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ECOLOGICAL SECURITY MEASUREMENT BASED ON FUNCTIONALITY-ORGANIZATION-STABILITY IN INLAND OF THREE GORGES RESERVOIR AREA

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Highlights

- Functionality-Organization-Stability evaluation model is first applied for the research paradigm for the landscape ecological security research.
- The Moran' I value of landscape ecological securities are more than 0.5, which shows strong spatial positive correlation property.
- Spatial autocorrelation analysis was applied to examine the landscape ecological security pattern.
- The obstacle degree factor changes from ecosystem service and land use diversification to instability of the landscape pattern.

Abstract. The spatial-temporal heterogeneity of landscape ecological security has been carried out for the Zhong County in this work based on the framework of "functionality-organization-stability" using the multidate Landsat TM image of 2000, 2006, 2012 and 2018 as the basic data. During the research period, landscape ecological security situation in Zhong County indicates a trend of deteriorating. The high ecological security zone was constantly shifting to the low ecological security zone from 2000 to 2018. The ratios were 13.40%, 61.32%, 28.34%, and 13.33%. The low ecological security area in research area focuses on the northeast part and middle part, while the high-security area focuses on Yangtze river way and its both sides and Northwest. The main obstacle factor of landscape ecological security transfers into stability from functionality. Therefore it suggests to optimize land use pattern in landscape planning and construction in the future in order to raise the landscape ecological security level.

Keywords: landscape ecological security, landscape index, spatial autocorrelation, obstacle degree.

Introduction

Maintaining ecological security has become an important task for human society to achieve sustainable development in the 21st century (Lu et al., 2018). As an important part of ecology, the security of landscape ecology plays a key role in the ecological security. Landscape ecological security refers to the health level of landscape ecosystem and sustainability of regional landscape environment influenced by natural factors and human activities (Chu et al., 2017). Assessment on landscape ecological security refers to the state assessment and trend research of landscape ecological security. Landscape ecological security is not only the goal of regional sustainable development, but also an important guarantee for regional sustainable development (Li et al., 2019a).

The construction of a comprehensive and effective ecological security evaluation index system is the key to accurate and quantitative evaluation of ecological security. Among all the systems available, the index system based on pressure-state-response (PSR) proposed by the United

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Nations Development Programme (Shi et al., 2018; Hazbavi et al., 2019) and the index system based on the conceptual framework of driver-pressure-state-impact-response (DPSIR) (Ruan et al., 2019) are two of the best-known and most widely used index systems at present. Due to the fuzziness and uncertainty of ecological security, when conducting evaluations, most of the existing research index thresholds refer to the ecological rating standards specified at home and abroad, while the evaluation indicators are mostly social, economic statistical indicators and ecological environment indicators. The evaluation frameworks mostly used are grey GM(1,1) framework (Yang & Wang, 2020; Bai et al., 2021), system dynamics method (Lu et al., 2019), ecological framework (Li et al., 2019a; Čuček et al., 2015; Wang et al., 2012) and BP neural network (Wu & Xie, 2019). The interaction and mechanism of various influencing factors have not been clarified in the current research. Hence, the research on the formation mechanism of landscape ecological security needs to be furthered (Ou, 2019). It has drawn the scholars' attention that the evaluation index system of landscape ecological security relies too much on social statistical data such as statistical yearbooks (Wei et al., 2018). Therefore, more explanations to the natural attributes of regional land ecology should be emphasized in future studies. Most of these evaluation indicators are based on natural indicators and social indicators, which leads to the lack of in-depth evaluation as well as reduces the general applicability of the evaluation methods (Lu et al., 2020).

Too many human activities in ecologically fragile areas could have a great extent impact in the ecological security by damaging the landscape health of the region, causing eco-environmental problems and thus resulting in economic and social instability (Strain et al., 2019). Therefore, the effective evaluation of landscape ecological security in ecologically fragile areas is of great significance in the process of grasping, constructing, and optimizing the landscape ecological security pattern in ecologically fragile areas. The Three Gorges Project in China is the largest hydropower project in the world, and its construction has benefited the particular region in flood control (Zhao et al., 2017), power generation, shipping and water supply. The place where the Three Gorges Project was implemented is an ecologically fragile area, where many researchers went to examine the geological features (López-Pujol & Ren, 2009; Qian et al., 2020). The ecological security of the Three Gorges Reservoir area is tightly connected to the sustainable development of the whole Yangtze River Basin (Gao et al., 2017).

With the construction of the Three Gorges Reservoir Project and the stimulus of municipal policies, the landscape pattern of Zhong County in the hinterland of the Three Gorges Reservoir area has changed greatly in the past two decades (Xu et al., 2020). Such artificial disturbance has greatly changed the original landscape pattern, and it is also a typical case in landscape ecology research (Ke et al., 2021). However, most of the existing literature focuses on research on a larger scale, and there are few studies on the landscape ecological security of such typical districts and counties (Wen & Hou, 2021). So, this study based on the ecosystem service value, land use diversification index and landscape index, and established a "functionality-organization-stability" landscape ecological security assessment framework, taking Zhong County as the research object, a typical county in the Three Gorges Reservoir area, to evaluate the ecological security by superposition method. This research provides a new landscape ecological security assessment framework and ideas based on remote sensing big data.

1. Data sources and research methods

1.1. Overview of the research area

Zhong County, located in the hinterland of Chongqing province, China, in the belly of the Three Gorges Reservoir, in the north bank of the Yangtze River, between 107°3′–108°14′E and 30°03′–30°35′N. The county town is surrounded by mountains and water, and has the unique style of an island country. It is the only "semi-damped county town" remaining in the Three Gorges Reservoir Area. Zhong County is adjacent to Wanzhou in the east, Shizhu in the south, Fengdu and Dianjiang in the west, and Liangping in the north. It is a key county for the migration of the Three Gorges. The Yangtze River winds from the northeast into the county area and winds southwest. The length of the Yangtze River in the study area is about 88 km. Hills are the dominant terrain, with a summit that reaches 1674 m. The geographic location of Zhong County is shown in Figure 1. This region has a typical subtropical monsoon climate with an annual average precipitation 1200 mm. The total area of this land is approximately 2,187 km^2, with a population of 1.02 million people in the end of 2018. The urbanization level (urbanization rate) was 44.9%, and GDP was 30.795 billion yuan in 2018 at this regional.

1.2. Data source and preprocessing

The 2000, 2006, 2012 and 2018 remote sensing data are used in this study. These data set is provided by Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences. These data have a spatial resolution of 30 m. Then the fourth phase of TM image data are preprocessed based on ENVI 5.2 remote sensing image processing platform, such as radiometric calibration, atmospheric correction and so on.

According to the national land use status classification standards and actual research aims, the land cover of Zhong County is divided into six types of land features include forest land, grassland, construction land, cultivated land, water area and unused land. Field selection and verification of land use interpretation results and vegetation coverage were carried out and surveys were conducted. According to statistics, the interpretation accuracy of each land use and cover is above 88%, and the classification accuracy is high, which meets the requirements of subsequent analysis changes.

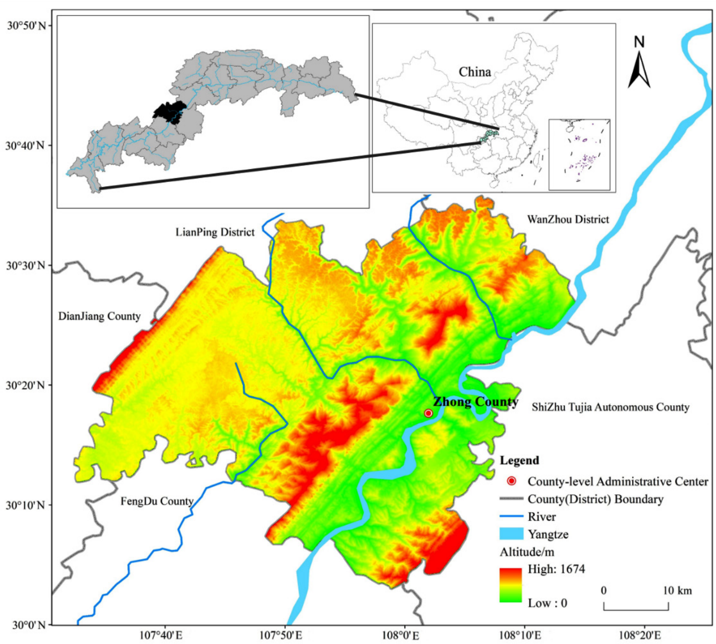

Figure 1. Geographic location of Zhong County

1.3. Indicators selection

1.3.1. Selection of functional indicators

When selecting specific indicators, high-frequency indicators in previous literature (Ke et al., 2021; Ruan et al., 2019; Carlier & Moran, 2019; Chu et al., 2017; Wang & Pan, 2019; Guo & Wang, 2019) are referred to and the important influencing factors mentioned in the study "Guiding Opinions of the State Council of China on Promoting the Development of the Yangtze River Economic Belt by Relying on Golden Waterways" are combined to construct the ecological security assessment of Three Gorges Reservoir area in accordance with holistic, representative, and operable principles.

Landscape pattern security and landscape quality security are two important references for ecological security assessment, but with the increasing interactions between human and landscape and the awareness of the influences of ecological services on the sustainability of landscape development, the value of landscape ecological services has raised considerably (Bommarco et al., 2013). The premise of a secure ecology is the positive ecological services provided by the ecosystem for human beings (Wang & Pan, 2019). As a direct indicator of the coordination between nature and human production and living activities, the value of ecosystem services is an important reference to measure the quality of land ecological environment (Xu et al., 2016). Land is an important resource and material guarantee for human survival and development (Chen, 2015). The diversity of land use has a potential impact on the productivity and function of the ecosystem (Zhu et al., 2020; Xie et al., 2020), ranging from the diversity of butterfly species (Sharma et al., 2020) to the difference of forest function (Pyles et al., 2020). Therefore, the degree of land use diversification is also a necessary factor to measure landscape ecological security.

The rapid development of the city has contributed to the rapid growth of the demand for construction land. Most of construction land is converted from cultivated land and ecological land, including forestland and grassland. Due to the limited cultivated land resources, cultivated land is often supplemented by reclaimed ecological land (Xie et al., 2020). At the same time, because of the unsustainable land use change and intensification, the landscape fragmentation is intensified (Kovacs-Hostyanszki et al., 2017). Since the weakening of landscape connectivity also has an impact on landscape ecological security (Carlier & Moran, 2019), it is necessary to measure the landscape connectivity. How to obtain landscape connectivity information objectively has become an important research question. Landscape index, in a simple and quantitative form, digitizes the landscape, highly condenses the landscape pattern information, and reflects the characteristics of some aspects of its structural composition and spatial allocation (Turner, 2005). It is also the basis of the analysis of the structure, function and process of the landscape. Furthermore, being a simple quantitative index (Wu, 2007) that reflects the characteristics of landscape structure and spatial allocation, it can provide a quantitative basis for scientific measurement of landscape structure characteristics (Zhang et al., 2020b). According to the actual characteristics of Zhong County, the corresponding landscape pattern index is selected from both the patch level and the landscape level.

1.4. Landscape ecological security assessment framework based on "functionality-organization-stability"

Based on the discussion of "1.3", this paper constructs a scientific and reasonable ecological security assessment

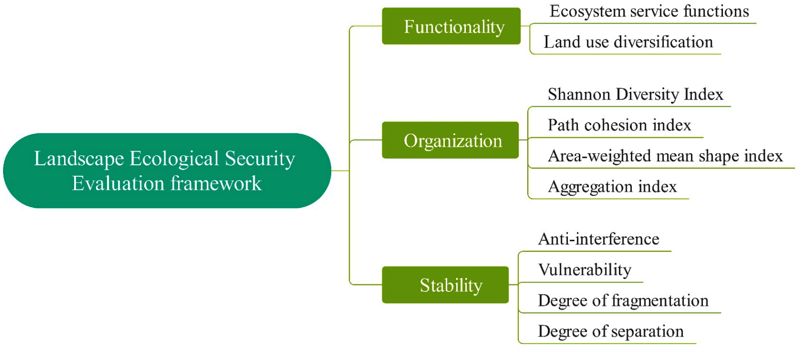

Figure 2. Landscape ecological security assessment framework

framework based on "function-organization-stability" (Figure 2).

Combined with the regional characteristics of Zhong County in the three Gorges Reservoir area, following the scientific nature, comparability, accessibility and extensibility of indicators, referring to other studies, based on the "function-organization-stability" evaluation system, using different indicators to measure the security status of the ecosystem in the dimensions of function, land use, landscape connectivity and stability, the landscape ecological security evaluation index system of Zhong County was constructed. It consists of 3 second-level indices and 10 third-level indices (Table 1).

1.4.1. Calculation of a comprehensive index of landscape ecological security

On the basis of global comprehensive analysis, the Zhong County area is gridded, and then the landscape ecological security index of each grid is calculated, and the landscape index is spatialized by interpolation, so that a more detailed analysis of landscape ecological security can be made. The specific method is as follows:

In the grid division method and scale of the study area, the area and scope characteristics of the study area were fully considered by referring to researches of relative scholars (Wu, 2011; Jin et al., 2021) and a 3.25 km × 3.25 km

Table 1. Regional ecological security assessment system based on the functionality, organization and stability

Target later	Project layer	Index layer	Positive or negative	Weight	Meaning
Landscape Ecological security index	Functionality	Ecosystem service functions	+	0.1734	Ecosystems not only provide food, medicine and raw materials for industrial and agricultural production necessary for human survival, but also maintain the life support system for human survival and development. The stronger the service function, the relatively security the regional ecology
		Land use diversification	+	0.1511	This is an important indicator reflecting the overall type structure and completeness of land use types. The value ranges from 0 to 1, and the closer to 1, the higher the degree of land use diversification, the greater the functionality in the region
	Organization	Shannon's diversity index	+	0.0678	The Shannon Diversity Index is sensitive to the uneven distribution of various types of patches in the landscape. The richer the land use, the higher the heterogeneity and the stronger the organization of the landscape
		Path cohesion index	+	0.0703	A high path cohesion index indicates that certain dominant patch in the landscape has had the good aggregation connectivity; that is, the higher the patch aggregation index, the better the connectivity and the stronger the organization of the landscape
		Area-weighted mean shape index	+	0.0705	This indicator characterizes the overall characteristics of the regional landscape pattern, to some extent, it reflects the impact of human activities on the landscape pattern
		Aggregation index	+	0.0893	The aggregation index usually measures the degree of aggregation of the same type of plaque. The higher the degree of aggregation, the more the plaque is clustered. The better the connectivity, the stronger the organization of the landscape
	Stability	Anti-interference	+	0.1109	The anti-interference ability of the landscape to the outside world and the ability to recover itself after being stressed by the external pressure, the greater the ability to restore the original function and structure, the more stable the landscape structure

End of Table 1

Target later	Project layer	Index layer	Positive or negative	Weight	Meaning
		Vulnerability	–	0.0921	It mainly describes the ability of the natural properties of landscape to resist the interference after the external interference
		Degree of fragmentation	+	0.0832	The degree of fragmentation represents the degree of fragmentation of the landscape, reflects the complexity of the landscape spatial structure, and to a certain extent reflects the degree of human interference with the landscape. It is a process in which the landscape caused by natural or man-made interference tends to be complex, heterogeneous and discontinuous patch mosaic from a single, homogeneous and continuous whole
		Degree of separation	–	0.0914	The degree of separation is used to describe the degree of separation of the distribution of different landscape types within a research grid

grid was created for input sampling and evaluation o by using the Fishnet Tool of ArcGIS10.2, and 204 grids were obtained. The calculated values of 204 fishing grids were assigned to the central point corresponding to the number in turn. Finally, the temporal and spatial distribution of landscape ecological security was obtained in the study area by using Kriging interpolation method for interpolation, which realized the spatialization of the landscape ecological security.

The weighted summation method was applied to calculate the functional index, organizational index and stability index of each grid, respectively and those three indexes were summed and multiplied by the corresponding weight values. Then the standardized values were used in the calculation process. The equation is as follows (Li et al., 2019b):

$$Y_j = \sum_{i=1}^{n} w_i \times X_{ij}, \tag{1}$$

where: Y_j is the index of regional landscape ecological security in the *j*th year, w_i is the weight of the *i*th indicator, and X_{ij} is the standardized value of indicator of *i*th index in the *j*th year.

1.4.2. Analysis on the framework of landscape ecological security evaluation

(1) Functionality. Ecosystem service function is the basis for human beings to provide a variety of products and services, and the greater the value of services, the more dynamic the ecosystem, and the healthier the landscape ecology. Besides land use change is affected by many factors, such as nature, society, economy, man and so on. At the same time, methods, by which land is used, are diversified due to the different action mode and intensity of each driving factor, the way of land use is diversified. Thus, it has a certain impact on the structure of the whole ecosystem, and finally affects the quality of landscape ecological security. Different land use types will lead to different ecological functions, and the ecological functions and value of different land use types are also different. Therefore, the function of regional ecological security is measured according to the land use diversification index GM and the improved Chinese terrestrial ecosystem service value coefficient (Xie et al., 2015). Based on the "Equivalent Table of Ecological Service Value per Unit Area of Chinese Ecosystem" proposed by Xie Gaodi (Xie et al., 2015), there is a one-to-one correspondence between the land use types in this study and their ecosystems have a one-to-one correspondence: cultivated land to farmland, woodland to forest, grassland to grassland, water area to Rivers/lakes, unused land to deserts, appropriately modified according to the actual situation of Zhong County, so as to determine the value equivalents of the six types of ecosystem services in this study, as shown in Table 2.

Table 2. Ecosystem service equivalent value of different land use type

Land cover type	Coefficient of ecosystem services value per unit area (hm^2)
Forestland	22.95
Grassland	12.06
Water bodies	125.61
Construction land	0
Cultivated land	3.95
Unused land	1.3

The equation for estimating the value of ecosystem services is:

$$ESV = \sum A_i \times VC_i, \tag{2}$$

where: ESV refers to the the total value of ecosystem services for each grid; A_i indicates the area of the *i* land use type (hm^2) and VC_i means the coefficient of the ecosystem service value coefficient per unit area (hm^2).

The degree of land use diversification reflects the overall type structure and complete degree of land use, and is an important index to quantify regional land function (Vizcaíno-Bravo et al., 2020). The equation is as follows (Patel & Rawat, 2015):

$$\mathrm{GM} = 1 - \frac{\sum_{i=1}^{n} f_i^2}{(\sum_{i=1}^{n} f_i)^2}, \tag{3}$$

where: *GM* is the degree of land use diversification, and f_i is the area of land use type-i. The *GM* value is between 0 and 1, and the closer it is to 1, the higher the degree of land use diversification in this area.

(2) Organization. From the perspective of landscape ecology, regional ecological security is determined by the landscape pattern related to spatial heterogeneity and landscape connectivity (Fu et al., 2011). In this paper, the quantification of the landscape heterogeneity of the landscape was based on Shannon diversity index, patch cohesion index, aggregation degree and area-weighted mean shape index, and the patch cohesion index describes the natural state connectivity of each patch type. Importing land use data into Fragstats 4.2 software for analysis can get these landscape indexes through calculation with this software. Generally speaking, the high cohesion index indicates that the aggregation degree of this patch type in the landscape is higher. In other words, the higher the degree of sprawl and the index of patch cohesion, the better the connectivity of the landscape and the stronger the organizational force of the landscape.

(3) Stability. The absolute stability does not exist because the landscape changes at any time, but it is relative to the stability of a certain time and space (Fu et al., 2011). As for the anti-interference ability of the landscape to the outside world and the ability of self-recovery after external pressure stress, the greater the ability to restore and maintain the original function and structure, the smaller the degree of vulnerability and landscape fragmentation and separation, and the more stable the landscape structure.

The anti-interference of the landscape indicates the anti-interference ability of the landscape to the outside world, and the calculation equation is as follows (Xu, 2018):

$$\mathrm{K} = \frac{C}{P \times T}, \tag{4}$$

where: K is the landscape anti-interference; *C* indicates the contagion index (CONTAG); *P* represents the path density and *T* is the total edge contrast index (TECI). Reference is based on related literature, and adding edge contrast index (Xu et al., 2018) is made (Table 3) in order to calculate the data of each indicator with Fragstats 4.2 software.

Table 3. Edge contrast settings

Land cover type	Unused land	Water bodies	Construction land	Cultivated land	Grassland	Forestland
Land cover code	1	2	3	4	5	6
1	0	0.4	0.9	0.3	0.2	0.3
2	0.4	0	0.8	0.3	0.4	0.6
3	0.9	0.8	0	0.3	0.9	0.9
4	0.3	0.3	0.3	0	0.3	0.3
5	0.2	0.4	0.9	0.3	0	0.3
6	0.3	0.6	0.9	0.3	0.3	0

Because patches have different boundary types: curved or straight, gradual or abrupt, hard or soft, patches with straight, abrupt, and hard boundaries have high contrast with other patches (Huang et al., 2020). Those with relatively neat boundaries Artificial patches (such as cultivated land and construction land) have high contrast with other patches. Accordingly, when setting the edge contrast between patches of different land types, the following principles shall be followed: between hard boundary (construction land, cultivated land, etc.) and soft boundary (woodland and grassland) > hard boundary and neutral hardness boundary (water area, Unused land).

Landscape vulnerability is used to describe the degree of difficulty of landscape changes due to the combined effects of humans and nature, and the calculation equation is as follows (Zhi et al., 2017):

$$F_i = \frac{A_{ki}}{A_k} \times \delta, \tag{5}$$

where: F_i is the landscape vulnerability of landscape type *i*, and δ is the weight. Combined with the previous research results, the land use type is divided into six relative weight scores: unused land = 6, grassland = 5, cultivated land = 4, woodland = 3, water area = 2, construction land = 1, according to the difficulty of transforming land use type into other land use. A_{ki} is the area of landscape type *i* in the grid, and A_k is the area of *k*-area of the evaluation unit.

The degree of fragmentation represents the degree of fragmentation of the landscape and it reflects the complexity of the landscape spatial structure, and the Mean patch size (MPS) can indicate the degree of fragmentation of the landscape. At the patch level, a patch type with a smaller MPS value is more broken than a tile type with a larger MPS value (Wu, 2007). So, the change of MPS value can feedback richer landscape ecological information, and MPS is also the key to reflect landscape heterogeneity.

Split, as the landscape index, is applied to describe the degree of fragmentation of the ecosystem after it is disturbed. The larger the value, the more scattered the landscape types are in the region. The size of this indicator reflects changes in biodiversity. Division is Landscape Division index and it represents the division degree of individual distribution of different patch numbers in a landscape type.

If a landscape has a greater the degree of landscape separation, it gets easier affected by natural factors and human activities, so there will be more drastic changes in the landscape. On the contrary, a landscape becomes more stable if its degree of separation is lower. Landscape index MPS and Division both indicate the degree of landscape separation, so they are selected to represent the degree of landscape separation, and the equation is as follows:

$$C_i = 0.5 \times Division + 0.5 \times Split, \tag{6}$$

where: C_i is landscape separation degree. Because that they have different meanings and cannot be substituted for each other, the weights of them are equal. The index weights are both set to 0.5, and they are calculated by Fragstats 4.2.

1.4.3. Standardization of indicator data

In the regional ecological security assessment, given that the properties of the index are different from those of the selected index and the units used are not exactly the same, normalization standard processing was carried out on the initial data before measurement and analysis for the sake of ensuring the comparability of index data and eliminating the dimensional influence between indexes, so that the result was mapped between [0,1]. In this way, the process can eliminate the effect of size and numerical size on the results (Ma et al., 2019)

Positive index:

$$X = \frac{x - \min}{\max - \min}. \tag{7}$$

Negative index:

$$X = \frac{\max - x}{\max - \min}, \tag{8}$$

where: x and X are the initial and the standardized values of sample index; max and min are the maximum and minimum values of sample index (Table 1).

1.4.4. Calculation of each indicator weight in the framework

In order to reduce the influence of subjective factors on the determination of weights, the inherent information of evaluation indicators is used to judge the utility value of indicators, so this study uses the approach of combining the AHP and entropy method to weight the indicators. That is, the sub-goal level and the criterion level are weighted by the AHP; the index layer is weighted by the entropy method, and finally, each index weight is obtained based on weighted processing (Wu et al., 2021; Ke et al., 2021). Then the final weighted weight of each index is:

$$w = x \times y \times z, \tag{9}$$

where: w is the weight of the evaluation index. The influence weight of the sub-goal layer on the goal layer be x; the influence weight of the criterion layer on the sub-goal layer be y, and the influence weight of the index layer on the criterion layer be z. According to the AHP and expert scoring, the weight of each sub-goal layer to the total goal layer and the criterion layer to the sub-goal level are equal. That is, the weight of functionality, organization, stability to landscape ecological security is 0.3333, and the weight of each criterion layer is 0.5. The weight of each index layer to different criterion layers is determined by the entropy value of each indicator (Table 1).

1.5. Spatial autocorrelation analysis of landscape ecological security

Spatial autocorrelation analysis is used to examine whether the value of a spatial variable is related to the value of the variable in adjacent spaces and the spatial autocorrelation coefficient is calculated to quantitatively describe the distribution pattern of things in space (Zhang et al., 2008). In this way, the spatial dependence of variables and spatial heterogeneity are revealed. And the spatial autocorrelation coefficient is often applied to quantitatively describe the spatial dependence of things.

Moran's I index and global spatial autocorrelation were used to verify the spatial correlation of ecological security and scientific degree of the assessment system (Zhang et al., 2020b). The equation of the Moran's I index is as follows (Ren et al., 2020).

$$\text{Moran's } I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right)}{S^2 S_0}, \tag{10}$$

where: $\{x_i\}$ is the value of i at a location or area; $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ is mean value of variable; $S^2 = \frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{\boldsymbol{x}}\right)$ is variation, $S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}$ is Sum of spatial weights of all variables; n is the total number of variable observations and it is also the total number of areas or positions corresponding to the observations; W_{ij} is the aggregate of all spatial weights. If the pixel i and pixel j are adjacent, the value of corresponding element in the matrix W_{ij} is 1, otherwise it is 0.

To investigate the statistical significance of the Moran's I statistic, $Z(I)$ is calculated as follows (Ren et al., 2020):

$$Z\left(I\right) = \frac{1 - E\left(I\right)}{\sqrt{Var\left(I\right)}}, \tag{11}$$

where: $E(I)$ is the expected value of I: $E(I) = -\frac{1}{n-1}$, and $\sqrt{Var\left(I\right)}$ is the expected variance of I: $\sqrt{Var\left(I\right)} = E\left(I^2\right) - E\left(I^2\right)$. When a significance level is established, a Moran's I approaching +1 indicates that landscape ecological security value is spatially correlative. When the value of Moran's I is close to −1, it indicates a discrete data pattern. If the Moran's I value is close to 0 and the z-score is high (more than the significance level), the null hypothesis is accepted and the landscape ecological security value is distributed randomly.

The application of the Local Indicators of Spatial Association (LISA) index is made in the analysis of the local autocorrelation of landscape ecological security, so as to describe the correlation degree of landscape ecological security between each local and adjacent grids. It can also measure the degree of difference in landscape ecological security among a grid and its adjacent grids and its significance, and it is actually a decomposition of the global Moran's I index. The equation is as follows (Ren et al., 2020):

$$I = Z_i\left(W_{ij} Z_j\right), \tag{12}$$

where: Z_i and Z_j are standardized value of the attribute of i observation of area unit; $\{W_{ij}\}=W$. Generally speaking, it is a row normalized spatial weight coefficient matrix. Namely, $\sum W_{ij}=1$, at this time, $\frac{1}{n}\sum_i I_i = i$ Moran's *I*. With a statistical test (Z-test), the Anselin Local Moran's I can identify HH (High–High clusters), LL (Low–Low clusters), LH (low value surrounded by high values) and HL (high value surround by low values) at 95% confidence level.

A positive value of *I* means that a grid with a high (low) landscape ecological security value is surrounded by a high (low) grid, which is recorded as HH (High–High clusters) or LL (Low–Low clusters); a negative Ii means that a grid with a high (low) landscape ecological security value is surrounded by a low (High) surrounded by a grid, which is recorded as LH (low value surrounded by high values) and HL (high value surround by low values) (Zhang et al., 2020b). Although both the Lisa index and the Moran's *I* scatter plot can identify the distribution of the security value of a grid in a landscape and the specific related characteristics of the surrounding grids. It can more intuitively compare the difference in landscape ecological security values between adjacent areas based on the size of the Lisa value.

1.6. Landscape ecological security obstacle degree model

In order to deeply study the obstacle factors affecting the landscape ecological security of Zhong County in the study area, and reveal the contribution of each evaluation index, that is, the action mechanism of the obstacle factors, it is necessary to evaluate the obstacle degree of each index and find out the main factors that affect the landscape ecological security (Zhang, 2013; Ou, 2018; Feng et al., 2018), and reveal as soon as possible how the driving factors affect the changes in landscape ecological security. The calculation equation of the obstacle degree of each indicator is as follows Equations (13)–(15):

$$U_{ij} = 1 - X_{ij}; \tag{13}$$

$$b_{ij} = U_{ij} \times w_i \,/ \sum_{j=1}^{n} U_{ij} \times w_i \times 100\%; \tag{14}$$

$$B_j = \sum_{i=1}^{m} b_{ij}, \tag{15}$$

where: U_{ij} is the gap between each indicator and the landscape ecological security goal. That is, the difference between each standardized indicator and 100%; w_i is the index weight of each index in the entire index system, b_{ij} is the obstacle degree of the i th classification index in the *j*th year to the overall goal of landscape ecological security. B_j is the impact degree of the classification index in the *j*th year on the overall goal of landscape ecological security.

2. Results

2.1. Changes in landscape ecological security over time in the study area

At present, there is no unified standard for the classification of landscape ecological security. Based on the relevant research results (Ou, 2018), this article uses the natural breakpoint method to divide the landscape ecological security standards into 6 levels, as shown in the Table 4. Natural breakpoint method, when the classification number is determined, iteratively calculate the data breakpoints between the classes to minimize the differences in the classes and maximize the differences between the classes, so as to group the similar values in the data most appropriately. This method better maintains the statistical

Table 4. The class level of landscape ecological security evaluation criteria

Class	Landscape ecological security value range	Landscape ecological security level	Landscape ecological security status
I	[0, 0.36]	Very unsecurity	The landscape pattern is severely damaged, changes are severe, the structure of the ecosystem is seriously unbalanced, the function of the landscape ecosystem is completely lost, the ecological environment is severely damaged, and human life is restricted
II	(0.36, 0.42]	Unsecurity	The landscape pattern is further destroyed, the ecosystem structure is missing, the landscape ecosystem function and the ecological environment are greatly degraded, and human life is restricted by obvious environment factors
III	(0.42, 0.48]	Critical security	The stability of the landscape pattern has been destroyed, the structure of the ecosystem has undergone certain changes, the function of the landscape ecosystem is basically normal, and the ecological environment has begun to degenerate
IV	(0.48, 0.54]	General security	The landscape pattern is generallly stable and harmonious, the ecosystem structure is generallly complete, and the landscape ecosystem function is generally complete
V	(0.54, 0.60]	Relatively security	The landscape pattern is relatively stable and harmonious, the ecosystem structure is relatively complete, and the landscape ecosystem function is relatively complete
VI	(0.60, 1]	Ideal security	The landscape pattern is stable and harmonious, the ecosystem structure is complete, and the landscape ecosystem has perfect functions

characteristics of the data (Zhang et al., 2020a). The higher the value of landscape ecological security, the higher the degree of ecological security, the better the landscape ecological security.

The area and proportion of each ecological security grade in 2000, 2006, 2012 and 2018 are calculated in ArcMap software, and the result as shown in Table 5. The proportion of the area of each level of landscape ecological security shows the characteristics of "small at both ends and prominent in the middle", that is, the area of very unsecurity, unsecurity, relatively security and ideal security is minority, the area of critical security is the majority, and the general security is the second. On the whole, the landscape ecological environment of Zhong County is in a steady state of improvement, but the overall landscape ecological security is in a critical security level, and the quality needs to be further improved. From 2000 to 2018, the proportion of low-level has increased, the proportion of lower critical level has decreased first and then increased, the proportion of general and higher level has increased first and then decreased, the proportion of high-level has an overall increasing trend, but the proportion is minority, indicating that the ecological environment is gradually improving, and further protection and construction are still needed.

In 2000, the research area is at the initial phase of construction, the ange of critical security levels occupy the most parts of research areas. The land utilization degree is relatively low and the disturbance of human being is less. From the comparison, the ecological security condition within the areas in 2006 is relatively better and the area of above the security level is 27 665.55 hm^2, which occupies 12.65% of the total areas. The unsecurity grade and below area is 30443.04 hm^2, which occupies 13.92% of the total areas. The ecological security condition sharply worsens within the areas till 2012, and reduce to 9054.18 hm^2 compared with above security level, which occupies 4.14% of the total areas, which is less than 18 611.37 hm^2 in 2006; while the unsecurity grade and below area reached 57518.1 hm^2, which occupied 26.30% of the total areas, and increase 27 075.06 hm^2 than 2006. Till 2018, the regional security condition is still worsening. At this time, the areas than above relatively security level is 7785.72 hm^2, which reduces to 4.56% of proportion of total areas, among which the acreage of security area is only 3389.85 hm^2, which only occupied 2.55% of total areas, which is almost disappearing; The area of unsecurity grade and below this level are more to occupy 38.04% of total area. Compared with 2012, it will keep increasing 38 797.38 hm^2. It is hard to recognize that during the period of study, regional ecological security condition is mainly unsecurity and critical security and both occupies above 80% of total areas; while the general security area is gradually decreased and it reduces 39.9% in 2018 than the one in 2006; The very unsecurity and unsecurity area is gradually increasing year by year, and it separately increases 2.52% and 29.50% in 2018 than 2006, both of the area are more to occupy the 1/3 of total areas; the area change of relatively security and security is separately taken inverted "V" and "/" changes, but recently both of the total areas occupy less than 5%. It can be seen that regional ecological security is relatively weakened as a whole, its own anti-disturbance ability is relatively weak and ecological quality is waiting for improvement. Therefore, under the double disturbance of nature and human being, the landscape ecological security level is easily changing urgently and take on the deteriorating situation, and plus my relatively low recovery and long-term critical security level easily lead to the occurrence of ecological disaster.

2.2. The changes of space in landscape ecological security

The region with high landscape ecological security values in Zhong County from 2000 to 2018 were generally concentrated on the north and south sides of the Yangtze River, and the security value was above 0.54 (Figure 3), indicating that the ecological environment on both sides

Table 5. Landscape ecological security grades and their cover area in Zhong County from 2000 to 2018

Landscape ecological security level	Proportion of each ecological security level							
	2001		2006		2012		2018	
	area/hm^2	proportion/%	area/hm^2	proportion/%	area/hm^2	proportion/%	area/hm^2	proportion/%
Very unsecurity	1399.68	0.64%	349.92	0.16%	2208.87	1.01%	5861.16	2.68%
Unsecurity	48485.79	22.17%	30093.12	13.76%	55309.23	25.29%	90454.32	35.36%
Critical security	139508.73	63.79%	54150.12	24.76%	99202.32	45.36%	95418.81	48.63%
General security	23728.95	10.85%	106441.29	48.67%	52925.40	24.20%	19179.99	8.77%
Relatively security	5073.84	2.32%	26418.96	12.08%	7042.14	3.22%	4395.87	2.01%
Ideal security	503.01	0.23%	1246.59	0.57%	2012.04	0.92%	3389.85	2.55%

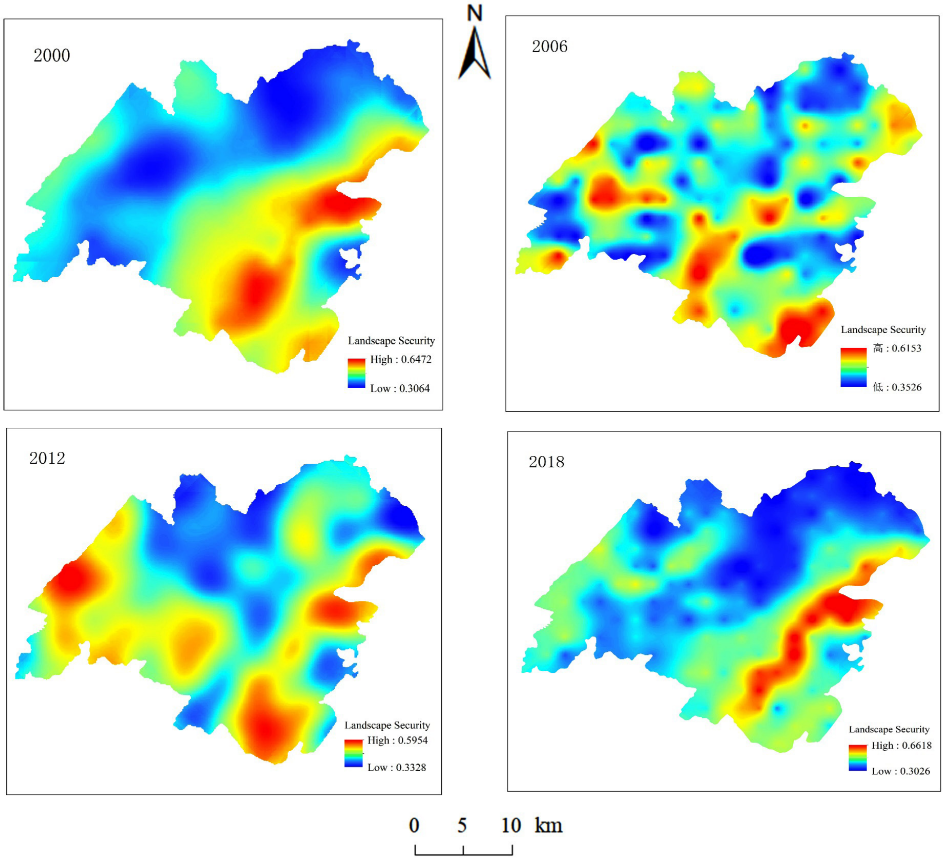

Figure 3. Spatial distribution of landscape ecological security in Zhong County from 2000 to 2018

of the Yangtze River in the study area was relatively good. This is because the patches in the Yangtze River Basin of this study area are relatively complete, the landscape heterogeneity is strong, the ecosystem is stable, and the degree of human disturbance is relatively small. The low value of landscape ecological security is mainly concentrated in the northeast and middle of the study area. These two areas are fragile in their own ecological environment. They are concentrated areas of ecological environment such as desertification and soil erosion. They are greatly affected by human activities and have a high degree of landscape fragmentation. The ecological security of landscape in the central area of the study area is low. The artificially planted citrus forests and grasslands are the main landscape types. The terrain has large fluctuations, the patches are broken, and the human disturbance factors are the largest. This indicates that the ecological protection of the area is at a low level. The ecological environment has been damaged to a certain extent.

In 2006, in the Yangtze River Basin of this region, the value of landscape ecological security fluctuated, and the value fluctuated greatly. There was a significant improvement in 2012. During this period, in order to alleviate the flood disaster, the Three Gorges Reservoir was built to greatly increase the water level of the Yangtze River. Residents on both sides of the Yangtze River migrated extensively, thus affecting the ecological landscape on both sides of the bank, and the value of landscape ecological security has fluctuated in different ranges. In the study area, the three regions of northwest, central mountain and south are relatively high in altitude, difficult to develop, and less affected by human activities. Therefore, the ecological security value of the fourth phase is relatively stable and is in an unsecurity or very unsecurity range. The quality of the ecological environment needs to be further improved.

2.3. Spatial correlation analysis of landscape ecological security

The Moran' *I* scatter plot of landscape ecological security of Zhong County in 2000, 2006, 2012 and 2018 were obtained by using GeoDa software, and the correlation degree in the whole study area was analyzed with scatter chart, as shown in Figure 4. The distribution of the scattered points of landscape ecological security values is mainly concentrated in the first quadrant (High-High) and the third quadrant (Low-Low), and most of the scattered points are distributed close to the regression line. This shows that the spatial distribution of landscape ecological security values in the study area is not random, and the characteristics of spatial agglomeration are very obvious. The change of Moran's *I* index also shows that the spatial correlation degree of landscape ecological security exists. The Moran' I values of the four periods are all greater than 0.5, indicating that the degree of landscape ecological security has a positive correlation in space, and

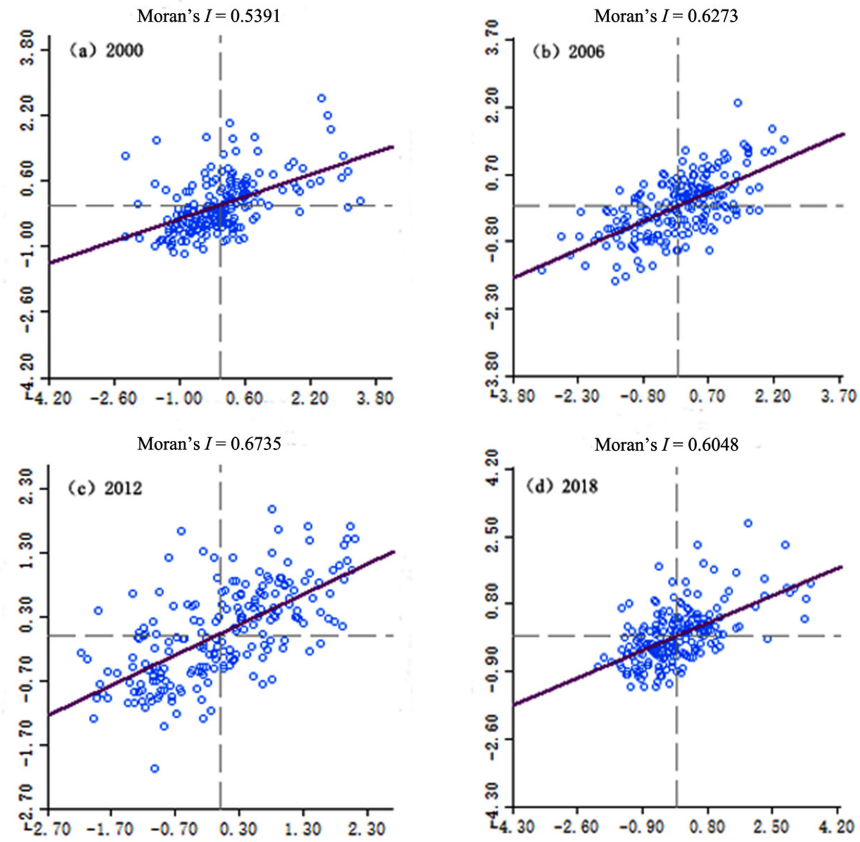

Figure 4. The Moran' I scatter plot of landscape ecological security in Zhong County

presents a general intensity of agglomeration phenomenon. The spatial distribution of landscape ecological security values in the study area is not random, there is a certain internal relationship, which is represented by the spatial aggregation between spatial similarity values. From 2000 to 2012, the Moran' I value increased from 0.5391 to 0.6735. From 2012 to 2018, the Moran' I value decreased from 0.6735 to 0.6048, indicating that the agglomeration trend of landscape ecological security increased at first and then decreased. Before 2012, the regional landscape dominance is increasing, and the trend of landscape pattern aggregation and distribution is increasing, but after 2012, the regional landscape dominance weakens, pays attention to the protection of the environment, and the regional ecological environment is more balanced.

The Moran' I value reflects the overall self-correlation of the landscape ecological security value, while for the correlation degree between a geographical element or attribute of a local area and the same element or attribute on the adjacent local community, and it is necessary to analyze the LISA agglomeration map (Figure 5) and the LISA significance test map (Figure 6), so as to analyze the local spatial association pattern of the landscape ecological security degree of the unit.

The LISA agglomeration map reflects the characteristics of agglomeration and distribution of landscape ecological security degree in space. In terms of quantity, 14 grids showed H-H characteristics, and 13 grids showed L-L characteristics in 2000. 18 grids showed H-H characteristics, and 14 grids showed L-L characteristics in 2006. 25 grids showed H-H characteristics, and 20 grids showed Lmurl characteristics in 2012. In 2018, 18 grids showed the characteristics of H-H and 27 grids showed the characteristics of L-L. The grid number of L-L characteristics showed an increasing trend in four periods, while the grid number of H-H characteristics showed an increasing trend from 2000 to 2012. From 2012 to 2018, the original high value gathering areas in the northwest and central regions have disappeared, and the high value gathering areas in the Yangtze River basin of Zhong County are connected together, but on the whole, the number of H-H characteristic grids is in a state of decrease, which also verifies that the Moran' I value decreases in this period. This shows that before 2000–2012, the aggregation situation of each landscape in the study area continues to rise, and the single dominant landscape has obvious control over the overall landscape of the study area, accounting for a large difference; from 2012 to 2018, the landscape pattern of the study area gradually changed from aggregation to scattered distribution, and the landscape types gradually diversified.

In terms of spatial distribution, the spatial autocorrelation distribution of ecological security degree of each grid in Zhong County in the study area shows three obvious low-value agglomeration areas and three obvious high-value agglomeration areas. The low-value agglomeration area

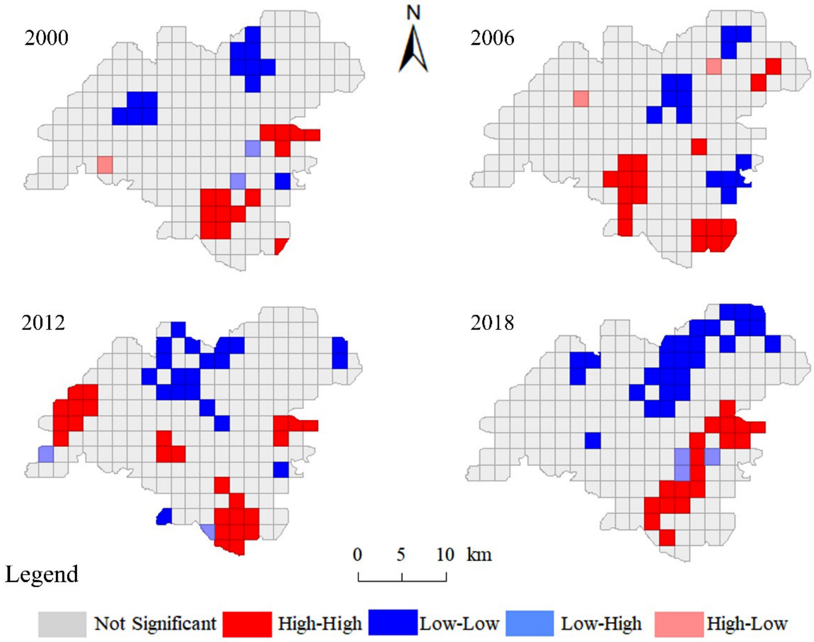

Figure 5. LISA cluster map of landscape ecological security in Zhong County from 2000 to 2018

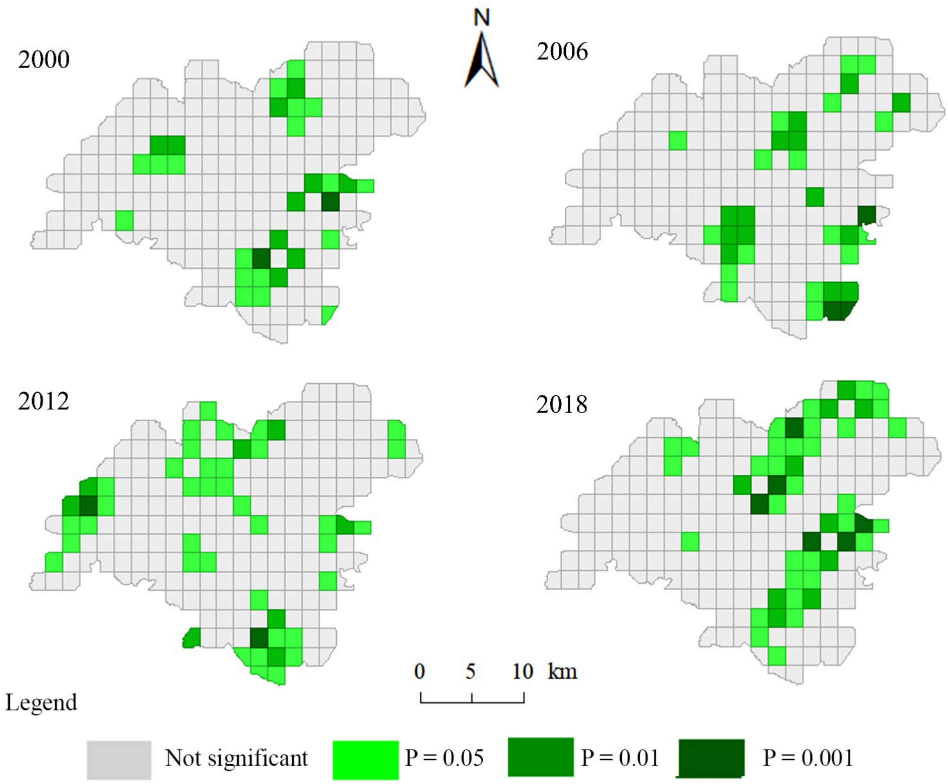

Figure 6. LISA significance level of local spatial autocorrelation of landscape ecological security in Zhong County in the study area

is mainly located in the north-central part and extends to the northeast. Sporadic distribution in the Yangtze River basin; The high value gathering area is mainly located in the Yangtze River basin of Zhong County, followed by sporadic distribution in the northwest and central areas with relatively high elevation, and their distribution pattern is consistent with the Kriging interpolation distribution pattern in the same period. The regions of "Low-High" agglomeration and "High-Low" agglomeration show the characteristics of spatial heterogeneity, but the number of grids of these two types is very small, and both of them are sporadic. The Yangtze River Basin of the region and the northwest of this study area are the areas where these two kinds of heterogeneous grids are more distributed.

From the LISA significant level, the study area adout L-L region significant level is high, generally reached 0.01 significant level, the Yangtze River basin of Zhong County significant level has improved, and most of them are 0.05 significant level. The north-central and northeast of the region have changed from insignificant to significant level, and the significant level is gradually increasing.

2.4. Obstacle degree model of single indicator of landscape ecological security

As shown in Table 6, the top four obstacle factors affecting regional landscape ecological security from 2000 to 2018 are extracted and analyzed,

Table 6. The main obstacles to landscape ecological security

Year	Ranked	1	2	3	4
2000	Obstacle factors	Eco-system service value	Land use diversification	Anti-interference	Vulnerability
	Obstacle degre (100%)	1.708	1.051	0.693	0.408
2006	Obstacle factors	Eco-system service value	Land use diversification	Degree of separation	Anti-interference
	Obstacle degree (100%)	0.994	0.764	0.432	0.35
2012	Obstacle factors	Land use diversification	Degree of separation	Eco-system service value	Aggregation
	Obstacle degree (100%)	0.468	0.341	0.304	0.236
2018	Obstacle factors	Path cohesion	Aggregation	Degree of fragmentation	Anti-interference
	Obstacle degree (100%)	0.391	0.352	0.292	0.186

The main obstacle factors of landscape ecological security in the study area are in dynamic change, and the main obstacle factors in each stage show different characteristics, reflecting that the factors that affect landscape ecological security in each stage are not the same. From 2000 to 2012, the main obstacle factors of landscape ecological security are the value of ecosystem services and the degree of diversification of land use. According to the statistical yearbook of Zhong County from 2000 to 2012, the economic level of Zhong County and the level of agricultural technology is relatively backward, and the degree of land development is low during this period. The value of the ecosystem needs to be developed. In 2018, the registered population of Zhong County was approximately 1.02 million, an increase of 39,400 from 980.6 million in 2000. At the same time, the urban built-up area of Zhong County reached 43.51 km^2 and the urbanization rate reached 44.9%. With the acceleration of urbanization, the main obstacle factors changed from "functionality" to "stability" from 2012 to 2018. Affected by a series of economic development activities and the increase of urban population, the impact of human activities on patches deepened, resulting in the weakening of landscape connectivity, more and more fragmentation, the decline of the stability of the overall landscape, thus threatening the overall security level of the landscape.

3. Discussion

How to verify the evaluation results of landscape ecological security has always been a key academic problem in the field of ecological security evaluation. According to the above comprehensive analysis, it is found that landscape ecological security is a multi-index comprehensive score result, which cannot be easily verified by another independent quantitative method. With reference to related research (Liu & Xu, 2015), the landscape ecological security is verified based on the vegetation coverage index. Vegetation coverage is the ratio of forest area to total land area, which reflects the distribution rule of aboveground vegetation and the regional ecological environment quality. Therefore, it is critical to accurately understand vegetation dynamics, which is a leading evaluation indicator of ecological conditions and the most intuitive embodiment of changing or degrading ecosystem stability.

3.1. The relationship between landscape ecological security and vegetation coverage

Generally, vegetation coverage is directly proportional to vegetation density and landscape ecological security, and vice versa. According to such characteristics, with the study area in 2018 as an example, the average coverage and the evaluation value of landscape ecological security are extracted according to the grid center point, and regression analysis is carried out to discuss the relationship between them. After preliminary analysis of the sampling points, given the particularity of the Yangtze river basin,

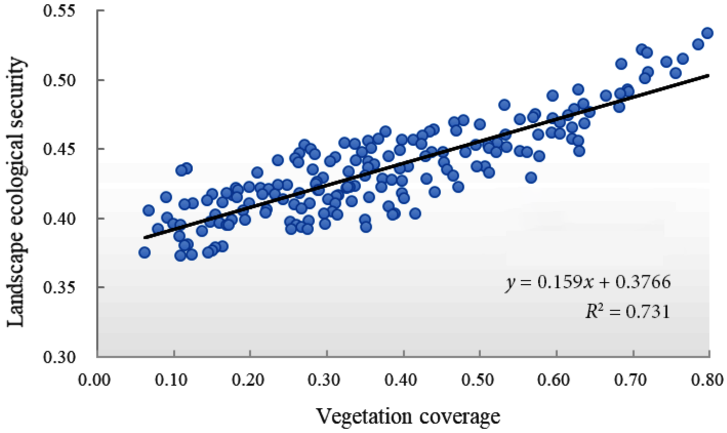

Figure 7. The correlation between landscape ecological security and vegetation coverage in Zhong County

the center points distributed in the Yangtze river basin and the major city of Zhong County are excluded in order to better explore the rules. The results are shown in the Figure 7, and their fitted equation is as follows:

$$y = 0.3766 + 0.159x,\ R^2 = 0.731.$$

The correlation coefficient between landscape ecological security and vegetation coverage is 0.731, indicating there is a high correlation between them. Vegetation coverage index determinates about 3/4 of the areas of landscape ecological security. In a sense, the regional vegetation coverage largely decides the landscape ecological security in a region. However, since this correlation coefficient has a small squared value, it indicates that the landscape ecological security is a quite complicated problem, which is not only dependent on the number of vegetation, but also the result of the combined action of multiple factors. The study of such relationship between vegetation coverage and landscape ecological security makes it possible to verify the evaluation results of landscape ecological security based on the landscape coverage index. Hence, the evaluation system and index of landscape ecological security in this study has a certain practicality, and the evaluation results can favorably reflect the ecological conditions in the study area.

3.2. The advantages and feasibility of the methods

In this paper, the 3S method and landscape ecological security assessment based on the functionality -organization-stability were applied to assess landscape ecological security landscape and optimize pattern. Compared with other landscape ecological security evaluation frameworks (mentioned in the introduction), it makes the practical operation of complex large-scale landscape analysis possible and realizes qualitative and quantitative in depth research. Data are easily available in this evaluation framework based on this article. Also, the regional landscape ecological security and reflect the overall and local landscape ecological quality under various disturbances can be comprehensively and quantitatively evaluated. The greatest difference between this paper and the landscape ecological security evaluation and landscape optimization in the conventional region is that the factors and results were implemented on each "point" of the space, thus greatly improving the visualization and practicability of the results.

Traditional research places more emphasis on the application of social statistics dates (Wei et al., 2018), and a landscape ecological security evaluation framework based on "functional-organization-stability" is different from the traditional landscape ecological security evaluation framework in this study. This kind of assessment framework achieves a double consideration of the impact of natural systems and human activities. In addition, by means of Kriging interpolation, the results broke through the boundaries of villages and towns, providing a clearer indication for the construction of regional ecological environment. Moreover, the resolution of multi-source spatial data is different, which may cause the deviation of the results. In addition, the Functionality -Organization-Stability framework could assess the landscape ecological pattern well and the results are also consistent with reality (Xu et al., 2020; Li et al., 2018). And the integrity of ecosystem and health of overall ecosystem status can be reflected by this model. At present, more and more attentions are paid to the changing trend, vulnerability, sensitivity, and heterogeneity analysis methods of landscape pattern, such as landscape pattern index, the particle size effect, and spatial statistics algorithm (Lu et al., 2019). Some scholars analyzed the spatiotemporal pattern of ecological security in Jiangsu's coastal wetland zone using the landscape disturbance index and the vulnerability index (Xu et al., 2016). And, landscape metrics (landscape diversity indexes) is used on land use optimization using in order to solve the urgent problem of biological and landscape diversity loss due to intensive agricultural activities (Kuchma et al., 2013).

The ecological principle and process behind it still need to be further discussed, and it is also inevitable to have subjective judgment factors. In future work, the comprehensive influence of multiple factors, the effective integration of multiple source spatial data, the ecological optimization plan under the multiple circumstances, and the ecological interpretation of multiple frameworks should be considered to improve landscape ecological security assessment.

Conclusions

(1) The landscape ecological security of the study region demonstrated an overall trend of decreasing from 2000 to 2018, which is in the critical security range, and the ecological security still needs to be strengthened. The area of critical security level and high ecological security level accounts for more than 60% of the total area of the study area, and the critical security area is constantly shifting to the low ecological security area, while the scope of the relatively security and higher ecological security area is generally decreasing. The area of the four periods accounted for 13.40%, 61.32%, 28.34%, and 13.33% respectively. The Yangtze River basin of the study region and the northwest are the areas with the highest landscape ecological security values. Landscape ecological security value decreases from the north and south sides of the Yangtze River basin of the study region and from the northwest to the central part, showing that natural factors have a certain impact on the regional landscape ecological security pattern.

(2) The global Moran' I index of Zhong County in 2000, 2006, 2012 and 2018 are 0.5391, 0.6273, 0.6735 and 0.6048. Respectively, indicating that the landscape ecological security degree of the study area has a positive correlation in the overall space. The autocorrelation pattern of landscape ecological security in the past four years has been relatively consistent, mainly in the areas of high-high value and low-low value. Most of the areas with a high-high value are in the Yangtze River basin, reflecting a good ecological environment; low-low value areas are mainly distributed in the north-central and northwest regions, indicating a serious fragmentation in this area.

(3) The major obstacles to landscape ecological security from 2000 to 2012 were ecosystem service value and land use diversification. As the economy develops, the degree of human influence on the landscape has deepened, which has facilitated the fragmentation of the landscape and complicated the landscape pattern. Therefore, the major obstacle to landscape ecological security from 2012 to 2018 became the instability of the landscape pattern, which could be indicated by the patch connection degree, aggregation degree, and crushing degree etc.

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