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Original Research

Dynamic Evaluation of Ecological Vulnerability in a Lake Watershed Based on RS and GIS Technology

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Abstract

Located northeast of Yuxi City, Yunnan Province, China, the Fuxian Lake Basin is not only a famous scenic area, but also an ecological and environmental protection zone. The basin is a plateau mountainous lake region that has key ecosystem vulnerability and sensitivity. A dynamic evaluation of ecological vulnerability is important for assessing the ecological environment of a region, which is significant for the protection of ecological environments and providing ecological security early warnings. Based on remote sensing (RS) and geographic information system (GIS) technology, remote sensing data, meteorological data, and economic statistics were used to perform a vulnerability analysis for the Fuxian Lake Watershed. Using the "cause and effect" evaluation model that relies on the remote sensing image pixel as the basic evaluation unit, the ecological vulnerability and the dynamic changes of the basin were evaluated using the analytic hierarchy process (AHP) method. Data collected in 1974, 1977, 1987, 1990, 1996, 2000, 2006, 2012, and 2015 were analyzed to determine the temporal and spatial distribution characteristics and the dynamic changes over longer time-spans for ecological vulnerability. Afterward, the effects of land use and the consequential changes to ecological vulnerability were studied. The results indicated that the ecological vulnerability showed a trend of "overall stability but local strengthening" in the Fuxian Lake Basin from 1974 to 2015. The annual ecological vulnerability integrated index for the basin was 2.55±0.16, which indicates a transitional state between micro-vulnerability and mild vulnerability. On the basis of maintaining the degree of original vulnerability, the vulnerability of each grade was most commonly converted to the adjacent grade. The degree of ecological vulnerability was more commonly converted toward a more severe grade, and regions were less likely to recover from the severe vulnerability grade. The ecological vulnerability integrated index of the bare land was the

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highest (3.28), and the ecological environment of bare land was most vulnerable in the Fuxian Lake Basin.

Keywords: ecological vulnerability, Fuxian Lake Watershed, remote sensing, dynamic evaluation, land use

Introduction

In recent years, with the rapid development of human society and growing global environmental problems such as climate change and environmental pollution, assessing the vulnerability of regional ecological environments scientifically and consistently has become increasingly important [1]. The concept of eco-environment vulnerability can be traced back to the "ecological transition zone," which is the transition zone between different ecosystem communities [2]. It is widely known that ecological vulnerability refers to the sensitive reaction of an ecological system to external disturbances and the recovery capability of an ecological system relative to specific temporal and spatial scales. Additionally, vulnerability is not only attributed to natural ecosystem disturbances, but also can result from the interaction between natural and human activities [3-6]. Contained within the societal influences, the rapid growth of urban populations and the continuous expansion of urban areas has created ecological problems such as soil erosion, land degradation, and decreases in vegetation coverage. These problems are becoming more and more serious, and ecological environment systems have suffered significant damage and impact in some areas. With the increasing scope and intensity of human impacts on land use, land use spatial patterns and landscape styles have also greatly changed. As a consequence, ecological and environmental problems are emerging. Therefore, it is crucial to evaluate regional ecological vulnerability in order to alleviate the contradictions between social development and ecological security, and also to promote the coordinated development of population, resources, environments, and the social economy.

In recent years, researchers have conducted a large number of studies using different research areas or research methods that have incorporated comprehensive interdisciplinary approaches, made rapid progress, and achieved many valuable results [7]. At present, a series of ecological vulnerability assessment methods have been developed, including the comprehensive evaluation method [8-9], fuzzy evaluation method [4, 10-12], analytic hierarchy process (AHP) method [13-14], principal component analysis [15-16], the landscape evaluation method [17-18], and others. The development of remote sensing (RS) and geographic information system (GIS) technology has not only provided more abundant basic data for the study of ecological vulnerability, but also makes it possible to evaluate long time-span dynamic changes. The use of RS technology combined with traditional evaluation methods for ecological vulnerability has become an essential method for ecological environment assessment research [19-20]. Ma Jun et al. [16] used the "stress-state-response" model combined with RS data to study the ecological vulnerability changes for the Three Gorges Reservoir Region from 2001 to 2010. Based on RS technology, Xu et al. [21] studied the ecological vulnerability of northern Shanxi, and determined that human factors were the main influence on ecological vulnerability changes. Future research on ecological vulnerability needs to focus on the development of a greater number of RS metrics that can be used in a prospective mode for assessing the vulnerability of terrestrial vegetation to natural and human-induced changes [22]. The objective facets of ecological environment heterogeneity require that ecological vulnerability assessment methods have strong applicability; therefore, different evaluation indicators and research methods are needed for different research areas. Typical ecological vulnerability assessments mainly focus on ecological vulnerability areas at different scales such as the ecotone between agriculture and animal husbandry [23-24], cold mountain areas [25-27], wetlands in watersheds [28-30], and karst areas [31-33]. However, these assessments are mainly based on urban and county administrative regions, and they rarely reflect the specific differences in the degree of fragility of the ecological environment within the regional geography. Temporally, these studies have only analyzed the ecological environment during a single year, and have lacked an assessment of the dynamic changes that occur over long time-spans.

Located in the Yunnan-Guizhou Plateau in southwestern China, Fuxian Lake is the deepest lake in the region and belongs to the Nan Pan River in the Pearl River Basin. The lake covers an area of 211 km^2, the water level is 1721 m above sea level, the maximum length is 31.5 km, and maximum width is 11.5 km. The maximum depth is 155 m and the average depth is 87 m. The volume of Fuxian Lake is 20.62 billion cubic meters, accounting for 72.8% of the water in Yunnan Province, and 9.16% of the national freshwater lake water storage capacity. Fuxian Lake is a national drinking water source, and the water quality is among the best of natural lakes in China. Fuxian was incorporated into the China national key lake support system in December 2013. In recent years, the Fuxian Lake Basin ecological environment has faced great pressure due to the growth of human activities and tourism. Vegetation in the basin is dominated by secondary vegetation, such as Yunnan pine forest, Huashan pine forest, shrub, and shrub grassland. The forest coverage rate is only 23.70%

in the restricted area, which is one of the lowest rates of forest coverage in Yuxi city, and this results in soil erosion and land degradation. With the development of tourism in the Fuxian Lake Watershed, population, resource, and environmental problems have become increasingly prominent, and the ecological environment of the basin has received greater attention. The attention is mainly paid to geological disasters, soil erosion, land use/land cover, environmental pollution, and landscape damage. Nevertheless, the basin still lacks ecological environment vulnerability research over the entire region, and especially lacks studies that focus on the vulnerability of the ecological environment due to the influence of human factors.

The objectives of this study were: 1) to develop a dynamic evaluation method for environmental vulnerability integrating AHP, RS, and GIS over longer time scales; 2) to establish an index system for ecological vulnerability assessments in small watersheds, relying on RS image pixels as the basic evaluation unit instead of an administration cell; and 3) to analyze the spatial and temporal distribution and variation trends of ecological vulnerability as well as the relationship between the trends and land use.

Material and Methods

Study Area

Fuxian Lake is located in Yuxi City, central Yunnan Province, northwest of China (24°21'28" N ~ 24°38'00" N, 102°49'12" E ~102°57'26" E; Fig. 1). It is 60 km southeast of Kunming, the capital of Yunnan Province. The watershed of Fuxian Lake crosses Chengjiang, Jiangchuan, and Huaning counties. The basin is located within the laterite plateau lake basin area in the center of Yunnan Province, and the main basin geomorphic type is a plateau landform. The terrain in the basin displays the characteristics of the surrounding elevation, the middle of the basin is low lying, and there are large differences in the relative elevations. The east and west sides of the mountain surrounding Fuxian Lake are steeper from north to east, and are consistent with the tectonic line. Fuxian is the largest deep freshwater lake by volume in China, the largest lake near the source of the Pearl River, and a member of the Nanpanjiang River system. The water quality of Fuxian is Class I, which means that it is counted as one of the natural lakes with best water quality in China.

Data

The data used in the study mainly included multi-source RS image data, meteorological data, economic data statistics, and other reference data within the basin, including the following:

1) RS data, including Landsat multi-scanner system (MSS) images collected from the following sources (1974, 60 m spatial resolution multispectral data), Landsat TM/ETM+/OLI images (1987/1990/1996/2000/2006/2009/ 2012/ 2015, 30 m spatial resolution multispectral data and 15 m resolution panchromatic data); SPOT-5 HRG (2006, 10 m spatial resolution multispectral data and 2.5 m resolution panchromatic data); Quick Bird

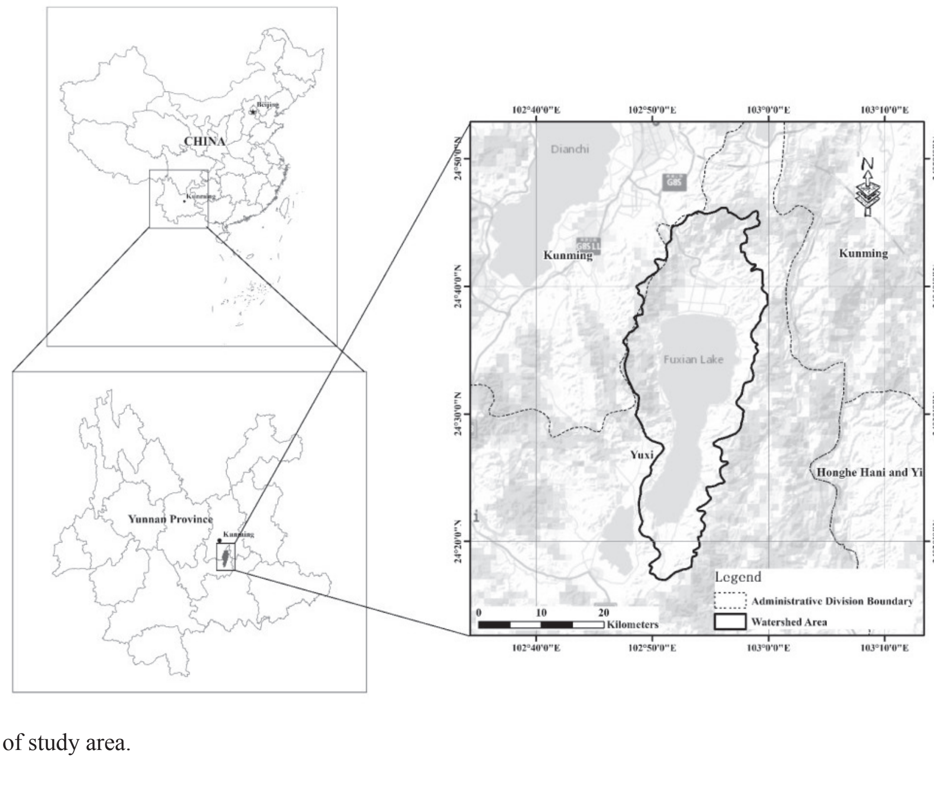

Fig. 1. Location of study area.

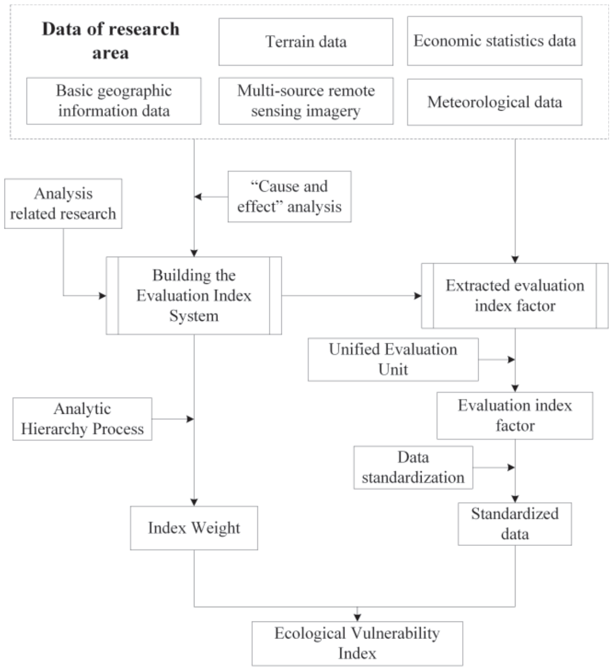

Fig. 2. Flowchart detailing the method in this study.

images (2009, 2.44 m spatial resolution multispectral data and 0.61 m resolution panchromatic data); WorldView-2 images (2012/2014/2015, 1.8 m spatial resolution multispectral data and 0.5 m resolution panchromatic data). The Landsat series of satellite data were collected from the geospatial data cloud (gscloud.cn), and other image data were taken from the Yunnan Provincial Geomatics Centre in Kunming, China.

2) Basic geographic information data of the Fuxian Lake Watershed from 2014 at a 10 m spatial resolution, including the first national census results of geographical environments that included data on land use for cultivated land, garden plots, woodlands, grasslands, urban construction land, roads, structures, artificial digging land, bare land, water networks, residential information, and digital elevation map (DEM) data collected from the Yunnan Provincial Geomatics Center in Kunming, China.
3) The study also collected years of precipitation and evaporation data from major meteorological stations, forestry second survey data, 1:10 million topographic maps, vegetation maps, land use maps, soil survey data and regulations, policies, documents, and other reference data from the Fuxian Lake Basin.

Methodology

The choice of a specific evaluation method for assessing ecological vulnerability is significant. Based on the different characteristics of an index, the evaluation method for the system characteristics were selected according to the characteristics of the different data types. The fuzzy comprehensive evaluation

Table 1. Index source description

Indicator	Formula and explanation	Relationship
Slope	Spatial analysis software was used to extract data via DEM data	++
Relief degree of land surface	Maximum elevation of the evaluation unit - Minimum elevation of the evaluation unit	++
Per Capita Arable Land	Cultivated area / Population	++
Land Use/Land Cover	(Based on the geography and national conditions census) Data, according to the multi - period remote sensing data artificial visual interpretation [39]	+-
Land Degradation Index	The land degradation assessment system was constructed from the land use, compound vegetation index, land desertification index, soil erosion area, and soil moisture content as the evaluation factors for estimating the land degradation status [40]	+-
Water Loss and Soil Erosion	Based on the Universal Soil Loss Equation (USLE), the influencing factors of soil and water loss were extracted to estimate the soil and water loss in the basin [41]	+-
Vegetation Coverage	By calculating the normalized vegetation index (NDVI), the vegetation coverage of the study area was obtained by using the dimidiate pixel model [42]	--
Annual Evaporation and Annual Precipitation	Data interpreted from meteorological stations using inverse distance weights	++
		--
Real GDP per capita	GDP/ number of population	--
Per capita net income of farmers	Regional farmers' net income / Total agricultural population	--
Population Density	Population / Land area	++
Urbanization Rate	Urban population / Total population	--
Engel's Coefficient	Food expenditure / Total expenditure amount	++

Relationship ++: *positive indicators,* +-: *qualitative indicators,* --: *negative indicators* method, the ecological frangibility index (EFI) method, AHP method, and principal component analysis have all been widely used in the analysis of domestic ecological environment vulnerability. Additionally, these methods have also often been used for other types of evaluations. From the above methods, the AHP method has been applied to the assessment of ecological vulnerability in China, for example in sites that have a certain representative significance such as the Hengyang Basin [34], Hangzhou Xixi Wetland [35], Poyang Lake area [36], and the Wujiang River Basin [37]. Compared with other methods, the AHP method has been widely used. Therefore, combining RS and GIS technology, we applied the AHP method to study and establish a scientific and reliable evaluation index system for the dynamic assessment of ecological vulnerability. The research comprehensively analyzed the existing research results in the study area, and established a comprehensive evaluation system combined with a variety of spatial data, and analyzed the causes and results of ecological environmental changes in Fuxian Lake (Fig. 2).

Evaluation Index System

To establish a scientific and reliable ecological vulnerability evaluation index system as the basis of the vulnerability assessment, the selected indicators should not only reflect the ecological environment of the river basin, but also reveal the nature of the environmental vulnerability, developments, and dynamic changes. Based on the basic concept of ecological environment vulnerability, this study has taken into account the natural conditions and social development characteristics of Fuxian Lake Basin, and fully utilized the capabilities of RS technology while developing an evaluation index. Additionally, the complex relationship between the vulnerability evaluation factors in Fuxian Lake Basin and the availability of data have been fully explored. Based on relevant national and international research results, the ecological vulnerability assessment of the basin was carried out using the "cause and effect" index system, and an assessment index and evaluation system standard for small watersheds was established. The indicators and calculation methods used during the study are shown in Table 1 and Fig. 3.

Index Weight

The weight of the evaluation index was determined using the AHP method [38]. First, the importance of the evaluation index was compared by the experts, and then the relative importance matrix for the evaluation index was established. Next, the eigenvalue of the matrix and the corresponding eigenvector were calculated.

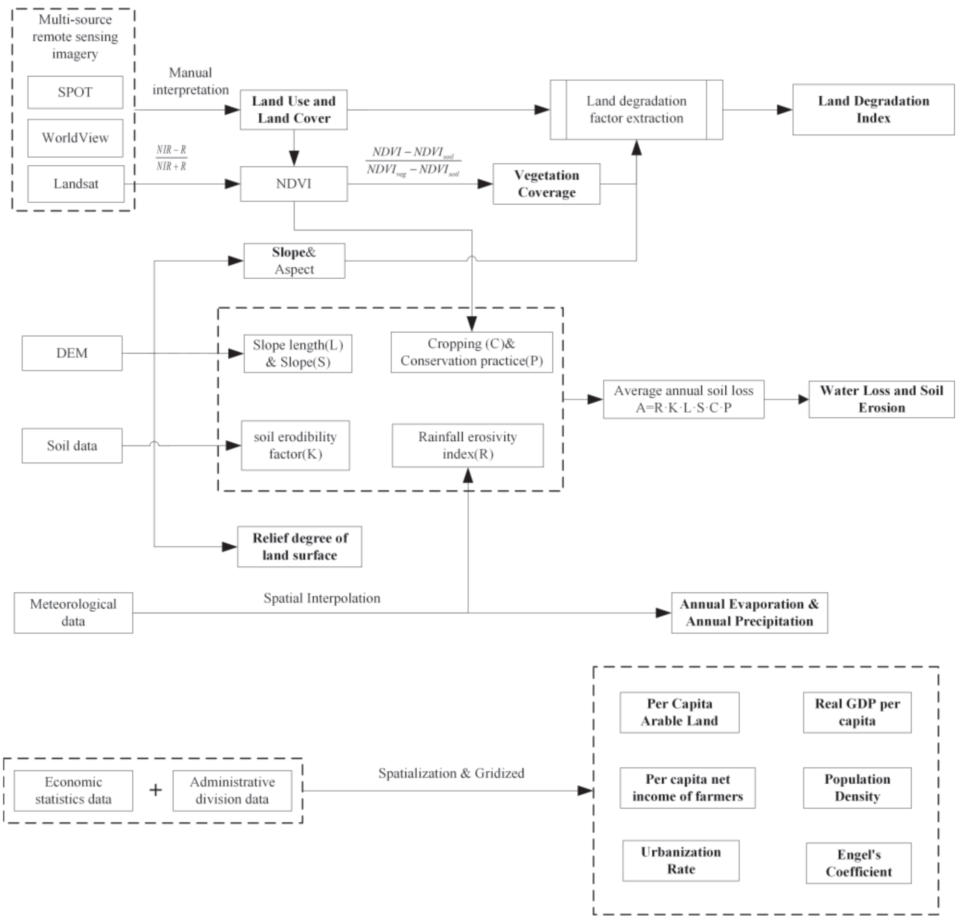

Fig. 3. Flowchart of the method for obtaining each evaluation factor.

Table 2. Evaluation index system and index weight of ecological carrying capacity.

Evaluation synthesis		Evaluation item	Evaluation factor	Factor weight
Ecological Vulnerability Assessment(A)	Natural Genetic Indicators	Terrain B1	C11 Slope	0.1239
			C12 Relief Degree of Land Surface	0.062
		Land B2	C21 Per Capita Arable Land	0.0376
			C22 Land Use/Land Cover	0.1036
			C23 Land Degradation Index	0.1286
		Force B3	C31 Water Loss and Soil Erosion	0.105
		Vegetation B4	C41 Vegetation Coverage	0.1371
		Climate B5	C51 Annual Evaporation	0.0712
			C52 Annual Precipitation	0.0456
	Results Performance Indicators	Economic Development B6	C61 Real GDP per capita	0.0226
			C62 Per capita net income of farmers	0.0377
			C63 Population Density	0.0286
			C64 Urbanization Rate	0.0354
		Social Performance B7	B71 Engel's Coefficient	0.0611

The normalized eigenvector corresponding to the maximum eigenvalue that satisfied the consistency test determined the weight of the corresponding index. Finally, the weights of each index system were determined as shown in Table 2.

Data Standardization

Since there were substantial time-span gaps in the collected data, it was necessary to standardize the raw data for all the collected indexes in order to eliminate the temporal influence caused by the lack of time continuity in the original data. After several experiments and attempts, we found that the maximum and minimum values of the data treated by the "maximum-minimum" normalization method were considerably different. When the economic statistics were processed, the results did not correlate to the real values. Therefore, this study used the maximum standard method for standardizing the original data series according to the formula shown below:

$$T_{ij} = \frac{T_{ij}(0)}{T_j(max)} \quad (1)$$

…where T_{ij} is the normal value for each index, $T_{ij}(0)$ is the original value of the j index of the i region, and $T_j(max)$ is the maximum value of the j indicator in all regions.

The ecological vulnerability was positively correlated with 6 indicators in all, and negatively correlated with 5 indicators. Therefore, during the calculation process, the 5 indicators with negative correlations were calculated by using Formula (2), so that the relevance of each indicator factor could be unified:

$$T_{ij} = 1 - \frac{T_{ij}(0)}{T_j(max)} \quad (2)$$

Based on the relevant research results [16, 43], expert knowledge, practical characteristics, and qualitative indicators that included land use type, soil degradation intensity, and soil erosion intensity, the data inputs were standardized by the direct grading method as listed in Table 3.

Evaluation Unit

As the data obtained for the evaluation of ecological vulnerability of the small watersheds were from multiple sources and were of variable types, it was necessary to determine the specific evaluation unit in order to evaluate the ecological fragility of the basin spatially. The size of the evaluation unit often varied depending on the data and the size of the evaluation area. The evaluation of the ecological vulnerability for small watersheds was problematic, because the spatial area was relatively small, and if the evaluation unit was set too large, it would lead to problems such as large differences between the adjacent evaluation unit data. Therefore, evaluation results were low in spatial resolution accuracy and it was difficult to reconcile with the statistics of the administrative region. After testing and research, it was determined that in watershed areas of less than 1000 km^2, the size of the evaluation unit should be less than 60 m (square evaluation unit side length) according to the evaluation accuracy requirements and

Table 3. Qualitative index assignment standard.

Item	Standardized assignment				
	0.2	0.4	0.6	0.8	1.0
Land Use	Woodland Water	Grassland, Garden plot	Cultivated land	Urban construction land, Road, Structures, Artificial digging land	Bare
Land Degradation	Not degraded	Mild degradation	Moderate degradation	Severe degradation	Extremely degraded
Intensity of Soil Erosion	Micro erosion	Mild erosion	Moderate erosion	Severe erosion	Extremely eroded

the software computing ability. Therefore, considering the full use of the RS image pixel information and software calculation ability, the study identified the size of the evaluation unit as 30 m in order to evaluate the ecological vulnerability of the Fuxian Lake Watershed.

Calculated Ecological Vulnerability

The various factors used for the ecological vulnerability assessment system were independent. The ecological vulnerability index (EVI) was calculated by constructing a comprehensive evaluation model for ecological vulnerability, and the weighted summation method was used to integrate the impact of each evaluation index on ecological vulnerability. The EVI index, which can reflect the regional ecological vulnerability quantitatively, can be calculated using the following formula:

$$\mathrm{EVI} = \sum_{i=1}^{n} (A_i \cdot W_i) \tag{3}$$

…where A_i is the normalized value of i indicator, W_i is the index weight, and n is the number of indicators.

In order to measure and compare, the EVI index needs to be standardized, and the standardized calculation method [44] was used as follows:

$$S_i = \frac{EVI_i - EVI_{min}}{EVI_{max} - EVI_{min}} \times 10 \tag{4}$$

…where S_i is the standardized value of the ecological vulnerability index of i year, and its value range is between 0 and 10. Moreover, the greater the value, the more vulnerable the ecological environment. EVI_i is the actual value of the ecological vulnerability index of i year. EVI_{max} is the maximum value of the ecological vulnerability index over several years. EVI_{min} is the minimum value of the ecological vulnerability index over several years.

In order to analyze and compare the results of the study appropriately, we needed to calculate the ecological vulnerability index of the Fuxian Lake Basin in line with certain rules. Due to differences between the evaluation index system and evaluation method, there were substantial variations in the classification of ecological vulnerability. Based on the comparative analysis of the results, the ecological fragility of the Fuxian Lake Basin was divided into 5 grades on the basis of the specific characteristics of the existing ecological vulnerability assessments. The grades included potential vulnerability, micro-vulnerability, mild vulnerability, moderate vulnerability, and severe vulnerability [16, 45-47].

Using the quantitative comprehensive index can be more intuitive and can more accurately reflect the ecological vulnerability of an environment. The ecological vulnerability integrated index (EVSI) for the Fuxian Lake Basin was calculated by using the multiplication model to reflect the overall ecological environment status of the basin. The calculation method was as follows:

$$\mathrm{EVSI} = \sum_{i=1}^{n} P_i \times \frac{A_i}{S} \tag{5}$$

…where *EVSI* is the ecological fragility composite index, P_i is the grade value of the ecotype of i type ecological vulnerability, A_i is the area of i type of the ecological vulnerability, and S is the total area of the region.

The regression trend method (also called the change trend method) [48], is a way to use the grid computing function of the GIS software to analyze the trend of the ecological vulnerability index (EVI) yearly based on grid unit, which can reflect the dynamic characteristics of the ecological fragility in the watershed. The formula is as follows:

$$\mathrm{K} = \frac{n \times \sum_{i=1}^{n} i \times EVI_i - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} EVI_i\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{6}$$

…where K is the slope of the change, n is the total number of years in the study period, and EVI_i is the ecological vulnerability index for year i. If the slope is positive it indicates that the ecological vulnerability index is increasing, if the slope is negative, it indicates that the ecological vulnerability index is decreasing.

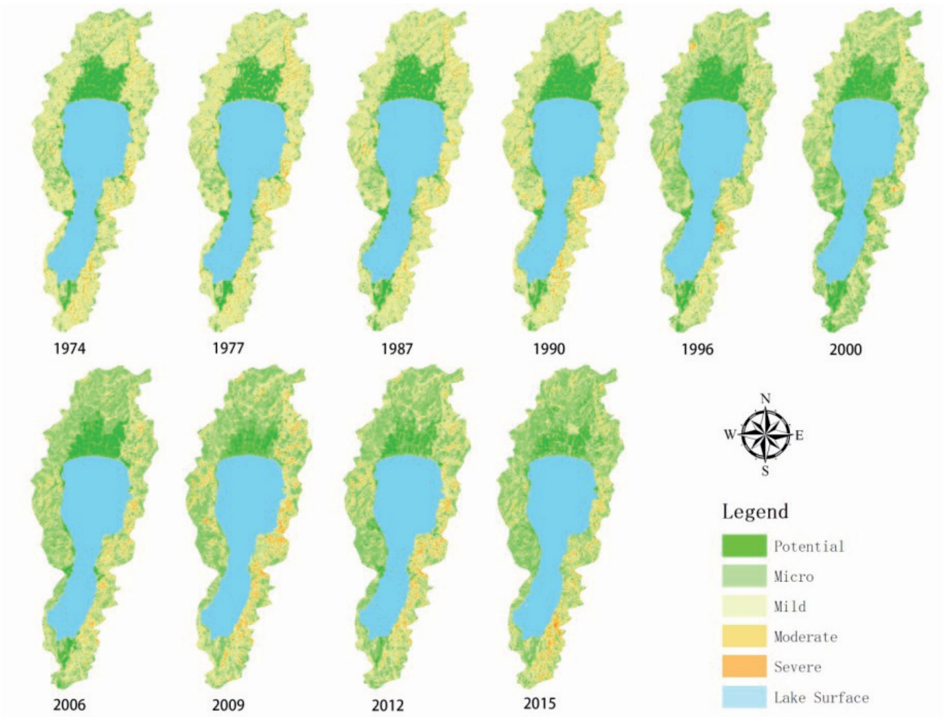

Fig. 4. Evaluation results of ecological vulnerability in Fuxian Lake Watershed (1974-2015).

Results and Discussion

Temporal and Spatial Distribution of Ecological Vulnerability

The spatial distribution of the ecological vulnerability assessment for Fuxian Lake Basin from 1974 to 2015 (Fig. 4) was obtained by using GIS analysis software to synthesize multiple parameters and to classify ecological vulnerability according to the standard (Table 4). According to the spatial distribution, the severe vulnerability regions and the moderate vulnerability regions were mainly scattered in locations where soil and water losses were relatively acute, such as on the east and west coasts of Fuxian Lake, near Chengjiang county on the north shore, and in the northern mountainous areas, especially the east coast of Fuxian Lake where the environment was most vulnerable. Mild vulnerability regions were mainly concentrated in locations with human activities such as Chengjiang County, including the roads surrounding the city and the arid regions between the mountains.

Table 4. Classification standards of ecological vulnerability in Fuxian Lake Basin.

Ecological vulnerability level	Standardized value of the ecological vulnerability index	Description of ecological vulnerability
Potential	≤2.0	Stable ecosystem, low pressure, resistance to outside interference and ability to self-recover, no ecological abnormalities, and there is low ecological vulnerability.
Micro	2.0-4.0	Stable ecosystem, low stress, strong ability to resist external interference and ability to self-recover, the possibility of ecological anomalies, and there is low ecological vulnerability.
Mild	4.0-6.0	The structure and function of the ecosystem can be maintained, the pressure is close to the ecological threshold, the ecosystem is unstable, the external disturbance is more sensitive, the ability to self-recover is weak, there are few ecological abnormalities, and the ecological fragility is higher.
Moderate	6.0-8.0	The structure and function of the ecosystem are flawed, the pressure is strong, the ecosystem is unstable, the sensitivity to external disturbance is strong, recovery is difficult after damage, there are more ecological abnormalities, and the ecological fragility is high.
Severe	≥8.0	The structure and function of the ecosystem are seriously degraded, the pressure is extremely strong, the ecosystem is extremely unstable, and it is extremely sensitive to external disturbance. After damage, recovery is extremely difficult and even irreversible, and the ecological area is large and the ecological fragility is extremely high.

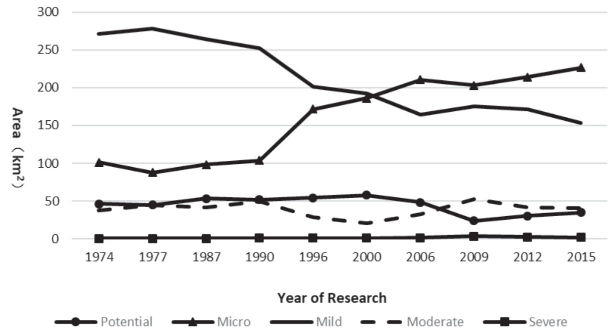

Fig. 5. Area change of ecological vulnerability in different categories.

The micro-vulnerability and potential vulnerability regions were mainly distributed in the mountainous forest locations around the basin and the fields, including the paddy fields and the arid regions around Chengjiang County.

From the temporal perspective, the ecological vulnerability trends for Fuxian Lake Basin showed an overall regional decrease in vulnerability. However, local increases for some areas were observed. During the 1970s and 1980s, the entire basin was dominated by mild vulnerability that was mainly distributed in the mountainous regions around Fuxian Lake, as shown in Fig. 4. The micro-vulnerability and potential vulnerability regions were only distributed in the relatively flat areas of the lake, including Chengjiang County town, the cultivated land surrounding the town, and the southern part of Fuxian Lake. With the improvement of environmental awareness and the implementation of national environmental protection policies, the ecological environment of the Fuxian Lake Basin has improved since the 1990s, and the mild vulnerability of the mountainous areas around Fuxian Lake have gradually changed to micro and potential vulnerability areas. At the same time, the areas of potential vulnerability expanded from the lakeside to the mountain woodland and grassland areas. However, the moderate vulnerability region on the southeastern coast of Fuxian Lake has shown a tendency to increase, and there has been a region of severe vulnerability identified in this location.

Analysis of Changes to the Ecological Vulnerability of the Watershed

It can be seen from changes in the unit square area values of regions with different ecological vulnerabilities (Fig. 5) that the potential vulnerability of the basin was relatively stable from 1974 to 2000. The unit square area changed from 46.01 km^2 (1974) to 57.58 km^2 (2000), and reached a minimum value (23.48 km^2) in 2009, then slowly rose to 34.66 km^2 in 2015. Micro-vulnerability and mild vulnerability unit square areas have shown a shift during the past 40 years. The micro-vulnerability unit square areas increased from 101.34 km^2 in 1976, to 226.47 km^2 in 2015, while the mild vulnerability areas decreased from 278.59 km^2 (in 1974) to 153.86 km^2 in 2015. During the past 40 years, the moderate vulnerability unit square areas showed small fluctuations, and reached a minimum value (20.44 km^2) in 2000. The unit square areas of severe vulnerability showed an increase, rising from 0.11 km^2 in 1974 to 1.92 km^2 in 2015. Some of these increases occurred at a faster rate, while others showed a less steep increase.

This study analyzed the evaluation results from the ecological vulnerability assessment in the Fuxian Lake Watershed by using the spatial overlay analysis function of the GIS software from 1974 to 2015, with the aim of obtaining the unit square transfer areas for each grade vulnerability over 40 years (Table 5). We can see from Table 5 that: 1) on the basis of maintaining the degree of original vulnerability, the ecological vulnerability of each grade was most commonly transferred to the adjacent grade. In addition, the largest (132.94 km^2) unit square land area shifted from the mild vulnerability grade to the micro vulnerability grade; and 2) the degree of ecological vulnerability was most commonly converted toward a more severe grade, and regions were less likely to recover from the severe vulnerability grade. For example, 6.4823 km^2 unit square land area at the potential vulnerability grade changed to the mild vulnerability grade, and 0.0775 km^2 were converted into moderate vulnerability grade land, but only 0.0492 km^2 of land areas with a severe vulnerability grade reverted to moderate vulnerability grade land.

The ecological vulnerability integrated indexes (EVSI, Fig. 6) of the Fuxian Lake Basin from 1974

Table 5. Different types of ecologically vulnerable area transfer from 1974 to 2015.

Area (km^2)		Year 2015				
		Potential	Micro	Mild	Moderate	Severe
Year of 1974	Potential	18.2551	21.0969	6.4823	0.0775	0.0000
	Micro	9.6085	64.5751	24.4759	1.8733	0.0428
	Mild	6.5703	132.9395	106.5054	24.5275	0.3486
	Moderate	0.0678	6.4139	15.2064	14.0881	1.4431
	Severe	0.0000	0.0000	0.0100	0.0492	0.0480

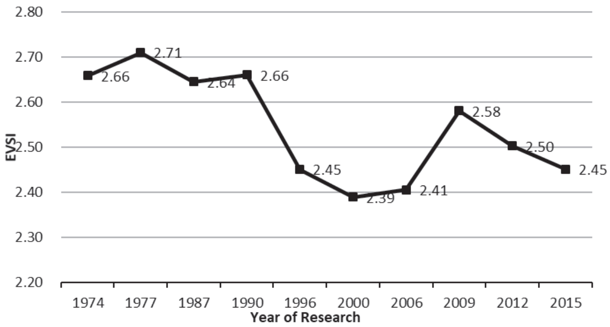

Fig. 6. EVSI changes from 1974 to 2015.

to 2015 were calculated by analyzing the unit square area values of the different vulnerability grades. The results showed that the EVSI of the watershed reached a maximum value (2.71) in 1977, and then was followed by a trend of decreasing volatility where the EVSI reached a minimum value (2.39) in 2000. The value of the EVSI had a relatively high index (2.58) exhibited by an upward trend in 2009. The value then reached 2.45 with a steady decline annually until 2015. The EVSI value showed an overall decreasing trend, and the average annual value was 2.54. The degree of ecological vulnerability was between the micro- vulnerability status and the mild vulnerability status, and the ecological environment of the watershed was overall improved.

In order to analyze the change trend for the ecological vulnerability index in the Fuxian Lake Watershed from the spatial distribution characteristics, our study used a regression method to calculate the change trend of the EVI. Based on existing research [49], the dynamic trend of the EVI was divided into 5 grades (Table 6). GIS software was used to generate the representative changes in the trend for the ecological environment vulnerability in Fuxian lake watershed that are shown in Fig. 7, which shows that due to the influence of factors such as climate change and human activities, the ecological vulnerability of the Fuxian Lake Watershed experienced significant temporal and spatial changes. Due to the expansion of the city and the intensification of human activities, the EVI showed a significant increase trend, especially in the area near Chengjiang County town, Fuxian Lake east and west coast, and the large region around the

Table 6. Grading table of EVI change.

EVI change	Degree of change
Significantly Reduced	K<-0.01
Moderate Decrease	-0.01<K≤-0.005
Almost Unchanged	-0.005<K≤0.005
Moderate Increase	0.005<K≤0.01
Significant Increase	K>0.01

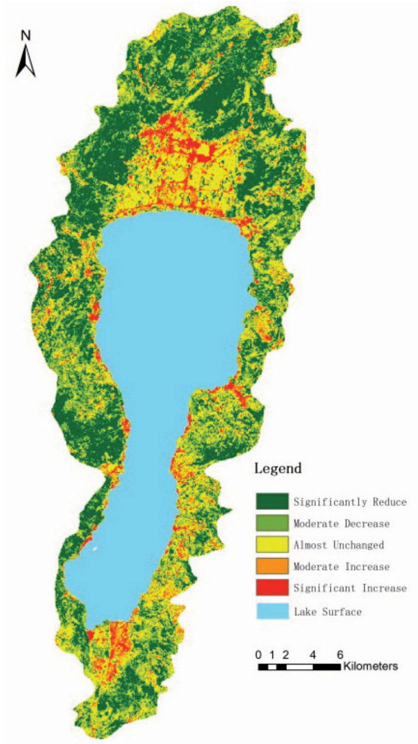

Fig. 7. Trends in ecological vulnerability changes.

town of Jiangchuan County. Due to the implementation of the policy that endeavors to return farmland to forest and grassland, the ecological environment has greatly improved and the EVI now shows a significant decreasing trend in the forest regions around the Fuxian Lake Watershed. The ecological and environmental changes were relatively small, and the EVI was almost identical in the north and south coast of Fuxian Lake and the mountainous farmland regions during the last 40 years.

Ecological Vulnerability and Land Use

From the ecological environmental problems resulting from human activities, land use pattern played an important role in influencing the ecological environment. Based on the land use data of Fuxian Lake Watershed from 1974 to 2015, the influence of land use status on the ecological environment was studied by using the ArcGIS spatial analysis function to calculate the EVSI under different land use conditions and analyze the changes in the EVSI caused by changes in land use condition.

By calculating the average EVSI of different land use types from 1974 to 2015 (due to the accuracy of the RS image data, some land use types were missing from the years between 1974 and 2000; the results are shown in Fig. 8), it can be found that the EVSI of bare land in Fuxian Lake had the highest index (3.28) overall and more closely to moderate vulnerability grade value. These regions were characterized by low vegetation coverage, poor ecological environment stability, and

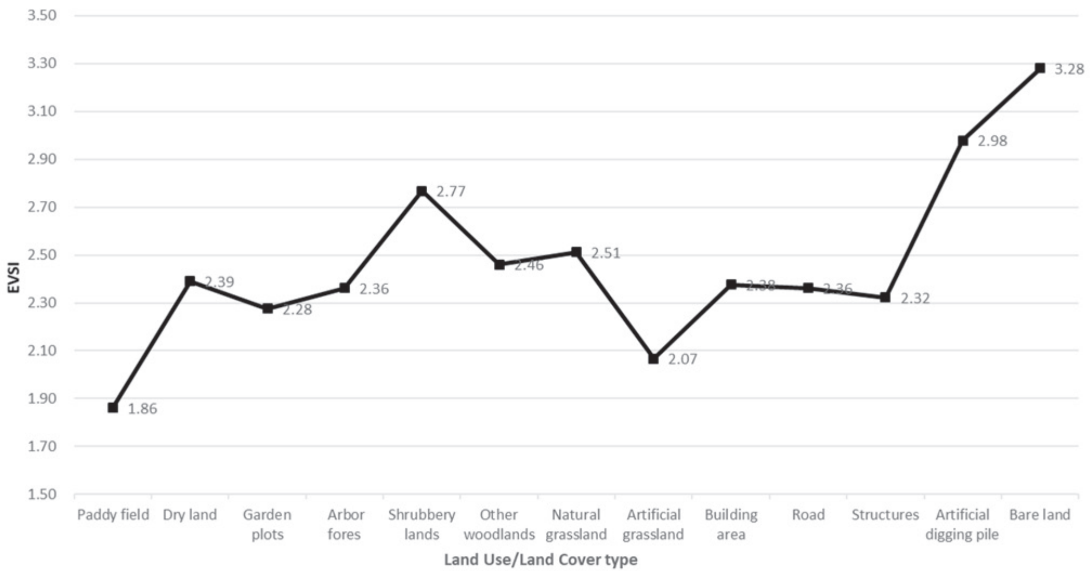

Fig. 8. Average value of ecological vulnerability index of different land types.

were more prone to land degradation and soil erosion. The ecological vulnerability indexes of the paddy fields and artificial grasslands were lower than those of other land use types, among which the EVSI of the paddy fields (1.86) was the lowest and was significantly lower than that of dry land (2.39). The EVSI of artificial grass (2.07) was lower than that of natural grassland (2.51). The EVSI values of the garden, arbor forest, and other forest land (mainly green forest land) were relatively close, but the EVSI of shrub land was higher than that of other forests, which was the most vulnerable forest type and reached the grade of mild vulnerability.

The change of land use type has an important influence on the ecological environment and its vulnerability. In order to analyze and explore the impact of different land use types on vulnerability, land use data and ecological vulnerability data were used for a spatial overlay analysis during 2006 and 2015. The results are shown in Table 7. It can be seen from the table that when other land use types are converted to bare land, the EVSI rises by an average of 0.7750, and the ecological levels have the maximum rise in vulnerability. When the grassland was converted to bare land, the ecological environment deteriorated by the largest extent, and the EVSI value increased to 1.4057, followed by cultivated land (+1.2393) and forest land (+0.8822), and the smallest change was observed for gardens (+0.3949). When other types of land were converted to garden, the EVSI decreased by an average of 0.3208, and the degree of ecological vulnerability decreased by the largest amount. When the bare land was converted to garden, the ecological environment improved and the EVSI value decreased to 0.9661, followed by artificial digging land (-0.5617), forest land (-0.3397), and the smallest change was observed for gardens (-0.1235). When the grassland was converted to other land use

Table 7. Effects of different land use types on ecological environment vulnerability.

EVSI CL		Land use and land cover types in 2015									AVG
		GP	WL	GL	UC	R.	S.	AP	BL		
Land Use and Land Cover Types in 2006	**CL**	——	-0.1235	-0.3329	-0.3906	0.6833	0.2371	0.5782	0.7747	1.2393	0.2937
	GP	0.0381	——	-0.1808	0.3315	0.2218	-0.1409	0.1046	0.5988	0.3949	0.1066
	WL	0.2579	-0.3397	——	-0.0522	0.2223	0.2314	0.3507	0.8449	0.8822	0.2725
	GL	0.2728	-0.1570	0.2533	——	0.3035	0.3336	0.0699	0.7243	1.4057	0.3562
	UC	0.0834	-0.2743	0.0741	0.3619	——	0.3702	0.2722	0.8666	0.7499	0.3262
	R.	-0.0338	-0.1960	0.0560	0.0392	0.4319	——	0.2026	0.6850	0.6915	0.2256
	S.	0.1238	0.1398	-0.0716	0.1093	0.3281	0.1476	——	0.5343	0.4458	0.2344
	AP	-0.3302	-0.5617	-0.3391	-0.6744	-0.1085	0.0939	-0.0018	——	0.7417	-0.1015
	BL	-0.3377	-0.9661	-0.3861	-0.2987	0.3591	0.0222	-0.2317	0.7828	——	-0.0703
AVG		0.0058	-0.3208	-0.0969	-0.0638	0.3193	0.1610	0.1886	0.6753	0.7750	——

CL: Cultivated land; **GP**: Garden plot; **WL**: Woodland; **GL**:Grassland; **UC**: Urban construction land; **R.**: Road; **S.**: Structures; **AP**: Artificial digging land; **BL**: Bare land.

types, the degree of ecological vulnerability increased the most, and EVSI values increased by an average of 0.356. When grassland was transformed into bare surface, the EVSI values increased to the maximum value (+1.4057). When the artificial digging land was transformed into other land use types, the degree of ecological vulnerability decreased the most, with an average decrease of 0.1015. When other land use types were transformed into garden land, the degree of vulnerability decreased the most (-0.9661).

In general, the transformation from bare soil or artificial digging land into farmland, garden, woodland, and grassland decreased ecological vulnerability, and the ecological environment was greatly improved. On the contrary, when cultivated land, garden land, forest land, or grassland was transformed into bare land surface, the degree of ecological vulnerability was raised and the ecological environment suffered further deterioration.

Discussion on Dynamic Evaluation of Ecological Vulnerability

Much traditional research on ecological environment evaluation rely only on economic statistics on administrative units or perform assessment in a single time scale. It is different from traditional research that RS data, meteorological data, and economic statistics data are used in the Fuxian Lake watershed to evaluate ecological vulnerability. Based on RS and GIS technology, the ecological vulnerability of Fuxian Lake Basin and its changes in the past 40 years have been studied. Research results provide a scientific basis for the exploitation of tourism resources and the protection of ecological environment in this basin. Meanwhile, our study also analyzed the impact of land use and land use change on the ecological environment, which provided support for the study of the impact of human activities on the ecological environment. However, the impact factors of environmental change are numerous, and different research areas have different main impact factors. In this connection, future research should focus on driving force analysis of ecological environment change. As all economic statistics are spatialized according to administrative units, how to truly reflect the distribution of statistical data in the geographical space is also the focus of follow-up research.

Conclusions

Based on RS and GIS technology, RS data, meteorological data, and economic statistics were used in the Fuxian Lake watershed to evaluate ecological vulnerability. Using the "cause and effect" evaluation model, relying on the RS image pixel as the basic evaluation unit, the ecological vulnerability and the dynamic changes were evaluated using the AHP method in the Fuxian Lake Basin from 1974 to 2015. The main conclusions were as follows:

1) From 1974 to 2015, the ecological environment vulnerability of the Fuxian Lake Basin showed a trend of "overall stability but local strengthening." The annual EVSI value of the basin was between 2.55±0.16, which is a transitional grade between micro-vulnerability and mild vulnerability. The vulnerable areas of the ecological environment were mainly distributed in the regions of Fuxian Lake on the east and west coastal areas with steep terrain and relatively serious soil erosion, and also distributed in the regions near Chengjiang County on the north shore of the lake and in the northern mountainous areas, particularly the ecological region of the east coast of the lake, where the ecological environment was the most vulnerable. The stable zone of the ecosystem was mainly distributed in the forest area around the lake and the paddy fields or dry land fields of Chengjiang County town. These locations had a low degree of ecological vulnerability characterized by low environmental stress and no ecological abnormalities. The moderately vulnerable regions of the southeastern coast of Fuxian Lake showed a trend toward increasing vulnerability and further deterioration. Some areas showed obvious weaknesses in the structure and function of the ecosystems and sensitivity toward external disturbances, and ecological vulnerability was approaching or had reached the level of severe vulnerability.
2) The changes of vulnerability to unit area values mainly transformed the mild vulnerability grades to micro vulnerability grades, and the other grades exhibited fewer changes in the Fuxian Lake Watershed. The unit area values for severe vulnerability regions generally showed an upward trend, reaching 1.92 km^2 by 2015, which had a larger increase but smaller unit area value. On the basis of maintaining the degree of original vulnerability, the vulnerability of each grade was most commonly converted to the adjacent grade. The degree of ecological vulnerability was more commonly converted toward a more severe grade, and regions were less likely to recover from the severe vulnerability grade. Due to the expansion of the city and the intensification of human activities, the EVI showed a significant increasing trend, especially in the region near Chengjiang County town, Fuxian Lake east and west coasts, and the large area around the town of Jiangchuan County. Due to the implementation of a policy aimed at returning farmland to forest and grassland, the ecological environment has greatly improved and the ecosystem tends to be stable in the forests surrounding the mountainous regions of the Fuxian Lake Basin.
3) By comparing and analyzing the EVSI values of ecological vulnerability on different types of land use and the change of the ecological vulnerability index, this study has shown that land use type and changes had an important influence on the ecological

environment and its vulnerability. This study found that the ecological vulnerability index of the bare land in the Fuxian Lake Watershed was highest and most vulnerable (3.28), followed by artificial digging land (2.98), shrubs and woodland (2.77), natural grasslands (2.51), other woodlands (2.46), arid regions (2.39), urban construction land (2.38), roads (2.36), arbor forests (2.36), structures (2.32), gardens (2.28), artificial grasslands (2.07), and paddy fields (1.86). At the same time, the results showed that when other land use types were converted to bare land, the ecological vulnerability increased the most, and the ecological environment worsened when the grassland was converted to bare land. It can be seen that natural grasslands were the key to preventing the ecological environment from being weakened, and therefore grassland degeneration to bare land should be avoided. However, when the bare land or the artificial digging land were converted to woodland or grassland, the ecological vulnerability could be greatly reduced, and the ecological environment improved greatly, thereby showing that the policy aimed at returning farmland to forest and grassland was of great significance to regional eco-environmental protection, which could effectively avoid further deterioration of the ecological environment.

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Conflict of Interest

The authors declare no conflict of interest.

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