Study on the Spatial-temporal Differentiation and Driving Mechanism of Ecological Vulnerability in Zhangye City

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Abstract: Based on the "Sensitivity-Pressure-Resilience" evaluation model, combined with the spatial principal component (SPA) analysis method of GIS, we evaluated the ecological vulnerability of Zhangye City in 2000, 2005 and 2010, then we used geographical detector model to analyse the main driving factors of the ecological vulnerability. The results showed that: 1. The ecological vulnerability of Zhangye City was higher in the West and lower in the East. The average value of ecological vulnerability index was 0.45, which was mild fragile, ecological vulnerability index was the highest in Linze county, and the lowest in Minle county. 2. The overall ecological vulnerability showed a trend of improvement from 2000 to 2010, due to the increase of precipitation in 2005, the ecological vulnerability index was higher than that of 2000 and 2010. 3. Geographical detector results showed that six factors could explain the ecological vulnerability, which ranked as: rainfall in flood season (0.1138) > temperature in high temperature season (0.1116) > elevation (0.0581) > vegetation coverage (0.0532) > topographic relief (0.0411) > biological abundance index (0.0384), and the interaction of the 6 factors had a stronger explanatory power to the ecological vulnerability.

1. Introduction

Ecological vulnerability refers to the change of ecological environment under the pressure of various natural and human activities in a certain time and space, which is the inherent characteristic of the ecosystem [1]. When the adverse effects of human social activities and natural environmental factors exceeded the tolerance of ecological environment, the ecological environment vulnerability was appearing [2-4]. By assessing the vulnerability of the ecosystem, not only the vulnerable environment could be identified, but also the spatial distribution differences could be controlled, which brings significance to the sustainable development of the ecosystem. Scholars at home and abroad have done a lot of researches on the theories, methods and application fields of ecological vulnerability, and the assessment models include sensitivity-resilience-stress model, influence factor-performance factor-stress factor, natural cause index achievement index, and natural-ecological-social economic system analysis model [5-7]. The analysis methods include analytic hierarchy process (AHP), principal component analysis (PCA), and so on [8-10]. With the support of 3S technology, the spatial scale of ecological vulnerability assessment is continuously refined, and the assessment methods become more
diversified. Zhangye City is one of the sensitive area of ecological environment change, in recent years, series of ecological environmental threats have a great negative impact on the environment, so it is of great significance for ecological management of Zhangye City to carry out ecological vulnerability assessment on the grid scale.

2. Overview of the study area
Zhangye City, which located in the northwest of Gansu Province, The longitude is between $97^\circ 20' \sim 102^\circ 12' \ E$ and the latitude is between $37^\circ 28' \sim 39^\circ 57' \ N$. The longitude from east to west is 460 km, and the width from south to north is 180km, which is a long and narrow city, with a total area of 38592 $\text{km}^2$. From south to north, the areas can be divided into Qilian Mountain area, central corridor plain area and Heli mountain area. The climate type of Zhangye City is continental temperate climate, with the character of large temperature difference between day and night, long sunshine time and little rain.

3. Research methods

3.1. Data source and processing
The data of temperature and rainfall in high temperature season were processed by meteorological station data through inverse distance weighted (IWD) interpolation, data resource are from China Meteorological Data Network. Vegetation data was from MOD1301 250m, which obtained through NASA official website. The data of net primary productivity (NPP) of vegetation, spatial data of population and GDP, and remote sensing monitoring data of land use status were from the resource and environment science data center of Chinese Academy of Sciences. DEM data was from geospatial data cloud.

3.2. Methods and indexes

3.2.1 Indexes. Based on the characteristics of ecological environment of Zhangye City, the index system of ecological vulnerability was constructed by three aspects, which were the pressure, sensitivity and resilience of ecological system (Table 1).

| Target layer | Factor level | Indicator level | Index properties |
|--------------|--------------|-----------------|-----------------|
| Ecological vulnerability | Altitude | + |
| Ecological sensitivity | Topographic relief | + |
| | Vegetation coverage | - |
| | Rainfall in flood season | + |
| | Temperature in hot season | + |
| Ecological pressure | Landscape fragmentation | + |
| | Population density | + |
| | Primary net productivity of vegetation | - |
| Ecological resilience | Biological abundance degree | - |
| | Landscape dominance | - |
| | Economic density | - |

The range standardization method was used to standardize the positive and negative indicators, and the value of all indicators was $\in [0,1]$ through the process.

3.2.2 Spatial principal component (SPCA) analysis Method. With the support of ArcGIS software, the original spatial coordinate axis was rotated, and the original indexes were transformed into several comprehensive principal component indexes, so as to reduce data redundancy and preserve the original data information. The principal components were selected to replace the original indexes,
where the cumulative contribution rate was greater than 85%. The formula was as follows:

\[ PC_i = a_{1i}x_1 + a_{2i}x_2 + a_{3i}x_3 + \cdots + a_{ni}x_n \]  

(1)

Where, \( PC_i \) was the \( i \)th principal component,  \( a_{1i}, a_{2i} \ldots \) was the eigenvector corresponding to the \( i \)th principal component; \( x_1, x_2 \ldots \) was the index factor. In this paper, three principal components with cumulative contribution rate of more than 85% were selected to calculate the ecological vulnerability index (EVI).

3.2.3 Comprehensive index of Ecological Vulnerability. In order to compare the results of EVI, the value of EVI should be standardized, and the formula of comprehensive index of ecological vulnerability was:

\[ EVSI = \sum_{i=1}^{n} p_i \frac{A_i}{S} \]  

(2)

Where, \( EVSI \) was the comprehensive index of ecological vulnerability; \( P_i \) was the vulnerability level; \( A_i \) was the area of vulnerability level \( i \); \( S \) was the total area of the region; \( i \) refers to the type of vulnerability level. According to the existing classification standard of ecological vulnerability evaluation, the value of ecological vulnerability index of Zhangye City was classified by the method of equal interval classification \(^{[11]}\), and the ecological vulnerability of Zhangye City was divided into five grades: level I: potential vulnerability (\( EVSI < 0.2 \)), level II: micro vulnerability \( EVSI \in [0.2, 0.4] \), level III: mild vulnerability \( EVSI \in (0.4, 0.6] \), level IV: medium vulnerability \( EVSI \in (0.6, 0.8] \) and level V: severely vulnerability \( EVSI > 0.8 \).

3.2.4 Geodetector Model. Geodetector software can effectively judge the explanatory ability of each variable, factor detection and interactive detection were used to analysis the influencing factors of ecological vulnerability of Zhangye City. Factor detection was mainly used to analysis the driving situation of each influencing factor, the calculation formula was:

\[ P_{D,H} = 1 - \frac{1}{n\sigma_H^2} \sum_{h=1}^{L} n_h \sigma_h^2 \]  

(3)

Where, \( P_{D,H} \) was the explanatory power of influencing factor \( D \) to ecological vulnerability \( H \), \( P_{D,H} \in [0,1] \). The value of \( P_{D,H} \) was closer to 1, the stronger the explanatory power of the factor, \( n \) was the number of the study area; \( L \) was the classification number of factor, \( n_h \) was the sample size of \( h \), \( \sigma_H^2 \) was the variance of ecological vulnerability.

Interactive detection can determine whether the interaction of different driving factors can increase or decrease the explanatory power of analysis variables. Table 2 showed the detection type under the interaction of the two factors. Which can be judged whether the impact of the interaction of the factors on the ecological vulnerability of Zhangye City was enhanced or weakened.

| Type                                                                 | Interaction effect          |
|----------------------------------------------------------------------|-----------------------------|
| \( P(X_1 \cap X_2) < \min(p(X_1), p(X_2)) \)                        | Nonlinear weakening         |
| \( \min(X_1, X_2) < P(X_1 \cap X_2) < \max(p(X_1), p(X_2)) \)       | Unilinear weakening         |
| \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \)                        | Two factor enhancement      |
| \( P(X_1 \cap X_2) = p(X_1) + p(X_2) \)                             | Mutual independence         |
| \( P(X_1 \cap X_2) < \min(p(X_1), p(X_2)) \)                        | Nonlinear enhancement       |
4. Results and analysis

4.1. Spatiotemporal distribution characteristics of ecological vulnerability
Select three main components whose cumulative contribution rate were more than 85%, the result of principal component analysis was saw in Table 3.

Table 3. Characteristic value, contribution rate and cumulative contribution rate of each principal component

| Year | coefficient | principal component |
|------|-------------|---------------------|
|      |             | PC1     | PC2     | PC3     |
| 2000 | characteristic value λ | 0.123   | 0.038   | 0.017   |
|      | Contribution rate % | 60.133  | 18.965  | 8.302   |
|      | Cumulative contribution % | 60.133  | 79.099  | 87.402  |
| 2005 | characteristic value λ | 0.124   | 0.043   | 0.018   |
|      | Contribution rate % | 58.501  | 20.232  | 8.782   |
|      | Cumulative contribution % | 58.501  | 78.733  | 87.515  |
| 2010 | characteristic value λ | 0.123   | 0.040   | 0.015   |
|      | Contribution rate % | 59.177  | 19.352  | 7.575   |
|      | Cumulative contribution % | 59.177  | 78.529  | 86.105  |

According to table 3 and formula (2), the ecological vulnerability classification was carried out. The ecological vulnerability classification map of Zhangye City in 2000, 2005 and 2010 was shown in Figure 1:

The ecological vulnerability of Zhangye City was higher in the West and lower in the East, severely vulnerability area was mainly distributed in Sunan, which located in the Northwest of Zhangye, and medium vulnerability area was mainly distributed in Ganzhou, Gaotai and Linze County, mild vulnerability area was distributed in Shandan and Minle County, micro vulnerability area was distributed in the transition zone of mountain area and oasis area.
Figure 2. Histogram of minimum, maximum and average value of ecological vulnerability

According to the classification of ecological vulnerability (Table 4), we can see that there were 5 types of ecological vulnerability, among which the area of medium vulnerability was the largest, the proportion was 47.84%, 44.28%, and 40.09% in 2000, 2005 and 2010, respectively. The fallow rank was the mild vulnerability and micro vulnerability, and the proportion of severely vulnerability types was 8.64%, 11.25% and 4.79%, respectively. Generally speaking, the area of ecological vulnerable areas in Zhangye City increased or decreased in different degrees from 2000 to 2010. In general, the ecological vulnerability of different levels was changing with each other.

Table 4. Classification and the proportion of ecological vulnerability

| Classification | 2000/km² | Proportion/% | 2005/km² | Proportion/% | 2010/km² | Proportion/% |
|---------------|----------|-------------|----------|-------------|----------|-------------|
| potential     | 3329.75  | 8.70        | 1940.75  | 5.07        | 4899.75  | 12.80       |
| micro         | 6907.75  | 18.50       | 7912.75  | 20.67       | 6821.00  | 17.82       |
| mild          | 6422.25  | 16.78       | 7168.25  | 18.73       | 9383.25  | 24.51       |
| medium        | 18311.25 | 47.84       | 16950.00 | 44.28       | 15343.00 | 40.09       |
| severely      | 3308.00  | 8.64        | 4307.25  | 11.25       | 1832.00  | 4.79        |

The change of ecological vulnerability index showed that the difference value between 2010 and 2000 was 0.4707, the central, northeast and northwest regions of Zhangye City showed a trend of slight deterioration, while the southeast region of Zhangye City showed a negative growth trend, indicating that the habitat had been restored from 2000 to 2010, and the unchanging regions were scattered in Zhangye District.

4.2. The driving mechanism of ecological vulnerability

According to the results of principal component analysis, the main driving factors were basically the same. In this paper we selected six factors, including vegetation coverage (VC), elevation (E), topographic relief (TR), temperature in high temperature season (TH), rainfall in flood season (RF) and biological abundance degree (BD). Divided the grid of 2.5km×2.5km, taking the six factors as independent variable and the ecological vulnerability index as dependent variable, using geodetector to analysis the driving factors, the results was shown in Table 5.

Table 5. Single factor analysis of ecological vulnerability

| factors | RF     | E      | VC      | TH      | TR      | BD      |
|---------|--------|--------|---------|---------|---------|---------|
| q statistic | 0.1138 | 0.0581 | 0.0532  | 0.1116  | 0.0411  | 0.0384  |
| p value   | 0.0000 | 0.0000 | 0.0000  | 0.0000  | 0.0000  | 0.0000  |
The explanatory power of six factors ranked as follows: RF (0.1138) > TH (0.1116) > E (0.0581) > VC (0.0532) > TR (0.0411) > BD (0.0384). The rainfall in Zhangye City had the greatest impact on the ecological vulnerability, and then was the temperature in high temperature season, and then followed by the elevation. The topographic relief and the biological abundance degree had a small impact on the ecological vulnerability in Zhangye city. By comparing the driving factors from 2000 to 2010, it can be seen that the overall precipitation in Zhangye City was higher in 2005, which was obvious in Sunan, so the overall ecological vulnerability in 2005 was higher than that in other two years. By using the interaction detection, 15 pairs of factors were obtained (see in table 6) to analysis the driving mechanism of ecological vulnerability in Zhangye City.

Table 6. Interactive detection results of two factors

| X1∩X2       | P(X1∩X2) | Judgment criteria                          | interaction     |
|-------------|----------|--------------------------------------------|-----------------|
| RF (0.1138) ∩ TH (0.1116) | 0.1413   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| RF (0.1138) ∩ E (0.0581)   | 0.1403   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| RF (0.1138) ∩ VC (0.0532)  | 0.1338   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| RF (0.1138) ∩ TR (0.0411)  | 0.1563   | \( P(X_1 \cap X_2) > p(X_1) + p(X_2) \)   | Nonlinear enhancement |
| RF (0.1138) ∩ BD (0.0384)  | 0.1394   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| TH (0.1116) ∩ E (0.0581)   | 0.1466   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| TH (0.1116) ∩ VC (0.0532)  | 0.1248   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| TH (0.1116) ∩ TR (0.0411)  | 0.1255   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| TH (0.1116) ∩ BD (0.0384)  | 0.1311   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| E (0.0581)  ∩ VC (0.0532)  | 0.0935   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| E (0.0581)  ∩ TR (0.0411)  | 0.0999   | \( P(X_1 \cap X_2) > p(X_1) + p(X_2) \)   | Nonlinear enhancement |
| E (0.0581)  ∩ BD (0.0384)  | 0.0968   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| VC (0.0532) ∩ TR (0.0411)  | 0.0849   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| VC (0.0532) ∩ BD (0.0384)  | 0.0785   | \( P(X_1 \cap X_2) > \max(p(X_1), p(X_2)) \) | Two factor enhancement |
| TR (0.0411) ∩ BD (0.0384)  | 0.0842   | \( P(X_1 \cap X_2) > p(X_1) + p(X_2) \)   | Nonlinear enhancement |

The results of interactive detection showed that factors had interactive and synergistic effect, among which, rainfall in flood season and topographic relief, elevation and topographic relief, topographic relief and biological abundance degree were nonlinear enhancement, and the other two factors were two factor enhancement. As a single factor, rainfall in flood season had the highest explanatory power to the ecological vulnerability of Zhangye City, with the interaction of topographic relief, which become the strongest influence factor of ecological vulnerability. The interaction of
rainfall in flood season and temperature in high temperature season had great influence on the ecological vulnerability, which means that rainfall in flood season and temperature in high temperature season were the main driving factors of ecological vulnerability in Zhangye City.

5. Conclusion

11 indexes were selected to evaluate the ecological vulnerability of Zhangye City by using the spatial principal component analysis method, and the main driving factors of the ecological vulnerability were explored by using the geodetector software. The conclusions were as follows:

1. Spatially, the ecological vulnerability of Zhangye City showed a pattern of higher in the West and lower in the East. The ecological situation in the central region was better than the northwest and northeast. Timely, the change trend of ecological vulnerability in from 2000 to 2010 showed that the ecological environment of Zhangye City had been improved.

2. The ecological vulnerability level was between II and IV, among the five types of ecological vulnerability, the distribution area of the medium vulnerability was the largest, the area of mild vulnerability and the micro vulnerability were followed, and then was the severely vulnerability, which accounted for a small proportion of the ecological vulnerability. In general, ecological vulnerability was constantly changing in space.

3. The ecological vulnerability index of Zhangye City was between 0.12-0.77, with an average value of 0.45 for many years. The overall ecological environment of Zhangye City was mild vulnerability. The multi-year average value of the comprehensive index of ecological vulnerability was between 0.69 and 1.44, the value of Minle County was the lowest, and the highest was in Linze County.

4. The driving factors of ecological vulnerability of Zhangye City were analyzed by factor detection and interactive detection. The results showed that the ecological vulnerability were explained by rainfall in flood season and temperature in high temperature season, which showed that the two factors were the main driving factors of ecological vulnerability of Zhangye City.

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