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Gridded Assessment of Ecological Vulnerability in Loess Hilly Region of Western Henan Province, China

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Abstract:

Based on meteorological, remote sensing, socio-economic data in 2000 and 2019 and PSR (Pressure-State-Response) evaluation model, an evaluation index system of ecological vulnerability in the loess hilly region of western Henan Province was constructed. Using spatial principal component analysis and spatial autocorrelation analysis, the ecological vulnerability of the study area was quantitatively evaluated with 2km×2km grid as the research scale, and the driving force of ecological vulnerability was determined by principal component load matrix analysis. The results show that: (1) The ecological environment in the Loess hilly region of western Henan showed a deteriorating trend from 2000 to 2019. (2) The vulnerability degree of the ecological environment in different counties was obviously different, and the vulnerability degree in the main city and suburbs was always at an extreme vulnerable level, while other regions showed different trends. (3) From 2000 to 2019, the ecological vulnerability had significant positive correlation and aggregation characteristics. The H-H clustering areas were mainly distributed in extreme vulnerable areas, while the L-L clustering areas are mainly related to negligible and light vulnerable areas. (4) The main driving factors of ecological vulnerability in the loess hilly region of western Henan are elevation, slope, terrain relief, degree of land use, annual mean precipitation, NDVI, annual mean temperature, land use type and urbanization rate.

Keywords: *Ecological vulnerability, Loess hilly region, Western Henan Province.*

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I. INTRODUCTION

With the global socio-economic development and intense human activities, ecological environment problems such as climate warming, sharp decline in biodiversity and soil erosion have become increasingly prominent, and ecological vulnerability has become a research hotspot in the sustainable development of human society [1]. Ecological vulnerability assessment is aimed at the ecological environment situation in a specific region, analyzing the change law of ecological vulnerability, and clarifying the change mechanism and driving factors of ecological vulnerability. The results can provide a basis for ecological environment protection and restoration. At present, scholars have used a variety of methods [2-5] to evaluate ecological vulnerability in different scales [6-9] and different geomorphic types [10-13]. But the current research also has some problems, such as short research time span, coarse granularity of evaluation units, incomplete coverage of typical case areas, relatively single evaluation index and so on.

In view of the deficiency of current research, this paper takes the high-density grid as the evaluation unit, and selects the Loess hilly region in the west of Henan Province as the research object. Because of the inherent characteristics of Loess, the ecological environment in the Loess hilly region is extremely vulnerable. In recent years, with the rapid development of regional economy, the city scale has been expanding, resulting in a series of ecological environment problems such as soil erosion, environmental pollution and land resource shortage [14]. This paper is based on the spatial remote sensing technology and the actual situation of the ecological environment in the study area. Taking multi-factors into consideration and using PSR (pressure-state-response) evaluation model, an evaluation system of ecological vulnerability in the Loess hilly region of western Henan was constructed by selecting 15 evaluation factors, and the spatial principal component analysis method was used, combined with the global Moran's I index and LISA cluster diagram. The ecological vulnerability in the study area from 2000 to 2019 was dynamically and quantitatively evaluated, and then the spatial and temporal distribution characteristics and driving forces of ecological vulnerability in the Loess hilly region of western Henan were revealed, which provided theoretical basis for ecological restoration in western Henan.

II. STUDY AREA

The study area is located in the hilly region of western Henan (110°21′-113°30′ E, 33°32′-35°11′ N, Fig 1), including Gongyi in Zhengzhou, Yanshi, Xigong, Jili, Laocheng, Chanhe, Mengjin, Yanshi, Luolong, Yichuan, Xinan, Jianxi, Yiyang in Luoyang, Hubin, Yima, Mianchi, Shanzhou and Lingbao in Sanmenxia. The loess hilly region of western Henan

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belongs to the transitional zone from Loess Plateau to Huang-Huai-Hai Plain. The lowest altitude is 85m, and the highest altitude is 2192m. This area belongs to temperate semi-humid and semi-arid climate, with annual average temperature of 14.6℃ and average precipitation of about 643.4mm. The main rivers are Luo River and Yi River, in Yanshi after merging into the Yellow River, and are the largest first-class tributaries in the lower middle reaches of the Yellow River. In the region, the topography is undulating and complex, with diverse land use types. The landform types mainly include mountains, hills and plains.

III. RESEARCH METHODS

3.1 Data Sources

Landsat remote sensing image data in 2000 and 2019 with resolution of 30m were selected as remote sensing data. Based on this data, land use type data was constructed by man-machine interpretation under ArcGIS and ENVI software platform. Meteorological data came from the China Meteorological Data Service Centre, including the average annual precipitation and average annual temperature data of western Henan in 2000 and 2019. The normalized difference vegetation index (NDVI) in 2000 and 2019 was synthesized from Landsat-NDVI data with resolution of 30m in the United States Geological Survey, and the socio-economic data came from Henan Statistical Yearbook, Zhengzhou Yearbook and Luoyang Yearbook in 2001 and 2020. Combined with the actual situation of western Henan and after repeated verification and testing, the study area was divided into 2km×2km grids in this paper so as to ensure the accuracy of data. Geometric registration and resampling were carried out on all data before evaluation and analysis. To refine the 15 evaluation indexes to the grid unit as much as possible, the data with partial missing spatial attributes in data processing were obtained indirectly by the data acquisition technology based on the existing research results (Fig 1).

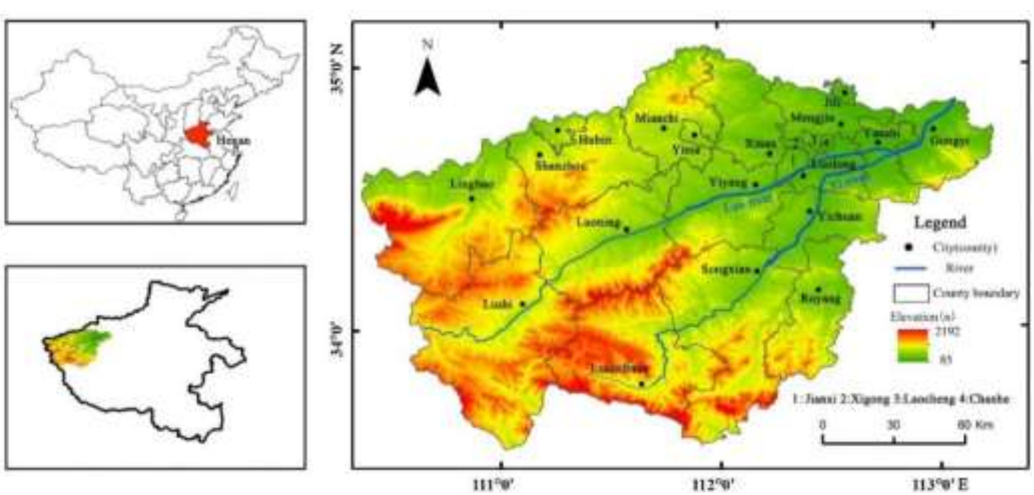

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Fig 1: The location and DEM of western Henan

3.2 Data Preprocessing

Topographic data: based on remote sensing data, the data of elevation, slope and topographic relief in the study area were obtained through ArcGIS 10.2 platform.

Landscape index data: the interpreted land use data calculated by using the software of Fragstats4.2 was taken as the object.

Data of land use degree: the land use degree comprehensively reflects the land use degree of a certain area [15], and the calculation method is shown in Formula (1):

$$\mathrm{L}_a = 100 \times \sum_{i=1}^{n} M_i \times B_i \tag{1}$$

La is the degree of land use; M_i is the grade *i* land use degree classification index; B_i is the area ratio of grade *i* land use degree classification.

Meteorological data: the annual average temperature and precipitation was based on the meteorological station data in the surrounding areas of the study area, and the inverse distance weighted interpolation method was used for spatial deterministic interpolation to realize data spatialization.

Socio-economic data: population density refers to the total population/area of each county and city; per capita cultivated land refers to the total cultivated land area/population of each evaluation unit; Per capita GDP refers to the regional GDP/total population of each county (city); urbanization rate refers to the urban land area/total area of each evaluation unit.

3.3 Evaluation Index System

Ecological vulnerability assessment is based on the construction of a scientific and reasonable index system, and the principles of scientificalness, dominance, operability and purposiveness should be followed in the accurate selection of evaluation factors affecting vulnerability. By referring to the relevant research results at home and abroad [16,17], Ecological Sensitivity-Ecological Recovery-Ecological Pressure Model (SRP) evaluation model was introduced to determine the index system is determined according to local conditions. Finally, five criteria layers were determined from the three target levels, including

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pressure, resilience and sensitivity, and 15 evaluation factors were selected to construct the evaluation index system of ecological vulnerability in western Henan. According to the impact on the ecological vulnerability of western Henan, the selected indexes were divided into positive and negative indexes, as shown in TABLE I.

TABLE I. Ecological vulnerability evaluation index system in western Henan.

TARGET LAYER	CRITERIA LAYER	INDICATOR LAYER	ATTRIBUTES
Ecological sensitivity	Terrain factor	Elevation/m	Forward
		Slope / (°)	Forward
		Terrain relief / (°)	Forward
	Surface factor	Landscape diversity	Negative
		Landscape fragmentation	Forward
		Land use type	Qualitative
	Meteorological factor	Annual mean temperature	Negative
		Annual mean precipitation/mm	Forward
Ecological recovery	Vegetation factor	Normalized difference vegetation index	Negative
Ecological pressure	Social factors	Population density (person/km^2)	Forward
		Per capita GDP (100,000/person)	Forward
		Per capita cultivated land (mu/person)	Negative
		Urbanization rate/%	Forward
		Degree of land use/%	Forward
		Proportion of the second industry/%	Forward

3.4 Standardization of Index Data

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Because of the different properties and dimensions of each evaluation index, this study adopted range method and hierarchical assignment method to standardize all indexes.

Range method: see formulas (2) and (3) for the calculation method:

Positive correlation:

$$V_{ij} = \frac{A_{ij} - A_{jmin}}{A_{jmax} - A_{jmin}} \times 10 \tag{2}$$

Negative correlation:

$$A_{ij} = \frac{A_{ij} - A_{jmin}}{A_{jmax} - A_{jmin}} \times 10 \tag{3}$$

V_{ij} is the result of standardization of indexes, with a range of 0~10, and A_{ij} is the index value of i index in evaluation unit *j*; A_{imin} is the minimum value of *i* index in all evaluation units, and A_{imax} is the maximum value of *i* index in all evaluation units

Graded assignment method: for qualitative indexes, according to the actual characteristics of land use in western Henan and combined with relevant research data [10], quantitative assignment was carried out according to the graded assignment method, as shown in TABLE II.

TABLE II. Standardized value assignment.

INDEX	GRADING INDEX				
	2	4	6	8	10
Land use type	Woodland, water body	Grassland and wetland	Farmland	Construction land	Bare land

3.5 Ecological Vulnerability Assessment Method

In this paper, the comprehensive index model of ecological vulnerability was constructed to quantitatively evaluate the ecological vulnerability in loess hilly region of western Henan. To shield the correlation, fuzziness and overlap among evaluation indexes, and determine the

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weight, the spatial principal component analysis (SPCA) was adopted, which could realize the reorganization and dimension reduction of evaluation data information, transform multiple variables into a few comprehensive indexes with extremely low correlation and determine the contribution rate of indexes on the premise of minimum loss of evaluation index information value. Supported by ArcGIS10.2 and IBM SPSS Statistics19.0, the spatial principal component analysis was used to analyze 15 evaluation indexes. According to the cumulative factor contribution rate of more than 80%, four principal component factors were determined (TABLE III). Based on the spatial principal component analysis, the ecological vulnerability index (EVI) was calculated. The model is as follows:

$$EVI = \beta_1 Y_1 + \beta_2 Y_2 + \beta_3 Y_3 + \cdots + \beta_n Y_n \quad (4)$$

EVI is the ecological vulnerability index of the evaluation unit of the study area; β_n is the nth principal component, and Y_n is the contribution rate corresponding to the nth principal component.

TABLE III. Eigenvalue, contribution rate and cumulative contribution rate of principal components.

YEAR	COEFFICIENTS OF PRINCIPAL COMPONENT	PRINCIPAL COMPONENT			
		1	2	3	4
2000	Eigenvalue λ /%	7.381	1.999	1.701	1.137
	Contribution /%	49.205	13.327	11.339	7.581
	Cumulative contribution /%	49.659	62.986	74.325	81.906
2019	Eigenvalue λ/%	7.778	1.999	1.355	1.107
	Contribution /%	51.852	13.325	9.035	7.378
	Cumulative contribution /%	51.852	65.177	74.212	81.590

3.6 Classification and Grading of Ecological Vulnerability

To fully grasp the ecological vulnerability of loess hilly region of western Henan, referring to the existing ecological vulnerability evaluation standards at home and abroad [2,18], and according to the specific characteristics of the western Henan, the ecological vulnerability of western Henan was divided into five grades by combining natural breakpoints with actual

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conditions, namely negligible, light, medium, strong and extreme vulnerability, as shown in TABLE IV.

TABLE IV. Classification standard and its ecological characteristics of ecological vulnerability.

VULNERABILITY LEVEL	LEVEL	STANDARDIZED VALUE OF ECOLOGICAL VULNERABILITY INDEX (S_{EVI})
Negligible	I	≤2.333
Light	II	2.333~3.914
Medium	III	3.914~5.331
Strong	IV	5.331~6.325
Extreme	V	>6.325

3.7 Comprehensive Index of Ecological Vulnerability

To facilitate the measurement and comparison of ecological vulnerability index, it needs to be standardized. The standardized calculation method is as follows:

$$S_{\mathrm{EVI}} = \frac{\mathrm{EVI} - \mathrm{EVI}_{min}}{\mathrm{EVI}_{max} - \mathrm{EVI}_{min}} \times 10 \quad (5)$$

S_{EVI} is the standardized value of ecological vulnerability index, with a value ranging from 0 to 10, EVI is the actual value of ecological vulnerability index; EVI_{max} is the maximum value of ecological vulnerability index of all evaluation units; EVI_{min} is the minimum value of ecological vulnerability index of all evaluation units.

3.8 Spatial Autocorrelation

Spatial autocorrelation analysis is to test whether a certain element is associated with its adjacent range and the degree of association. Global spatial autocorrelation can express the spatial dependence of an element in the whole range, while local spatial autocorrelation can express the similarity between a sampling unit and its neighboring units, which can directly reflect the spatial aggregation characteristics of an element. In this paper, global and local Moran's I index were selected. With the support of GeoDa software platform, and based on the grid scale, the spatial differences and agglomeration characteristics of the comprehensive index

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of ecological vulnerability in 2000 and 2019 were analyzed respectively. On the basis of calculating local Moran's I index, spatial clustering was carried out to obtain spatial LISA clustering diagram. Within the 95% confidence interval, the ecological vulnerability was further divided into five different types, See TABLE V for details:

TABLE V. The connotation of different LISA clustering models.

CLUSTERING TYPES	CONNOTATION
High-High (H-H)	The regional ecological vulnerability and the surrounding level are both high spatial agglomeration characteristics
High-Low (H-L)	The fragility of the ecological environment in the region itself is high, but the spatial agglomeration characteristics of the surrounding areas are low
Low-High (L-H)	The fragility of the regional ecological environment is low, but the surrounding areas have high spatial agglomeration characteristics
Low-Low (L-L)	Spatial agglomeration characteristics with low ecological vulnerability and low peripheral level in the region
No significant	There is no obvious spatial agglomeration feature

IV. RESULTS

4.1 Analysis on the Difference of Ecological Vulnerability in Western Henan

According to the results of assessment (TABLE VI, TABLE VII) and spatial distribution map (Fig 2) in western Henan from 2000 to 2019, the negligible, light and medium vulnerable areas in western Henan in 2000 accounted for 23.49%, 23.20% and 22.43 respectively. They were mainly concentrated in Luanchuan, Lushi, Songxian, Ruyang, south Lingbao, south Shanzhou and north Xinan in the middle and south of the study area. Strong and extreme vulnerable areas were relatively small, accounting for 14.98% and 15.90% of the study area, mainly distributed in the northeast and northwest in western Henan. These areas were cultivated land and urban center areas with high population density and strong influence of human activities. After 2000, with the gradual acceleration of urbanization in western Henan, the urban rate had been continuously improved. With the serious interference of human activities on the ecological environment, the ecological environment in the study area had further deteriorated. In 2019, the negligible, light and medium vulnerable areas accounted for 23.18%, 20.48% and 20.76% of the study area, respectively, which decreased slightly

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compared with 2000. Strong and extreme vulnerable areas accounted for 15.86% and 19.72% of the study area, respectively, which increased to a certain extent compared with 2000. On the whole, the extreme vulnerable areas were mainly distributed in the main urban area and its surrounding areas, the strong and medium vulnerable areas, were mainly distributed in the loess hilly areas. The light and medium vulnerable areas were distributed in the southern and northern mountainous areas. The ecological environment in loess hilly region of western Henan showed a deteriorating trend as a whole.

TABLE VI. The results of ecological vulnerability evaluation in western Henan from 2000 to 2019.

VULNERABILITY LEVEL	2000			2019		
	Grid	Area/km^2	Percentage of total area/%	Grid	Area/km^2	Percentage of total area
Negligible	1442	5768	23.20	1278	5112	20.48
Light	1466	5864	23.49	1447	5788	23.18
Medium	1400	5600	22.43	1296	5184	20.76
Strong	935	3740	14.98	990	3960	15.86
Extreme	997	3988	15.90	1229	4916	19.72
Total	6240	24960	100	6240	24960	100

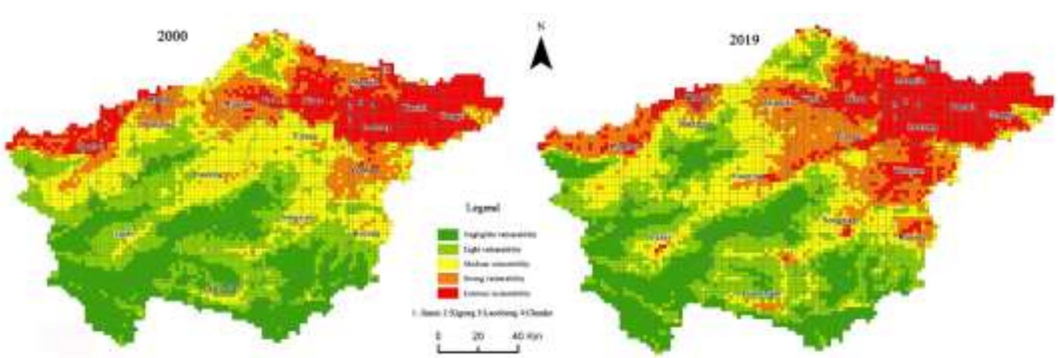

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Fig 2: Distribution of ecological Vulnerability Rating in western Henan from 2000 to 2019

From 2000 to 2019, the degree of vulnerability of ecological environment in different counties varies greatly. Xigong, Geely, Laocheng, Chanhe, Jianxi, Gongyi, Yima, Yanshi, Luolong, Xinan and Hubin, which are located in the main city and suburbs, have always been extreme vulnerable. However, Luanchuan, Songxian and Lushi, which are located in the southern mountainous areas, are always light and medium vulnerable areas. Other regions are changing in different directions. Yichuan and Mengjin, located in the Loess hilly area around the main city, changed from strong vulnerable area to extreme vulnerable area. Yiyang changed from medium vulnerable area to strong vulnerable area, and Ruyang changed from light vulnerable area to medium vulnerable area. It can be seen that with the gradual acceleration of urbanization and the intensification of human activities, the vulnerable degree of ecological environment in these areas is gradually deepening. In recent years, the vulnerable degree of ecological environment in Lingbao, Shanzhou and Mianchi, where large-scale projects of returning farmland to forests are carried out, tends to decrease. Among them, the extreme vulnerable areas in Lingbao and Mianchi decreased from 21.97% and 10.31% in 2000 to 8.29% and 7.25% in 2019, respectively.

To sum up, from 2000 to 2019, the ecological environment in the study area showed a deteriorating trend as a whole. The degree of vulnerability of ecological environment in different counties varies greatly, showing a trend of change in different directions.

TABLE VII. Assessment results of ecological vulnerability in different counties from 2000 to 2019/%.

COUNTY	MICRO DEGREE		LIGHT		MEDIUM		STRONG		EXTREME	
	2000	2019	2000	2019	2000	2019	2000	2019	2000	2019
Xigong	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	100.00
ChanHe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	100.00
Laocheng	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	100.00
JiLi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	100.00
Jianxi	0.00	0.00	0.00	0.00	8.70	2.17	6.52	4.35	84.78	93.48

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Hubin	0.00	0.00	0.00	0.00	0.00	0.00	44.00	8.00	56.00	92.00
Yanshi	0.00	0.00	0.00	0.00	4.44	5.56	8.33	5.00	87.22	89.44
Mengjin	0.00	0.00	0.00	0.00	2.33	0.78	59.69	17.05	37.98	82.17
Luolong	0.00	0.00	0.68	0.68	7.43	5.41	9.46	16.89	82.43	77.03
Gongyi	0.00	0.00	0.00	2.94	5.39	10.78	13.24	12.25	81.37	74.02
Yima	0.00	0.00	0.00	0.00	0.00	0.00	28.95	36.84	71.05	63.16
Xinan	0.00	0.63	5.66	7.23	16.35	10.06	30.50	32.39	47.48	49.69
Yichuan	0.00	0.00	1.32	0.00	23.25	6.14	71.05	48.25	4.39	45.61
Yiyang	3.41	1.42	19.03	10.51	69.89	20.45	7.39	57.95	0.28	9.66
Ruyang	26.71	11.64	27.74	34.25	36.99	18.15	8.56	27.05	0.00	8.90
Lingbao	0.92	13.82	26.11	26.27	30.11	28.88	20.89	22.73	21.97	8.29
MianChi	0.00	1.91	12.60	19.85	28.63	32.06	48.47	38.93	10.31	7.25
Shanzhou	0.00	9.66	21.26	21.26	32.37	43.48	41.79	18.36	4.59	7.25
songxian	49.01	38.21	31.14	28.91	18.73	25.93	1.12	5.83	0.00	1.12
LuoNing	27.26	25.70	27.26	19.31	42.37	40.81	3.12	13.08	0.00	1.09
Lushi	62.44	59.07	33.26	30.58	4.19	9.65	0.12	0.35	0.00	0.35
Luanchuan	41.71	21.12	51.13	60.91	6.98	13.44	0.17	4.36	0.00	0.17

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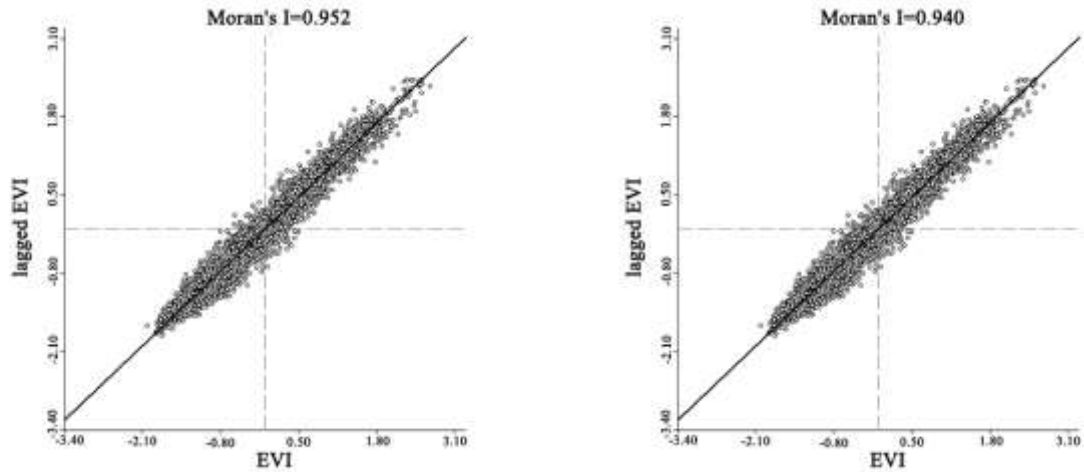

Fig 3: global Moran's I index in western Henan from 2000 to 2019

4.2 Spatial Agglomeration Characteristics

The global Moran's I index in 2000 and 2019 is 0.952 and 0.940, respectively, which shows that the ecological vulnerabilities in 2000 and 2019 have obvious spatial autocorrelation and positive correlation (Fig 3). From the LISA cluster diagram (Fig 4), the H-H clustering areas were distributed in extreme vulnerable areas in 2000, concentrated in the northeast and northwest of the study area; L-L clustering areas were distributed in negligible and light vulnerable areas, and concentrated in southern mountainous areas; by 2019, the H-H clustering areas further expanded from the city to the surrounding counties. Especially, the extreme vulnerable area around the main city increased greatly; it is closely related to the rapid expansion of construction land after 2000. The L-L clustering areas were mainly distributed in the southern mountainous areas. Therefore, from 2000 to 2019, the ecological vulnerability was characterized by significant aggregation. The H-H clustering areas were mainly distributed in extreme vulnerable areas, while the L-L aggregation areas were mainly related to negligible and light vulnerable areas.

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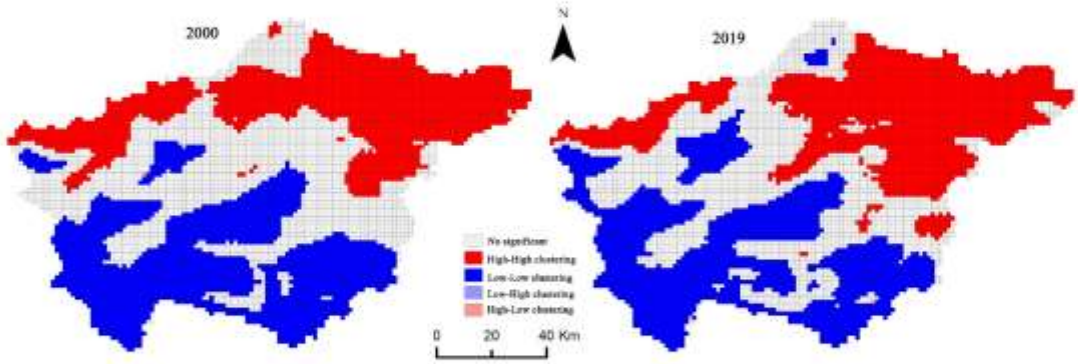

Fig 4: The LISA aggregation of ecological vulnerability in western Henan from 2000 to 2019

4.3 Driving Factors

By calculating the principal component load matrix, the information of many original indexes can be reflected in a few principal components, and the main indexes affecting the evaluation results can be highlighted. The closer the absolute value of load coefficient is to 1, the greater the impact of the driving factor on ecological vulnerability is. It can be seen from TABLE VIII and TABLE IX of calculation results that the first principal component in 2000 has a great correlation with elevation, slope, NDVI, annual mean temperature, terrain relief, degree of land use and land use type, with a contribution rate of 49.205%. These factors mainly reflect the topography, vegetation and climate of the study area, and can be regarded as the principal components of natural background. The 2nd, 3rd and 4th principal components have a great correlation with per capita cultivated land, proportion of the second industry, annual mean precipitation, per capita GDP and landscape diversity, representing the natural and socio-economic development respectively, with contribution rates of 13.327%, 11.339% and 7.581%, respectively.

TABLE VIII. Matrix of principal components in 2000.

EVALUATING INDICATORS	1	2	3	4
Elevation	-0.9041*	0.0681	0.1749	-0.0422
Slope	-0.9261*	0.1153	0.1244	0.1269
Normalized Difference vegetation index	0.8966*	-0.1494	-0.0397	-0.0226
Annual mean precipitation	-0.5889	0.2753	-0.6337*	0.1462
Annual mean temperature	-0.8717*	0.1132	0.2701	-0.0409
Population density	0.5507	0.5749	-0.1258	0.0979

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Degree of land use	0.9037*	0.0484	-0.0440	-0.2708
Land use type	0.9412*	-0.0094	-0.0226	-0.2006
Per capita cultivated land	-0.0003	0.6515*	-0.6187	0.3044
GDP per capita	0.3880	0.5025	0.6933*	0.1349
Landscape fragmentation	0.5377	-0.3689	-0.0420	0.5431
Landscape diversity	-0.3739	0.4061	-0.1039	-0.7032*
urbanization rate	0.5715	0.3433	-0.1872	-0.0920
Terrain relief	-0.8311*	0.1374	0.1090	0.1407
Proportion of the second industry	0.4385	0.6499*	0.4872	0.2097

* indicates the evaluation index with higher contribution rate among the principal components.

The first principal component in 2019 has great correlation with elevation, slope, NDVI, annual mean precipitation, annual mean temperature, terrain relief, degree of land use, Land use type and urbanization rate. The contribution rate reached 51.852%. Compared with 2000, the annual mean precipitation and urbanization rate were increased. Therefore, it is speculated that the ecological environment changes in the study area in recent years have great correlation with urbanization rate and annual mean precipitation. In 2019, the second, third and fourth principal components had great correlation with the per capita ratio of cultivated land, the per capita GDP and landscape diversity. Their contribution rates are 13.325%, 9.035% and 7.378%, respectively.

TABLE IX. Matrix of principal components in 2019.

EVALUATING INDICATORS	1	2	3	4
Elevation	-0.8888*	0.0646	0.0819	-0.0513
Slope	-0.8871*	0.1202	0.0977	0.0715
Normalized Difference vegetation index	0.9232*	-0.0237	-0.1208	-0.0562
Annual mean precipitation	-0.7921*	0.2560	-0.3083	0.2618
Annual mean temperature	-0.9137*	0.1167	0.0584	-0.0391
Population density	0.5451	0.5064	-0.2213	0.1903
Degree of land use	0.8981*	0.0434	-0.1656	-0.2005
Land use type	0.9366*	-0.0178	-0.1147	-0.1496
Per capita cultivated land	0.0781	0.6972*	-0.3084	0.5297
GDP per capita	0.4300	0.6656*	0.5313	0.0027
Landscape fragmentation	0.5158	-0.4112	0.2724	0.5416
Landscape diversity	-0.4646	0.4124	-0.3004	-0.5696
Urbanization rate	0.6471*	0.3225	-0.3013	-0.0258
Terrain relief	-0.8245*	0.1574	0.1083	0.0683

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Elevation	0.3660	0.4946	0.7014*	-0.1522

* indicates the evaluation index with higher contribution rate among the principal components.

V. CONCLUSIONS

From 2000 to 2019, the ecological environment in western Henan showed a deteriorating trend as a whole. Extreme vulnerable areas were mainly distributed in the main city and surrounding areas. Strong and medium vulnerable areas were mainly distributed in the loess hilly areas, and negligible and light vulnerable areas were distributed in southern and northern mountainous areas.

From 2000 to 2019, there are obvious differences in the degree of ecological vulnerability in different counties, with the highest degree of ecological vulnerability in the main city and suburban areas, which is always at an extremely vulnerable level. The degree of ecological vulnerability in the low-altitude Loess hilly areas around the northeast main city shows a trend of evolution from medium and strong vulnerability to strong and extreme vulnerability. With the implementation of the project of returning farmland to forest, the vulnerable degree of ecological environment in the loess hilly region in the west of the study area tends to decrease.

The ecological vulnerabilities from 2000 to 2019 have significant positive correlation and aggregation characteristics. The H-H clustering areas are mainly distributed in extreme vulnerable areas, while the L-L clustering areas are mainly related to negligible and light vulnerable areas.

The ecological vulnerability in western Henan is formed by natural and human factors, and its driving factors are mainly elevation, slope, terrain relief, degree of land use, annual mean precipitation, NDVI, annual mean temperature, land use type and urbanization rate. The ecological environment changes in the study area from 2000 to 2019 have great correlation with urbanization rate and annual mean precipitation.

Since 2000, with the rapid development of economy, the urbanization process in western Henan has been significantly accelerated, the overall vulnerability of the ecological environment in western Henan has shown a deteriorating trend. Affected by both natural and human activities, the vulnerability degree of low-altitude Loess hilly region in western Henan has changed obviously. Based on the grid micro-scale, this study selected the Loess hilly region in western Henan Province as the research object, and selected 15 indexes from natural background and human disturbance to build an ecological vulnerability evaluation system, trying to provide a theoretical basis for ecological construction and restoration in similar areas.

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