, and not included) (Chen et al., 2016a). This is consistent with the ranking of LER in each watershed in this study, indicating that the stronger the water conservation capacity, the smaller the LER of the river landscape (Leuven & Poudevigne, 2002).

Since the start of the 21st century, China's land policy system has been continuously improving, and land planning in various cities has become more targeted than before, resulting in a decrease in the spatial correlation between landscape patterns and LER (Zhang et al., 2020). The LER in Shaanxi Province exhibited significant positive spatial correlation, but the degree of autocorrelation decreased for LER, and distribution gradually shifted from agglomeration to uniformity in 1980 to 2017 due to the evolution of LUCC types (Liu et al., 2020). The spatial autocorrelation of LER in Shangluo exhibited the same trend from 2000 to 2020, indicating that land-use changes were closely related to human activity, but the degree of this correlation is declining (Gong et al., 2021). In addition, the high risk areas of Shangluo were mainly concentrated in urban areas and were clustered together, indicating that LER had a spatial dependence (Karimian et al., 2022).

4.3. Suggestions for future development of Shangluo

The implementation of the Shangluo Water Source Land Utilization Project aided water pollution prevention and control efforts, small watershed construction, terraced-field construction, and returning farmland to forests. However, soil erosion control is still required on 2.32 million hectares, non-point source pollution still exists, and some development projects resulted in damage to the environment (Zhang et al., 2017). With population growth and economic development, Shangluo's LER tends to rebound, especially in areas with frequent human activities, including concentrated water sources, industrial parks, and mining areas (Yang et al., 2019). Therefore, the overall LER in Shangluo declined, with a rebound trend in 2015–2020.

The changes in LER of Shangluo City are mainly due to urbanization and environmental management policies. LER is also related to the changes in ecological environment of the river basin during the control measures of water quality of the river. An increase in urban green space area does not necessarily mean the reduction of urban LER; on the contrary, if the new urban green space is too fragmented, the shape of green space landscape will be more complex, and the edge effect of green space will increase the risk for urban landscape (Chan & Vu, 2017). Therefore, in the process of urban development in the mountains, it is necessary to optimize the urban space growth model, and reduce the division between landscape types caused by urban construction (Hua et al., 2018). In particular, the protection and reconstruction of vegetation during road construction and the connection of patches during urban construction. The most important thing to protect the ecological environment of river ecosystem is to prevent more than repair (Leuven & Poudevigne, 2002).

Landscape ecological risks in various watersheds in Shangluo exhibited clear differences. Future focus for the Xunhe and Ganyou Rivers, with strong water conservation capacity, is on maintaining the stability of vegetation structure and continuation of ecological engineering, while in the Qianjinhe and Danjiang River Basins, LUCC results should be optimized to further increase ecological LUCC. The Luo River exhibited the greatest LER; therefore the focus needs to be on the governance of the ecological environment and improvement of environmental protection policies.

Shangluo's development goal to build "China's Wellness Capital" is based on the beneficial climate, beautiful natural environment, and pollution-free agricultural products. At the 6th Silk Road International Expo held in Xi'an in August, 2022, Shangluo contracted a total of 240 projects with a total investment of 150.729 billion RMB (official news). The economic development of Shangluo is inseparable from the dividends brought on by the advantages of the ecological environment, so it is particularly important to stabilize environmental improvement resulting from the reduction of LER in the landscape. Construction in areas surrounding the city needs to take into account protection of natural and man-made landscape connectivity, and seek a model that coordinates economic development and ecological protection.

5. Conclusions

Based on risk probability and ecological loss, LERA helps regional risk management by identifying the spatial structure of city and directly guiding landscape planning and restoration. We analyzed the spatiotemporal dynamics of LER in Shangluo for years 2000 to 2020. Our results showed that the overall LER in Shangluo was at a moderate level, and LER and its spatial correlation have declined in years 2000–2020. Our research provides guidance for the development of mountainous cities with healthy natural environments but a poor economic foundation and slow development. Although the overall LER of Shangluo City has not changed significantly, the change observed was the result of a simultaneous increase in low-risk and high-risk areas. This indicates that, in the process of urbanization, LER can be controlled with an increase in the level of ecological construction. We did not analyze the quantitative impact of environmental protection policies on changes in landscape ecological risks in this study, and this is the direction we aim to address in subsequent research.

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Author contributions

Shu Fang and Minmin Zhao conceived and designed the experiments; Shu Fang performed the experiments, analyzed the data and wrote the paper. Pei Zhao and Yan Zhang provided a lot of scientific input in the revision process.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Ayre, K. K., & Landis, W. G. (2012). A Bayesian approach to landscape ecological risk assessment applied to the Upper Grande Ronde Watershed, Oregon. *Human and Ecological Risk Assessment: An International Journal*, *18*(5), 946–970. https://doi.org/10.1080/10807039.2012.707925

Bin, L. (2012). Spatial development explorations of middle-and small-sized mountainous cities: A Case study of Shangluo City, China. *Journal of Landscape Research*, *4*(12), Article 22. https://doi.org/10.16785/j.issn1943-989x.2012.12.008

Cao, Q., Zhang, X., Lei, D., Guo, L., Sun, X., & Wu, J. (2019). Multi-scenario simulation of landscape ecological risk probability to facilitate different decision-making preferences. *Journal of Cleaner Production*, *227*, 325–335. https://doi.org/10.1016/j.jclepro.2019.03.125

Chan, K. M., & Vu, T. T. (2017). A landscape ecological perspective of the impacts of urbanization on urban green spaces in the Klang Valley. *Applied Geography*, *85*, 89–100. https://doi.org/10.1016/j.apgeog.2017.06.002

Chen, J., Wang, Q., & Li, Q. (2022). A quantitative assessment on ecological compensation based on water resources value accounting: A case study of water Source area of the middle route of south-to-north water transfer project in China. *Frontiers in Environmental Science*, *10*, Article 854150. https://doi.org/10.3389/fenvs.2022.854150

Chen, S., Liu, K., Bao, Y., & Chen, H. (2016). Spatial pattern and influening factors of water convervation service function in Shangluo City [in Chinese with English abstract]. *Scientia Geographica Sinica*, *36*(10), 1546–1554. https://doi.org/10.13249/j.cnki.sgs.2016.10.012

Chen, W., Ding, X., Zhao, R., & Shi, S. (2016). Application of frequency ratio and weights of evidence models in landslide susceptibility mapping for the Shangzhou District of Shangluo City, China. *Environmental Earth Sciences*, *75*, 1–10. https://doi.org/10.1007/s12665-015-4829-1

Cui, L., Zhao, Y., Liu, J., Han, L., Ao, Y., & Yin, S. (2018). Landscape ecological risk assessment in Qinling Mountain. *Geological Journal*, *53*, 342–351. https://doi.org/10.1002/gj.3115

Cui, L., Zhao, Y., Liu, J., Wang, H., Han, L., Li, J., & Sun, Z. (2021). Vegetation coverage prediction for the Qinling Mountains using the CA–Markov model. *ISPRS International Journal of Geo-Information*, *10*(10), Article 679. https://doi.org/10.3390/ijgi10100679

Darvishi, A., Yousefi, M., & Marull, J. (2020). Modelling landscape ecological assessments of land use and cover change scenarios. Application to the Bojnourd Metropolitan Area (NE Iran). *Land Use Policy*, *99*, Article 105098. https://doi.org/10.1016/j.landusepol.2020.105098

Environmental Sciences Research Institute. (2012). http://www.esri.com/

Gong, J., Cao, E., Xie, Y., Xu, C., Li, H., & Yan, L. (2021). Integrating ecosystem services and landscape ecological risk into adaptive management: Insights from a western mountain-basin area, China. *Journal of Environmental Management*, *281*, Article 111817. https://doi.org/10.1016/j.jenvman.2020.111817

Hayes, E. H., & Landis, W. G. (2004). Regional ecological risk assessment of a near shore marine environment: Cherry Point, WA. *Human and Ecological Risk Assessment*, *10*(2), 299–325. https://doi.org/10.1080/10807030490438256

Hope, B. K. (2006). An examination of ecological risk assessment and management practices. *Environment International*, *32*(8), 983–995. https://doi.org/10.1016/j.envint.2006.06.005

Hua, L., Liao, J., Chen, H., Chen, D., & Shao, G. (2018). Assessment of ecological risks induced by land use and land cover changes in Xiamen City, China. *International Journal of Sustainable Development & World Ecology*, *25*(5), 439–447. https://doi.org/10.1080/13504509.2017.1415235

Hunsaker, C. T., Graham, R. L., Suter, G. W., O'Neill, R. V., Barnthouse, L. W., & Gardner, R. H. (1990). Assessing ecological risk on a regional scale. *Environmental Management*, *14*(3), 325–332. https://doi.org/10.1007/BF02394200

Islam, M., Al-Mamun, A., Hossain, F., Quraishi, S., Naher, K., Khan, R., & Nahid, F. (2017). Contamination and ecological risk assessment of trace elements in sediments of the rivers of Sundarban mangrove forest, Bangladesh. *Marine Pollution Bulletin*, *124*(1), 356–366. https://doi.org/10.1016/j.marpolbul.2017.07.059

Ji, Y., Bai, Z., & Hui, J. (2021). Landscape Ecological Risk Assessment Based on LUCC—A case study of Chaoyang County, China. *Forests*, *12*(9), Article 1157. https://doi.org/10.3390/f12091157

Jin, G., Chen, K., Liao, T., Zhang, L., & Najmuddin, O. (2021). Measuring ecosystem services based on government intentions for future land use in Hubei Province: Implications for sustainable landscape management. *Landscape Ecology*, *36*, 2025–2042. https://doi.org/10.1007/s10980-020-01116-3

Kapustka, L. A., Galbraith, H., Luxon, M., & Yocum, J. (2001). Using landscape ecology to focus ecological risk assessment and guide risk management decision-making. *Toxicology and Industrial Health*, *17*(5–10), 236–246. https://doi.org/10.1191/0748233701th121oa

Karimian, H., Zou, W., Chen, Y., Xia, J., & Wang, Z. (2022). Landscape ecological risk assessment and driving factor analysis in Dongjiang river watershed. *Chemosphere*, *307*, Article 135835. https://doi.org/10.1016/j.chemosphere.2022.135835

Keshavarzi, A., & Kumar, V. (2020). Spatial distribution and potential ecological risk assessment of heavy metals in agricultural soils of Northeastern Iran. *Geology, Ecology, and Landscapes*, *4*(2), 87–103. https://doi.org/10.1080/24749508.2019.1587588

Khoroshev, A. (2020). Landscape-ecological approach to spatial planning as a tool to minimize socio-ecological conflicts: Case study of agrolandscape in the Taiga Zone of Russia. *Land*, *9*(6), Article 192. https://doi.org/10.3390/land9060192

Leuven, R. S., & Poudevigne, I. (2002). Riverine landscape dynamics and ecological risk assessment. *Freshwater Biology*, *47*(4), 845–865. https://doi.org/10.1046/j.1365-2427.2002.00918.x

Li, C., Zhang, J., Philbin, S. P., Yang, X., Dong, Z., Hong, J., & Ballesteros-Pérez, P. (2022). Evaluating the impact of highway construction projects on landscape ecological risks in high altitude plateaus. *Scientific Reports*, *12*(1), Article 5170. https://doi.org/10.1038/s41598-022-08788-8

Li, J., Pu, R., Gong, H., Luo, X., Ye, M., & Feng, B. (2017). Evolution characteristics of landscape ecological risk patterns in coastal zones in Zhejiang Province, China. *Sustainability*, *9*(4), Article 584. https://doi.org/10.3390/su9040584

Li, X., Li, S., Zhang, Y., O'Connor, P. J., Zhang, L., & Yan, J. (2021). Landscape ecological risk assessment under multiple indicators. *Land*, *10*(7), Article 739. https://doi.org/10.3390/land10070739

Lin, D., Liu, F., Zhang, J., Hao, H., & Zhang, Q. (2021). Research progress on ecological risk assessment based on multifunctional landscape. *Journal of Resources and Ecology*, *12*(2), 260–267. https://doi.org/10.5814/j.issn.1674-764x.2021.02.012

Liu, D., Chen, H., Zhang, H., Geng, T., & Shi, Q. (2020). Spatiotemporal evolution of landscape ecological risk based on geomorphological regionalization during 1980–2017: A case study of Shaanxi Province, China. *Sustainability*, *12*(3), Article 941. https://doi.org/10.3390/su12030941

Liu, D., Qu, R., Zhao, C., Liu, A., & Deng, X. (2012). Landscape ecological risk assessment in Yellow River Delta. *Journal of Food, Agriculture and Environment*, *10*(2), 970–972. https://doi.org/10.1016/j.foodres.2011.12.018

Liu, Y. X., Ren, Z. Y., & Li, C. Y. (2013). Response of ecosystem services value to the landscape patterns change in the Qinling Mountains [in Chinese with English abstract]. *Journal of Arid Resources and Environment*, *27*(03), 109–114.

Liu, Y., Liu, Y., Li, J., Lu, W., Wei, X., & Sun, C. (2018). Evolution of landscape ecological risk at the optimal scale: A case study of the open coastal wetlands in Jiangsu, China. *International Journal of Environmental Research And Public Health*, *15*(8), Article 1691. https://doi.org/10.3390/ijerph15081691

Mann, D., Anees, M. M., Rankavat, S., & Joshi, P. K. (2021). Spatio-temporal variations in landscape ecological risk related to road network in the Central Himalaya. *Human and Ecological Risk Assessment: An International Journal*, *27*(2), 289–306. https://doi.org/10.1080/10807039.2019.1710693

Mohajane, M., Essahlaoui, A., Oudija, F., Hafyani, M. E., Hmaidi, A. E., Ouali, A. E., & Teodoro, A. C. (2018). Land use/land cover (LULC) using landsat data series (MSS, TM, ETM+ and OLI) in Azrou Forest, in the Central Middle Atlas of Morocco. *Environments, 5*(12), Article 131. https://doi.org/10.3390/environments5120131

Mondal, B., Sharma, P., Kundu, D., & Bansal, S. (2021). Spatio-temporal assessment of landscape ecological risk and associated drivers: A case study of Delhi. *Environment and Urbanization Asia*, *12*(1 Suppl.), S85–S106. https://doi.org/10.1177/09754253211007830

Pan, Y., Zhang, Y., & Wang, R. (2019). Study on the evaluation of ecological environment quality in Shangluo City [in Chinese with English abstract]. *Value Engineering*, (36), 22–24. https://doi.org/10.14018/j.cnki.cn13-1085/n.2019.36.010

Peng, J., Zong, M., Hu, Y. n., Liu, Y., & Wu, J. (2015). Assessing landscape ecological risk in a mining city: A case study in Liaoyuan City, China. *Sustainability*, *7*(7), 8312–8334. https://doi.org/10.3390/su7078312

Qu, Y., Zong, H., Su, D., Ping, Z., & Guan, M. (2021). Land use change and its impact on landscape ecological risk in typical areas of the Yellow River Basin in China. *International Journal of Environmental Research and Public Health*, *18*(21), Article 11301. https://doi.org/10.3390/ijerph182111301

Ran, P., Hu, S., Frazier, A. E., Qu, S., Yu, D., & Tong, L. (2022). Exploring changes in landscape ecological risk in the Yangtze River Economic Belt from a spatiotemporal perspective. *Ecological Indicators*, *137*, Article 108744. https://doi.org/10.1016/j.ecolind.2022.108744

Sun, P., Yang, H., & Liu, Q. (2012). Study on dynamic security of land ecology in water source area of South-to-North Water Diversion Project: A case study of Shangluo City, Shanxi Province [in Chinese with English abstract]. *Journal of Natural Resources*, (09), 1520–1530.

Wang, B., Xu, G., Li, P., Li, Z., Zhang, Y., Cheng, Y., & Zhang, J. (2020). Vegetation dynamics and their relationships with climatic factors in the Qinling Mountains of China. *Ecological Indicators*, *108*, Article 105719. https://doi.org/10.1016/j.ecolind.2019.105719

Wang, H., Liu, X., Zhao, C., Chang, Y., Liu, Y., & Zang, F. (2021). 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. *Ecological Indicators*, *124*, Article 107454. https://doi.org/10.1016/j.ecolind.2021.107454

Wei, X., Yang, J., Luo, P., Lin, L., Lin, K., & Guan, J. (2022). Assessment of the variation and influencing factors of vegetation NPP and carbon sink capacity under different natural conditions. *Ecological Indicators*, *138*, Article 108834. https://doi.org/10.1016/j.ecolind.2022.108834

Xie, H., Wen, J., Chen, Q., & Wu, Q. (2021). Evaluating the landscape ecological risk based on GIS: A case-study in the Poyang Lake region of China. *Land Degradation & Development*, *32*(9), 2762–2774. https://doi.org/10.1002/ldr.3951

Xu, W., Wang, J., Zhang, M., & Li, S. (2021). Construction of landscape ecological network based on landscape ecological risk assessment in a large-scale opencast coal mine area. *Journal of Cleaner Production*, *286*, Article 125523 https://doi.org/10.1016/j.jclepro.2020.125523

Yang, W., Zhao, P., Ma, Y., Ye, Y., & Li, M. (2019). Analysis of the characters of montanic urban spatial expansion and the influencing factors [in Chinese with English abstract]. *Journal of Gansu Sciences*, (06), 129–135.

Yu, X., Liu, Y., Zhang, Z., Xiong, Y., & Dang, M. (2022). Urban spatial structure features in Qinling mountain area based on ecological network analysis-case study of Shangluo City. *Alexandria Engineering Journal*, *61*(12), 12829–12845. https://doi.org/10.1016/j.aej.2022.06.049

Zhang, C. (2002). The nonpoint source pollution and the control countermeasures for the Hanjiang and Danjiang river basins in Shaanxi province [in Chinese with English abstract]. *Northwest Water Resources & Water Engineering*, (01), 18–25.

Zhang, W., Chang, W. J., Zhu, Z. C., & Hui, Z. (2020). Landscape ecological risk assessment of Chinese coastal cities based on land use change. *Applied Geography*, *117*, Article 102174. https://doi.org/10.1016/j.apgeog.2020.102174

Zhang, X., Yao, L., Luo, J., & Liang, W. (2022). Exploring changes in land use and landscape ecological risk in key regions of the belt and road initiative countries. *Land*, *11*(6), Article 940. https://doi.org/10.3390/land11060940

Zhang, Y., Li, Z., Li, P., & Qin, J. (2016). Environmental impact assessment of land use planning in the water source area of Shangluo [in Chinese with English abstract]. *Journal of Soil and Water Conservation*, *30*(04), 308–311+335. https://doi.org/10.13870/j.cnki.stbcxb.2016.04.051

Zhang, Y., Li, Z., Liu, J., & Li, P. (2017). Evaluation on sustainable development of Shangluo water resource area for the Middle Route of South-to-North Water Transfer Project [in Chinese with English abstract]. *Journal of Xi'an University of Technology*, *33*(02), 132–137. https://doi.org/10.19322/j.cnki.issn.1006-4710.2017.02.002

Zhao, M., Li, Q., Feng, J., Chen, L., & Li, H. (2013). Evaluation of the urban land intensive use and it's regional differences in Shaanxi province based on GIS. In F. Bian, Y. Xie, X. Cui, & Y. Zeng (Eds.), *Communications in Computer and Information Science: Vol. 399. Geo-Informatics in Resource Management and Sustainable Ecosystem* (pp. 435–444). Springer. https://doi.org/10.1007/978-3-642-41908-9_45

Zhou, J., & Cao, X. (2020). What is the policy improvement of China's land consolidation? Evidence from completed land consolidation projects in Shaanxi Province. *Land Use Policy*, *99*, Article 104847. https://doi.org/10.1016/j.landusepol.2020.104847

Zhu, Z., Mei, Z., Xu, X., Feng, Y., & Ren, G. (2022). Landscape ecological risk assessment based on land use change in the Yellow River Basin of Shaanxi, China. *International Journal of Environmental Research and Public Health*, *19*(15), Article 9547. https://doi.org/10.3390/ijerph192113945

Appendix

Table A1. LER changes in different administrative districts of Shangluo from 2000 to 2020

Administrative division	Landscape risk	2000	2005	2010	2015	2020	Average	Standard Deviation
Shangzhou District	Low risk	2.13	2.36	2.36	2.84	2.84	2.51	0.2853
	Medium low risk	3.77	4.25	4.71	4.48	4.48	4.34	0.3191
	Medium risk	23.58	27.12	29.01	28.77	28.77	27.45	2.0496
	Medium high risk	42.69	41.98	41.04	41.27	41.27	41.65	0.6085
	High risk	27.83	24.29	22.88	22.64	22.64	24.06	1.9845
Zhashui County	Low risk	7.66	7.66	7.92	7.65	7.39	7.66	0.1676
	Medium low risk	14.25	14.25	14.78	15.04	15.04	14.67	0.3574
	Medium risk	37.2	37.99	36.41	36.41	36.68	36.94	0.5999
	Medium high risk	24.27	24.01	24.8	24.54	25.59	24.64	0.5426
	High risk	16.62	16.09	16.09	16.36	15.3	16.09	0.4422
Zhenan County	Low risk	6.08	6.08	6.08	6.08	5.9	6.04	0.072
	Medium low risk	6.08	6.08	6.08	6.08	6.26	6.12	0.072
	Medium risk	20.57	20.93	21.29	21.29	20.21	20.86	0.4198
	Medium high risk	32.39	31.31	30.06	30.06	32.03	31.17	0.9708
	High risk	34.88	35.6	36.49	36.49	35.6	35.81	0.6128
Shanyang County	Low risk	2.13	2.13	2.31	2.31	2.13	2.2	0.0882
	Medium low risk	4.8	4.98	4.8	4.61	4.8	4.8	0.117
	Medium risk	47.42	47.6	47.42	47.25	46.71	47.28	0.3057
	Medium high risk	26.11	25.75	25.75	26.11	26.47	26.04	0.2694
	High risk	19.54	19.54	19.72	19.72	19.89	19.68	0.1315
Luonan County	Low risk	5.69	5.69	5.91	5.69	5.91	5.78	0.1078
	Medium low risk	7.22	7.22	6.56	6.56	6.78	6.87	0.2984
	Medium risk	21.01	21.01	21.01	21.01	21.01	21.01	0
	Medium high risk	19.26	19.26	18.82	18.16	17.94	18.69	0.5496
	High risk	46.82	46.82	47.7	48.58	48.36	47.66	0.7415
	Low risk	1.82	1.82	1.82	1.82	1.82	1.82	0
	Medium low risk	5.19	5.19	5.46	5.46	5.46	5.35	0.1323
	Medium risk	56.62	56.62	55.84	55.58	56.88	56.31	0.5042
	Medium high risk	24.42	24.94	25.71	25.97	25.45	25.3	0.5556
	High risk	11.95	11.43	11.17	11.17	10.39	11.22	0.5042
Danfeng County	Low risk	4.09	4.09	4.09	4.09	4.09	4.09	0
	Medium low risk	9.26	9.54	10.35	10.35	9.81	9.86	0.4348
	Medium risk	31.88	31.88	32.15	31.88	32.15	31.99	0.1323
	Medium high risk	25.61	26.16	25.89	26.16	25.89	25.94	0.2053
	High risk	29.16	28.33	27.52	27.52	28.06	28.12	0.6082

Note: The unit of the proportion of LER level is %.

Table A2. LER changes in different subwatersheds of Shangluo from 2000 to 2020

Subwatershed	Landscape risk	2000	2005	2010	2015	2020	Average	Standard Deviation
Xun River	Low risk	10.92	10.92	10.92	10.92	10.92	10.92	0
	Medium low risk	12.32	12.32	11.97	11.97	11.97	12.11	0.1715
	Medium risk	14.79	14.79	14.79	14.79	14.44	14.72	0.14
	Medium high risk	23.24	22.89	22.89	22.89	23.59	23.1	0.28
	High risk	38.73	39.08	39.43	39.43	39.08	39.15	0.2619
Qianyou River	Low risk	6.2	6.2	6.48	6.2	5.63	6.14	0.278
	Medium low risk	11.55	11.55	11.84	12.12	12.68	11.95	0.4228
	Medium risk	29.01	29.01	29.01	29.01	27.89	28.79	0.448
	Medium high risk	29.86	29.3	29.01	29.01	30.7	29.58	0.642
	High risk	23.38	23.94	23.66	23.66	23.1	23.55	0.2855
Jinqian River	Low risk	2.55	2.55	2.69	2.69	2.55	2.61	0.0686
	Medium low risk	3.77	3.9	4.03	3.9	3.9	3.9	0.0822
	Medium risk	43.55	44.89	44.22	44.22	43.82	44.14	0.4529
	Medium high risk	30.51	29.44	29.03	29.03	30.38	29.68	0.6452
	High risk	19.62	19.22	20.03	20.16	19.35	19.68	0.3679
Tianqiao River	Low risk	6.59	6.59	6.59	6.59	6.59	6.59	0
	Medium low risk	10.99	10.99	10.99	10.99	10.99	10.99	0
	Medium risk	37.36	37.36	38.46	38.46	38.46	38.02	0.5389
	Medium high risk	21.98	21.98	21.98	21.98	20.88	21.76	0.44
	High risk	23.08	23.08	21.98	21.98	23.08	22.64	0.5389
Dan River	Low risk	2.32	2.4	2.4	2.56	2.56	2.45	0.096
	Medium low risk	5.79	6.04	6.45	6.37	6.21	6.17	0.2372
	Medium risk	37.39	38.3	38.88	38.54	38.96	38.41	0.5644
	Medium high risk	30.77	31.02	30.76	31.02	30.85	30.88	0.1153
	High risk	23.73	22.24	21.51	21.51	21.42	22.08	0.8756
Luo River	Low risk	5.76	5.76	5.98	5.76	5.98	5.85	0.1078
	Medium low risk	7.54	7.54	7.1	7.1	7.32	7.32	0.1968
	Medium risk	21.95	21.95	21.51	21.51	21.73	21.73	0.1968
	Medium high risk	19.07	19.07	18.85	18.4	17.96	18.67	0.4311
	High risk	45.68	45.68	46.56	47.23	47.01	46.43	0.6509

Note: The unit of the proportion of LER level is %.