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The Ecological Vulnerability Evaluation in Southwestern Mountain Region of China Based on GIS and AHP Method

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Abstract

The ecosystem seriously degraded in the southwestern mountain region of China is very vulnerable which has a great impact on regional sustainable development. In this paper, the ecological vulnerability index (EVI) including 13 factors is established synthetically reflecting ecological sensitivity (ES), natural and social pressure (NSP), and ecological recovery capacity (ERC) based on HPA method, and five grades for each factors is classified by expert consultation including potential grade, slight grade, light grade, medial grade and heavy grade. By the means of GIS spatial analysis, cluster analysis and spatial autocorrelation analysis, the regional ecological vulnerability is deeply analyzed in regional level, county level and in grade level. The conclusion is as follows. From the regional level, the ecological condition in southwest of China is relative stable reflected by area proportion of heavy and medial grade significantly less than the area proportion of potential, slight and light grade, which is accompanied by the heavy grade of ES, EP and EVI mainly concentrated in the east-southeast of whole region and four centers with high ecological recovery capacity. From county level, 152 counties are divided into two groups with centroid cluster method whose cluster level is determined by Cubic Clustering Criterion, Pseudo T-Squared Statistic, Semi-Partial R-Squared and Pseudo F Statistics. The first zone with high EVI locates in east-southeast region including 79 counties and the second one with forest, grassland, shrub as dominant land use type rules 73 counties in the west-northwest region where the disturbance from human activity is very scare. From grade scale, the clustering trend for EVI grades is apparent presented by global Moran' I about 0.6271 and the spatial adjacency is dominated by high-high and low-low relation significantly. From above, we can see that there exists the characteristics of regional division of ecological vulnerability in different level from west-northwest region to east-southeast region. So the study set a solid foundation for regional ecological restoration by applying research findings, which is obtained during the period National Key Technologies R & D Program of China during the 10th Five-Year Plan Period.

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Keywords: Ecological vulnerability evaluation; GIS; AHP; Cluster analysis; Autocorrelation analysis; South western mountain region of China

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1. Introduction

The study area about 818,330 km² locating in 25° 02'-35° 04' north latitude and 91° 18' -106° 20' east longitude, which is one of the most very high plateaus in the world (Feng 2009; Meybeck, 2001), involves 152 administrative counties belonging to Tibet Autonomous Region, Yunnan, Sichuan, Gansu and Qinghai province, the location of southwest mountainous region is showed in Fig.1. Because of dramatic difference in elevation, the region is characterized by large and deep valley where many rivers originate such as Jinsha River, Nu River and Lancang flowing from north to south, which greatly prevent human activity access to the region. In addition, the region concentrates abundant species and is the world-level gene bank and it is a key area for diversity protection in the world. So the region is selected as one of biodiversity hotspots for conservation priorities (Norma, 2000; Zhang, 2009) besides other ecological function including water resources conservation and the largest carbon sinks of China (Xu, 2008; Piao, 2009). The whole area plays very important role of ecological security barrier in the southwest, but economic condition in southwest of China is relative undeveloped with farmers on agriculture for a living because of the inconvenience of transportation system. When geological hazards such as landslide, rock-fall, mud-rock flow and earthquake occur, the life quality of local residents usually deteriorate which may lead to more pressure on limited land use resource, and soil erosion is a main ecological problem among all of the problems which is aggravated heavily by farmland reclamation activity in steep slope bigger than 25 degree. So it is difficult to break through the vicious cycle between poverty and ecological condition. From the view of land use type, the region is dominated by forest, so any pressure on forest will impact regional ecological vulnerability directly or indirectly. Forest fire is one important factor impacting the regional ecosystem. the forest ecosystem in our study region suffers heavily from fire seriously influencing stability of regional ecosystem according to the statistics of history fire events (Zhong, 2003). Though many research results have indicated that the impact of fire on forest ecosystem can be summarized as advantageous and disadvantageous aspects, more and more evidences show that increased fire activity has been observed due to climate change, which may reduce regional primary productivity and intensify soil erosion degree (Mike, 2008; Taylor, 2008). So in the paper forest fire factor is regarded as one pressure on ecological vulnerability. Acid rain is another important factor influencing the ecological vulnerability of regional ecosystem dominated by forest ecosystems (Rolf, 2007; Gene, 2009). The southwest region is adjacent to the center seriously polluted by acid rain, acid deposition not only directly interfere with normal plant growth resulting in contiguous forest death, but lead to soil acidification with soil fertility declined, pests resistance and other natural disasters weakened (Thorjorn, 2006). Besides acid rain and forest fire, human unsustainable economic activity has seriously impact on regional ecosystem such as excessive logging, unordered mining, over grazing and unplanned land use processing.

Because of the importance of ecological function, main ecological problems in the southwest mountainous region of China, social and natural pressure above-mentioned, the ecological vulnerability is placed an important position during process of regional economic development and national plan for ecological vulnerability zone protection has been made for future ecosystem restoration. In this paper, we fully considered various factors related to main ecological problem from ecological sensitivity, regional pressure, and ecological recovery aspects to carry out ecological vulnerability evaluation from multiple levels.

2. Data and Methodology

2.1. Data Acquisition and Processing

Slope data is derived from SRTM with resolution of 90 meters provided by Consortium for Spatial Information Consultative Group for International Agriculture Research (CGIARCSI). Vegetation type classification from SPOT-VGT in 2000 is acquired from the Joint Research Centre (JRC), which was compiled by the Institute of Remote Sensing Application, Chinese Academy of Sciences. The monthly precipitation data set provided by China Meteorological Administration (CMA) is derived from 726 meteorological stations by spatial interpretation method. The monthly vegetation coverage with 250 meters spatial resolution is acquired by maximum value composite method (MVC) which is from MODIS NDVI time series datum. The PH value of acid rain is interpreted from 87 meteorological stations in China and the annually average value in south western mountain region is extracted by

mask method to reflect the relative spatial distribution of acid deposition. The spatial datum of human population density and gross domestic product data are directly downloaded from Data-Sharing Network of Earth System Science of China (referred to as GEODATA), where the datum of occurred landslide and earthquake event records in history are also acquired and analyzed by spatial density analysis method. The potential rate of exposed carbonate rocks is classified according to geological map of China with 1:2,500,000 from Land Resource Science Data Sharing Center of China. The steep slope reclamation rate is extracted by overlaying 1:100,000 farmland percentage data with slope data more than 25 degree. The fire disaster event density from MODIS active fire data during the past ten years is provided by the Fire Information for Resource Management System (FIRMS), which is calculated by spatial density analysis in GIS. The annually Net Primary Productivity is estimated by a revised light use efficiency model (Zhu et al., 2006; Zhu et al., 2007).

Data processing including spatial interpretation, density analysis, spatial reference transformation are completed with ESRI ArcGIS 9.3 and all the dataset are transformed into Albers Conical Equal Area projection with spatial resolution of one kilometers in ESRI grid format. All the data sets used in the study area are showed in Table 1.

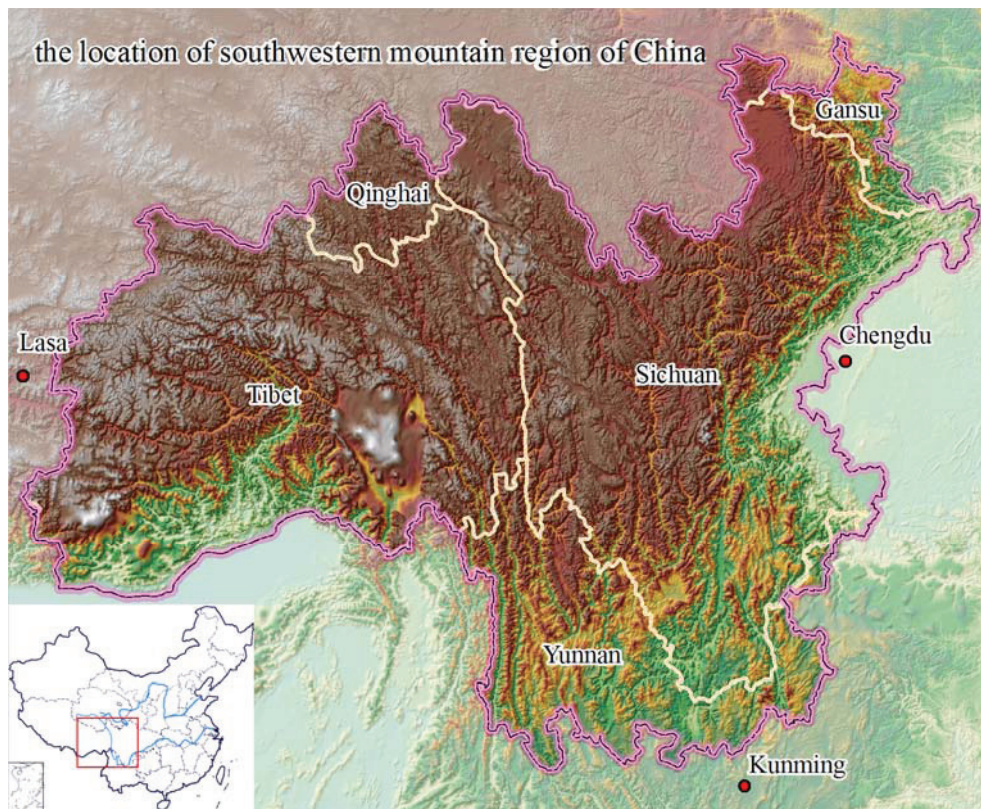


Fig 1. the location of southwestern mountain region of China.

2.2. Method of Solution

- Establishment of Ecological Vulnerability Index System

It is an important task to establish the index system to reflect regional ecosystem vulnerability condition, which is closely related to ecosystem service. According to the ecological vulnerability definition and regional main ecological problem, in this paper, the evaluation indicator system presented as Ecological Vulnerability Index (EVI) is established by three groups including ecological sensitivity, natural and social pressure and ecological recovery capacity with 13 factors being selected. The ecological sensitivity is composed of slope, vegetation type, vegetation

coverage, precipitation, which greatly influence the soil erosion degree, and potential rate of exposed carbonate rocks can reflect the Karst seriousness in south western mountain region of China. The frequency of landslide and earthquake are calculated by disaster event records in history. The human population density, gross domestic product, steep slope reclamation rate and the PH value of acid rain influencing forest ecosystem in a long run are selected to reflect human disturbance on regional ecosystem, while forest fire event in history is also introduced to quantify the disturbance from nature or society. Besides ecological sensitivity and regional pressure, the ecological recovery capacity is considered which can be reflected by vegetation net primary productivity estimated by revised light use efficiency model in which vegetation type, NDVI, radiation, temperature and precipitation factors are used. All factors are ranked into three levels belonging to ecological sensitivity, external pressure, and ecological recovery capacity subgroup. Corresponding construction for each subgroup are listed in Table 1.

- Ecological Vulnerability Model Based on Analytic Hierarchy Process (AHP)

Besides establishing vulnerability index system, another important task for vulnerability assessment is to determine the weight of each evaluation indicators. During past years, many methods have been used to determine indicator weights for evaluate ecological vulnerability including artificial neural network (Pam et al., 2003), analytic hierarchy process (AHP) (Liem et al, 2002; Rejaur et al., 2009) and the principle component analysis (PCA) (Li et al., 2006; Wang et al., 2008). In this paper, AHP method is selected to combine spatial information with expert advice to make comprehensive decision quantitatively based on multi-criteria system. By expert consultation, the evaluation criteria for each factor influencing EVI are ranked five grades and the relative score for each grade ranges from 0 to 100 with 20 as interval respectively presenting potential, slight, light, medial and heavy grade of ecological vulnerability condition.

According to expert advice, comparison matrix is constructed reflecting relative importance of EVI. The second level indicators, including ecological sensitivity, social or natural pressure and the ecological recovery capacity are equivalent importance to regional ecological vulnerability. In the third level, net primary productivity, gross domestic product and human population density are the three factors greatly impacted the EVI, while the factors such as potential rate of exposed carbonate rocks, frequency of landslide event and earthquake has the lightest influence on ecological vulnerability. By consistency check for single-level sorting the total level, the CR is 0.031, less than 0.10 meaning the matrix had a reasonable consistency. The weight of each evaluation indicators in different level is shown in Table 1.

Table 1. List of data set and corresponding weight of each evaluation indicator by AHP method

First level index	Second level indicators	Weight	Third level factors	Weight
Ecological Vulnerability Index (EVI)	Ecological Sensitivity (ES)	0.3333	Slope	0.0864
			Vegetation Type	0.0889
			Vegetation Coverage	0.0910
			Precipitation	0.0759
			Potential Rate of Exposed Carbonate Rocks	0.0415
			Frequency of Landslide Event	0.0454
			Frequency of Earthquake Event	0.0531
	Natural and Social Pressure (NSP)	0.3333	Human Population Density	0.0966
			Gross Domestic Product	0.1018
			Steep Slope Reclamation Rate	0.0840
			PH value of Acid rain	0.0625
			Fire Density during the past ten years	0.0535
	Ecological Recovery Capability (ERC)	0.3333	Net Primary Productivity	0.1195

- Cluster Analysis in Administrative County Level

The aim of ecological vulnerability assessing is to facilitate regional ecological restoration in administrative county level. Therefore, a cluster analysis for indicators in the second level 2 for 152 counties is carried out using centroid method in Statistics Analysis System (SAS 9.0) by cluster procedure and tree procedure. All the observations can be clustered into one group finally in the form of binary hierarchical tree. Another difficult problem how many clusters all county observations belongs to should be considered, because the cluster process with centroid distance changing includes many cluster number in different distance level. In this paper, the four statistic indicators including Cubic Clustering Criterion (CCC), Pseudo T-Squared Statistic (t2), Semi-Partial R-Squared (SPRSQ) and Pseudo F Statistic (F) are used to determine the cluster number in hierarchical tree diagram. For different cluster number, the ecological sensitivity, human or natural pressure and ecological recovery capacity vary greatly, and the corresponding investment for ecological restoration in different administrative county should be distributed efficiently from the perspective of regional ecosystem management.

- Spatial Autocorrelation Analysis on Ecological Vulnerability in Raster Level

After the EVI is calculated, the spatial statistic autocorrelation of different vulnerability grade should be studied to find out spatial adjacency from potential to heavy grade to potential grade. Moran's I, a popular autocorrelation coefficients, is widely used for measuring the existence and impact of spatial autocorrelation by calculating N observations on a variable x at locations i, j , which is shown as in formula (1).

$$I = \frac{N}{\sum_{i=1}^n \sum_{j=1}^n W_{ij}} \cdot \frac{\sum_{i=1}^n \sum_{j=1}^n W_{ij} (x_i - x_{ave})(x_j - x_{ave})}{\sum_{i=1}^n (x_i - x_{ave})^2} \quad (1)$$

where x_{ave} is the mean of the x variable, w_{ij} are the elements of the spatial weights matrix, Moran's I varies from -1 to +1, with an expected value approaching zero for a large sample size in the absence of autocorrelation.

Firstly, we draw the Moran scatter plot to analyze spatial association in global level, and then the ecological vulnerability correlation map and significance level map are generated for further analyzing local patterns of different EVI in grade level. Because of fully developed and mature in practice, the Moran's I indicator has evolved into a standard software tools for spatial pattern analysis. In our study, the spatial autocorrelation analysis is carried out in Geoda 0.9.5-i developed by Luc Anselin available from Arizona State University (Anselin, 2008).

3. Results and Analysis

3.1. Analysis of ES, NSP, ERC and EVI in Regional Level

The area statistics for ecological sensitivity (ES), natural and social pressure (NSP), ecological recovery capacity (ERC) and the ecological vulnerability index (EVI) are showed in Fig. 2. The result means that ecosystem in southwest mountainous region of China has considerable ecological sensitivity (ES) with 59.05% of total area about 483,224 km² belonging to light grade, medial grade and heavy grade, which implies the regional main ecological problem such as serious soil erosion condition because of steep slop along valley, high population density in local region, scare vegetation coverage, frequent human disturbance and heavy precipitation in summer. Frequent geological hazards occurrence has also strengthen ecological vulnerability. Especially during the process of restoration and reconstruction from disaster destruction, more materials for building reconstruction are badly needed or new farmland should be reclaimed from natural forest vegetation ecosystem. As for extra pressure from nature and society (NSP), the NSP proportion of light, medial and heavy grade is about 249,545 km² accounting for 30.50% meaning a relative slight human pressure on natural ecosystem wholly comparing to coastland region of China. But there exist NSP regional division between west-northwest and east-southeast, where human population highly accumulated. Another indicator influencing ecosystem vulnerability is ecological recovery capacity, especially when damaged ecosystem is to be established again, which can be represented by net primary productivity. Because the high temperature, adequate rainfall and solar radiation, the NPP in southwest study region

is comparatively high about 393,117,182 t · C totally in 2006 based on revised light use efficiency model. According to the classification standard, ERC proportion of potential, slight and light grade is more than 90%, which means it is possible to facilitate ecosystem recovery by vegetation restoration. Based on analysis of ES, NSP and ERC, the ecological vulnerability index (EVI) in regional level is calculated by map algebra in Arcgis. Fig. 2 indicates that the total EVI area proportion of potential grade, slight grade and light grade accounts for 85.95% with medial grade and heavy grade is 9.10% and 4.94% respectively. So the wholly ecological vulnerability in southwest of mountain China is relative slight expect the heavy EVI aggregation in the southeast and east of the study region.

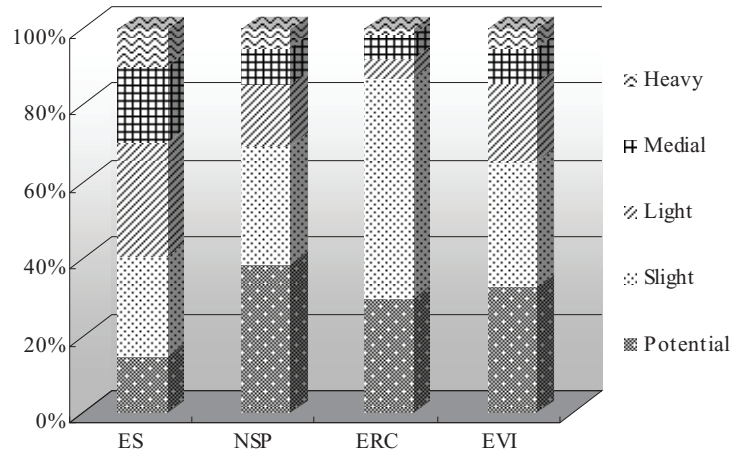


Fig. 2. Area Proportion Statistic of Units in Regional Level

As far as the spatial distribution of the ecological sensitivity, natural and social pressure, recovery capacity and the ecological vulnerability index are concerned, apparent spatial heterogeneity is observed in Fig. 3. The heavy ecological sensitivity mainly concentrated in three region including a- I , a- I and a-III, which is in the east of line spreading from Zhouqu in north to Jianchuan in south. As for the heavy NSP, whose distribution is similar to that of ES mainly concentrated in b- I region in the east of line from Wudu to Jianchuan, where the densely human population and economic activity have an inevitable intensive disturbance on regional natural ecosystem. Comparing with ES and NSP, the potential ERC distribution is heterogeneous characterized by four high NPP center including c- I , c- I , c-III and c-IV for the vegetation type three is dominated by evergreen broad-leaved forest with highly ability converting solar energy to chemical energy by photosynthesis. Determined by ES, NSP and ERC, the heavy EVI has a dispersed pattern in small scale mainly located in mountain basin and the EVI in b- I region is more serious than that in b- II . So the area with heavy EVI, ES, NSP and ERC should be given a prior consideration for taking effective measure to restore ecosystem in regional level.

3.2. Cluster Analysis of ES, NSP and ERC in Administrative County Level

The evaluation of ES, NSP, ERC and EVI above indicates the spatial distribution and quantitative relationship of different grade in regional level. While in practice, it is also important to apply our evaluation result in administrative county level to improve regional ecosystem management, especially when investment for ecological restoration is distributed among 152 counties. So we extract the average of ES, NSP and ERC in each county by spatial analysis method to constructing the matrix with 152 rows and 3 columns, based on which the cluster analysis of centroid method is carried out to classify all the administrative counties into different zones to understand the spatial division characteristics from ecological management view. The process of cluster analysis is carried out in SAS 9.0 a outstanding statistic software. The cluster process can be displayed in hierarchical tree diagram (Fig. 4).

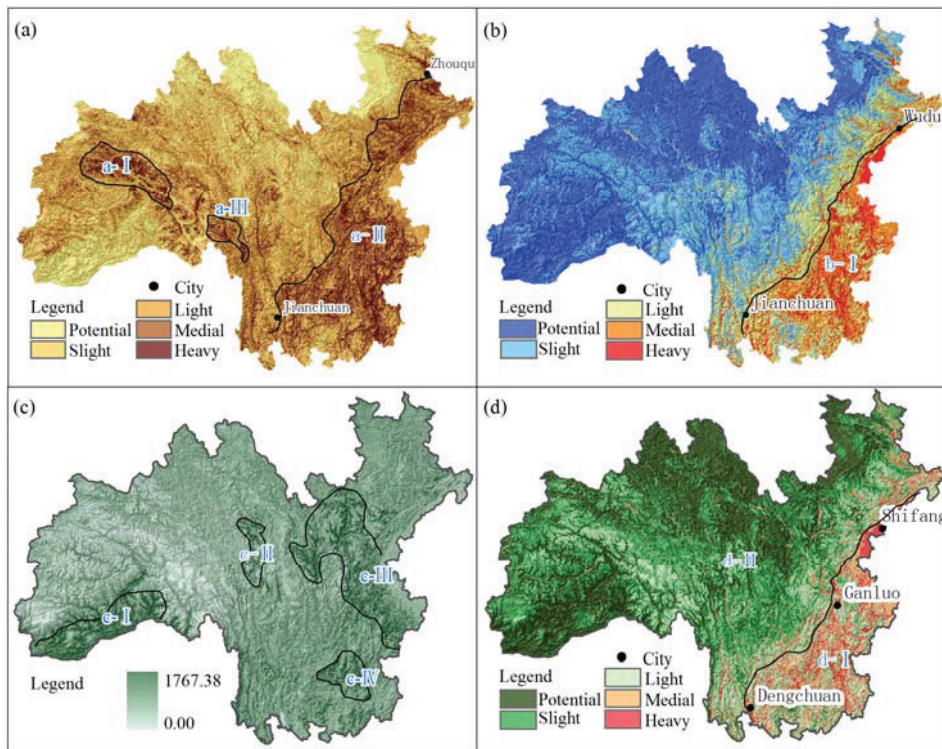


Fig. 3. (a)Ecosystem Sensitivity-ES; (b)Natural and Social Pressure-NSP; (c)Ecological Recovery Capacity-ERC; (d) Ecological Vulnerability Index-EVI in south western mountain region of China

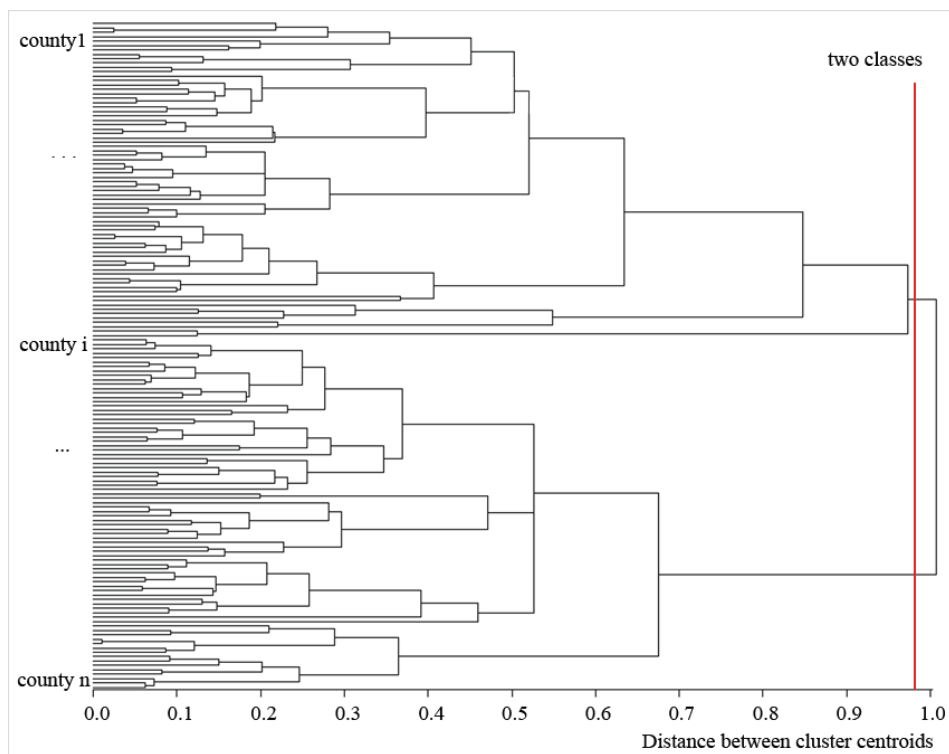


Fig. 4. Distance of different classes in the process of cluster analysis

Fig. 4 shows that a total of 151 merging process are needed to combine two types of each county by calculating centroid distance. In order to determine the reasonable cluster level, we selected the data set less than 30 because too much information is not necessary. Four statistic variables including Cubic Clustering Criterion (CCC), Pseudo T-Squared Statistic (t²), Semi-Partial R-Squared (SPRSQ) and Pseudo F Statistic (F) are used for rendering static graphics. The scatter plots of four Statistic test variable mentioned above are as follows in Fig. 5.

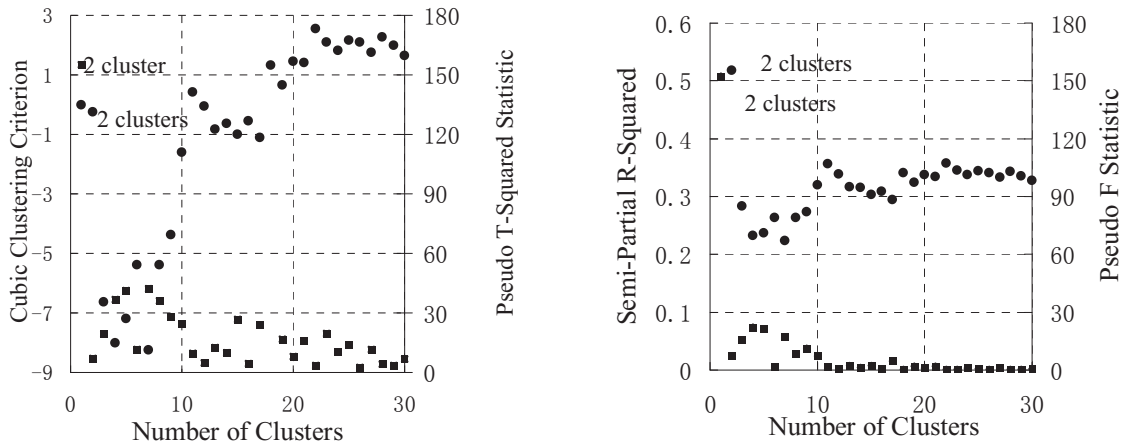


Fig. 5. Static graphics of static variables

From Fig. 5, CCC statistics recommends to take 2 classes with local maximum value, F proposed 2 classes because local maximum should not be merged and the number of local maximum class plus 1, SPRSQ and t² also suggested 2 classes, By graphics analysis, different statistic test variable reflects a consistent information that it is reasonable for all the 152 counties to classify into two categories, according to main ecological problem, the pressure from human activity or nature and ecological recovery capacity in county level. So the whole region is classified into two zones in Fig. 6(a).

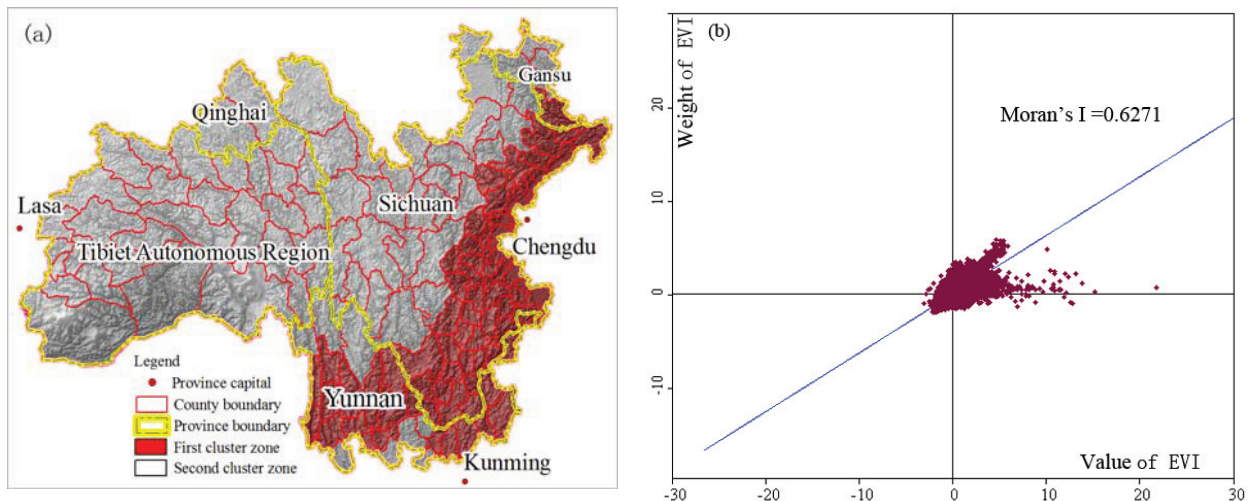


Fig. 6.(a) Zones classified by cluster analysis in administrative county level; (b) Scatter plots of Moran's I for EVI

By cluster analysis result showed in Fig. 6(a), the first cluster zone lying in the east-southeast of the region involves 79 counties with 211,264 km² about 26% of total area, among which 67 counties belong to Sichuan

province, 38 counties in Yunnan province and one county in Gansu province. The first cluster zone is highly influenced by human activities, where the resident population is 24 million about 82.97% of total population in the whole area, the farmland is 43,584 km² about 79.53%, and the GDP proportion accounts for 92.41% of the whole region, in addition to 42.05% of EVI. Comparing to the fire cluster zone, the ecological condition in the second cluster region is relative original with less human disturbance, less sensitive and more vegetation recovery capacity. So investment in the first cluster zone should be firstly considered from administrative province to administrative counties. Furthermore, when regional ecological restoration is carried out, the difference of ES, NSP, ERC or EVI in each county in the first cluster zone should be further analyzed to improve the cost-output efficiency of investment in ecological construction.

3.3. Spatial Autocorrelation Analysis of Ecological Vulnerability in grade level

Based on the classified data of ecological vulnerability grade, the average value of EVI is extracted by overlaying the grade data with the result of multiplying original continuous factors and weights. The number of units for spatial autocorrelation analysis is totally 86,561 whose area ranges from 1 km² to 95,469 km² covering all of the study area. With the help of GeoDa, the value of EVI for each unit is plotted against the weighted average of its surrounding 8-nearest neighbor based on standardized values, and the slope coefficient can be interpreted as the Moran's I for global autocorrelation in Fig. 6(b).

From above graphic, there is a strong incidence of clustering that there are 43.13% units positioned in the high-high (upper right) quadrant, and 51.85% units in the low-low (lower left) quadrant, strengthening high spatial autocorrelation for ecological vulnerability of mountainous region in the southwest of China. More detailed information about the specific vulnerability distribution is predicted in Fig. 7.

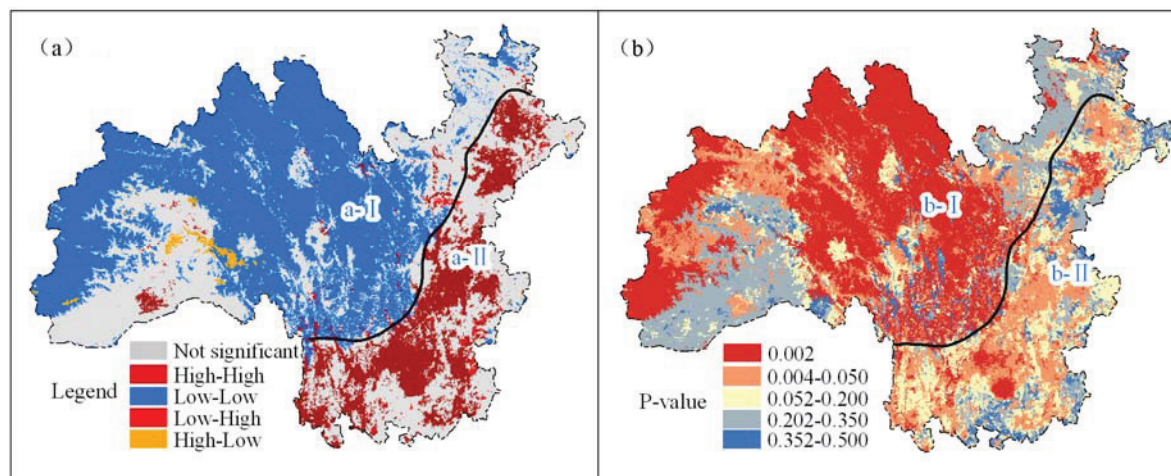


Fig. 7. (a) Correlation of ecological vulnerability index and (b) corresponding significance level of spatial auto-correlation

The characteristics are described as follows. There is no apparent cluster center of EVI like other exploratory spatial data analysis because area of the units used for spatial autocorrelation varies greatly. The LISA cluster map and corresponding significance map provides more insight into the result of regional division similar to that obtained in 3.1 and in 3.2. There is a trend dominated by low-low combinations in the west-northwest region a- I , which is likely to Fig. 3 and the second zone in Fig. 6(a), while in the east-southeast region a- II , the contiguity relation is mainly exhibited by high-high coincident with Fig. 3-(a)(b)(d) and with the first zone in Fig. 6(a) spatially. Except the high-high and low-low relationship with its neighbors, the low-high and high-low region are sparsely distributed with little area. The low-high area means the area with ecological stability is surrounded by vulnerable ecological landscape, implying that some original green island should be strictly protected for biodiversity conservation or other ecological function. As far as the significance for cluster map is concerned, the p-value ranging from 0.002 to

0.500 is used for the test. View the region of low-low and high-high a whole, the statistics are significant at p-value less than 0.050 and the autocorrelation of low-low is more significant than high-high region because p-value of the former is less than the latter (Fig. 7-b).

4. 4 Conclusion and Discussion

4.1. Conclusion

As above mentioned, the author established the evaluation index system EVI to study the ecological condition in the southwest mountainous region of China from the ecological sensitivity (ES), natural and social pressure (NSP) and recovery capacity (ERC) aspects both in regional level, county level and grade level. Besides the cluster analysis of statistics based on ES, NSP and ERC, analysis of spatial autocorrelation pattern on EVI is further investigated. The conclusions are as following.

Firstly, the area proportion of heavy and medial grade is obviously less than that of potential, slight and light grade, which means the ecological condition in southwest of China is fair stable wholly. But as the spatial distribution is considered, the spatial pattern of units with medial and heavy ES is similar to NSP and EVI approximately dividing the whole region into two parts the west-northwest area and the east-southeast area. The former land use is dominated by natural vegetation including forest, grassland or shrub and the land use in latter region is dominated by farmland and urban land greatly influenced by human economic activities. Comparing to ES, NSP and EVI the ERC presented by vegetation net primary productivity four center with high value can be founded (Fig. 3). Secondly, from the view of regional ecosystem management, all of the 152 counties can be clustered into two groups by the three second level indicators, and the class number of clustering is strengthened by Cubic Clustering Criterion (CCC), Pseudo T-Squared Statistic (t^2), Semi-Partial R-Squared (SPRSQ) and Pseudo F Statistic (F) consistently. The distribution of the two groups is similar to the division of ES, NSP and EVI, the first zone including 79 counties of Yunnan, Sichuan and Gansu province and the second zone including 73 counties mostly belonging to Tibet autonomous region and Sichuan province. Finally, an apparent clustering trend of EVI units is showed by global Moran indicator about 0.6271, and the spatial adjacency of low or high unit combination mainly is presented by high-high and low-low relation. Spatially, the distribution of low-low units and the high-high units are basically coincided with two county zones clustered by the second level indicators and the corresponding spatial adjacency is significant.

4.2. Discussion

(1) The result of ecological vulnerability evaluation is not only determined by ecological sensitivity, social or natural disturbance, and recovery ability in regional level, but influenced greatly by specie components, population structure and other indicators in small level. So the study cross scales should be enhanced to deduce the mechanism study in small scale to ecosystem management in large scale. (2) In this study, many data sets are involved from different organizations in different shared platforms, so it is important to establish a uniform metadata standard for different data sets in order to facilitate the interdisciplinary study such as ecological vulnerability evaluation and other study. (3) Spatial autocorrelation analysis in GIS is usually used for single or few factors to reflect spatial cluster of a certain problem, while the cluster analysis in statistics is effective to deal with more indicators such as poverty population, gross domestic productivity and other social and economic factors based on administrative unit boundary. So it is valuable to combine spatial autocorrelation analysis with traditional statistic method in order to generate more comprehensive results for ecological vulnerability analysis in multiple levels.

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