Postprint: Ecological Security and Evolutionary Process of Cultivated Land Landscape in Karst Mountainous Counties

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Abstract

To investigate the changing conditions of the ecological environment of farmland in karst mountainous areas, this study employs landscape ecological security theory and takes the farmland landscape of Chishui City, Guizhou Province as the research object. Seven landscape metrics were selected to construct an evaluation model for farmland landscape ecological security in karst mountainous areas: landscape ecological security index, landscape proximity index, patch fragmentation degree of landscape types, boundary fragmentation degree of landscape types, patch dominance index of landscape types, landscape isolation index, and landscape vulnerability index. The evolution of farmland landscape ecological security in the study area from 2000 to 2014 was analyzed, and the shift direction of the ecological security center of gravity and its driving factors were explored. The results indicate that: 1) Over the past 15 years, the center of gravity of farmland landscape ecological security in Chishui City has shifted toward the northwest, with decreases in patch density, fractal dimension, and fragmentation, and increases in patch shape index and connectivity. Farmland shapes have gradually transitioned toward more complex states, distribution has tended toward homogenization, and patches have become increasingly clustered. 2) Farmland area has continuously decreased while ecological security has continuously declined. The level I (danger zone) of dryland landscape ecological security has expanded toward the southeast, level III (safe zone) has transitioned to level II (relatively safe zone), and level II has transitioned to level I. The level II of paddy field landscape ecological security has shifted from concentrated to dispersed distribution, and level III has transitioned to level II and level I. The ecological security of both dryland and paddy field landscapes is not optimistic. 3) Grey relational analysis reveals that the factor with the greatest influence on the evolution and center of gravity shift of dryland landscape ecological security in the study area is total agricultural output value, followed by grain yield and crop planting area; for paddy fields, the most influential factor is grain yield, followed by chemical fertilizer application per unit area and population density.

Full Text

Preamble

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Analysis of Landscape Ecological Security and Evolution of Cultivated Land in Karst Mountainous Areas

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Abstract

To investigate changes in the ecological environment of cultivated land in karst mountainous areas, this study employs landscape ecological security theory and examines the cultivated land landscape of Chishui City, Guizhou Province as a case study. Landscape indices including patch density, patch shape index, patch fractal dimension, and patch stability factor were selected to analyze the evolution characteristics and spatial distribution patterns of landscape patches in the karst mountainous region. A landscape ecological security evaluation model for cultivated land in karst mountainous areas was constructed using five landscape indices: ecological security index, patch proximity index, patch fragmentation, patch boundary fragmentation, landscape type patch dominance index, separation index, and landscape fragile index. The centroid method, commonly used in geography and economics, was introduced to calculate the gravity center of cultivated land landscape ecological security, along with gravity transfer distance and moving direction models to measure the spatial dynamics of ecological safety centers. Finally, grey correlation analysis was performed using ten selected indices—population density, proportion of agricultural population, rate of regional construction land, grain yield, unit fertilizer application, arable area, gross agricultural output value, per capita disposable income of farmers, crop sown area, and number of rural practitioners—to explore driving factors of ecological safety evolution and gravity center shifts.

The results show that: (1) Over the past 15 years, the ecological security gravity center of cultivated land landscape in Chishui moved toward the northwest. Patch density, fractal dimension, and fragmentation decreased, while patch shape index and connectivity increased. Cultivated land shapes gradually became more complex, distribution tended toward homogeneity, and patches became increasingly clustered. (2) Arable land area continued to decline and ecological safety decreased. The ecological security zone of dry land expanded southeastward, with safe areas transitioning to relatively safe areas, and relatively safe areas becoming hazardous areas. The relatively safe zone of paddy field landscape changed from centralized to divergent distribution. The ecological security of both dry land and paddy field landscapes was not optimistic. (3) Grey correlation analysis revealed that agricultural gross output value, grain yield, and crop sown area were the primary factors affecting dry land landscape ecological security evolution and gravity center transfer. For paddy fields, grain yield was the most important factor, followed by fertilizer application level and population density.

Keywords: cultivated land; landscape ecological security; evolution; karst mountainous area

Introduction

Cultivated land, as an essential component for maintaining Earth' s life-support systems, carries critical functions including food production and landscape aesthetics. In recent years, China has experienced dramatic population growth, leading to increasingly prominent problems such as low productivity, insufficient reserve cultivated land resources, poor overall quality, severe land degradation, and scarcity of cultivated land resources. These issues have attracted high-level government attention and widespread concern among scholars both domestically and internationally. Research on regional cultivated land landscape ecological security has become urgent for guiding cultivated land protection and ensuring food security.

Regional ecological security analysis primarily includes dynamic early warning [1-2], evaluation and prediction [4-6], and other aspects. Landscape ecological security research often focuses on ecological risk assessment [7] and ecological restoration and reconstruction [8]. International research on cultivated land landscape ecological security concentrates on agricultural landscape monitoring and environmental security [10], food safety through agricultural landscape perspectives [11], cultivated land landscape ecological restoration [12], and agricultural landscape ecological protection [13]. Domestic scholars have conducted numerous case studies on landscape patterns and fragmentation at different slope levels using GIS technology [14-18]. Researchers such as Xu Hui [19], Wang Qian [20], Pei Huan [21], and Yu Xiao [22] have studied cultivated land ecological security from perspectives of evaluation and simulation prediction. Research on karst areas has focused on cultivated land quality [23], soil fertility [24], and cultivated land requisition-compensation balance [25], while studies exploring landscape ecological security and evolution processes in karst mountainous areas remain relatively weak.

Guizhou Province, located in the fragile ecological zone of southern limestone mountainous areas, has the largest and most intact karst plateau mountainous area in China and worldwide. The unique geological environment background, combined with unreasonable land development patterns during the survival-oriented economic development stage, has caused severe damage to the region's cultivated land ecological environment, serious soil erosion and degradation, and acute human-land contradictions [26]. Research on landscape ecological security pattern changes and driving mechanisms in this region is urgently needed. Therefore, this study takes Chishui City, a county-level city in Guizhou Province, as the research area. Based on landscape ecology and human-land relationship coordination theory, using ArcGIS software and technology, this research investigates the evolution of cultivated land landscape ecological security patterns in karst mountainous counties. When classifying cultivated land types to the second level, considering that few studies have deeply analyzed cultivated land landscape ecological security through subdivision, this paper selects two major cultivated land types: dry land and paddy fields.

1. Study Area Overview

Chishui City is located in the northwesternmost part of Guizhou Province (105°36 -106°15 E, 28°16 -28°46 N), with a total land area of 1,852 km². Situated in the transitional slope zone from the Sichuan Basin to the Guizhou Plateau, the terrain is predominantly plateau-canyon and mountain-plain canyon types, with dramatic elevation changes. The highest point is 1,730 m and the lowest is 221 m. The area has a mid-subtropical humid monsoon climate with significant vertical climate variations and regional differences. The river system belongs to the Yangtze River watershed, located in the middle and lower reaches of the Chishui River, with a river network density of 0.7 km/km² and abundant water resources. The bedrock consists mainly of quartz sandstone and mud shale from the Jurassic and Cretaceous periods, with strong water erosion and gully erosion. Soils are primarily immature soils developed on purple sandstone and mudstone [27]. Statistical yearbook data show that Chishui City has a grain sown area of 13.81 thousand hectares, total grain output of 61.85 thousand tons, and per capita grain possession of 0.445 tons.

[Figure 1: see original paper] Location map of the study area

2. Data Sources

Land use status maps from 2000 and 2014 were used as the basic database. Using ArcGIS 10.2, cultivated land use status data for two periods were extracted, including land area, number of patches, and inter-patch distances for dry land and paddy fields in each township and street, as well as centroid coordinates for gravity center transfer research. Statistical data from the Chishui City Statistical Yearbook and National Economic and Social Development Statistical Bulletin for 2000–2014 were collected, including population density, agricultural population proportion, regional construction land proportion, grain yield, cultivated land fertilizer application, agricultural gross output value, per capita disposable income of farmers, crop sown area, and number of rural practitioners. These data were used to explore driving factors of cultivated land landscape evolution and ecological security gravity center transfer.

3. Methods

3.1 Selection and Analysis of Cultivated Landscape Indices

Based on literature [28-31], and considering the complex land patch shapes and extensive slope cultivation in karst mountainous areas, four indices were selected to analyze cultivated landscape patch evolution and spatial configuration characteristics: patch density (PD), patch shape index (PSI), patch fractal dimension (PFD), and patch stability factor (PSF). Specific calculation formulas can be found in Qian Fengkui' s work [28].

3.2 Landscape Ecological Security Evaluation Model

Drawing on traditional landscape ecological security evaluation methods and introducing an ecological quality index, this study constructed a cultivated land landscape ecological security evaluation model for karst mountainous areas. The model effectively reflects landscape structure and function, ecosystem integrity, landscape patch dynamics and ecological succession, and system resistance and recovery capabilities [32]. It represents an organic combination of ecological risk and ecological health, unrestricted by statistical scale, and can fully reflect the risk or security status of landscape ecosystems in karst mountainous counties.

The landscape ecological security index is calculated as:

$$LSES = 1 - \frac{PX + PF + PBF + SHDI + DIVISION}{LFI \times 2.5}$$

where: - $LSES$ = Landscape Ecological Security Index - PX = Patch Proximity Index - PF = Patch Fragmentation - PBF = Patch Boundary Fragmentation - $SHDI$ = Landscape Type Patch Dominance Index - $DIVISION$ = Separation Index - LFI = Landscape Fragile Index

Calculation formulas for each landscape index can be found in Fu Bojie' s work [33-34]. Calculations were performed using ArcGIS 10.2 Spatial Analyst and Fragstats 4.2 software platforms. Based on Wei Yong' s [21] research results, the evaluation results were classified into three levels: Level I ($LSES \leq 0.45$), Level II ($0.45 < LSES \leq 0.75$), and Level III ($0.75 < LSES \leq 1$), corresponding to dangerous, relatively safe, and safe ecological security states.

3.3 Gravity Center Transfer of Cultivated Landscape Ecological Security

The movement of materials and energy in space creates a gravity center at any given moment. The direction, speed, and intensity of this center' s movement are the best indicators of spatial changes in a given phenomenon [35-36].

Changes in the gravity center of cultivated landscape ecological security represent an important aspect of studying spatial pattern changes, intuitively reflecting spatiotemporal evolution processes and trends while revealing dynamic change characteristics and driving mechanisms.

This study introduces the centroid method commonly used in geography and economics to calculate the gravity center of cultivated landscape ecological security. The gravity center position is expressed in longitude and latitude:

$$X = \frac{\sum LSES_i \times X_i}{\sum LSES_i}$$
$$Y = \frac{\sum LSES_i \times Y_i}{\sum LSES_i}$$

where $LSES_i$ is the cultivated landscape ecological security index of the ith research unit, and X_i and Y_i represent the centroid coordinates of the ith evaluation unit.

To quantitatively measure the transfer distance and direction of the cultivated landscape ecological security gravity center, the gravity center transfer distance model and moving direction model [37] were introduced. Let $P_m(X_m, Y_m)$ and $P_n(X_n, Y_n)$ be the landscape ecological security gravity centers in years m (starting year) and n (ending year), respectively. The spatial transfer distance d_{n-m} from year m to n is:

$$d_{n-m} = c \times \sqrt{(X_n - X_m)^2 + (Y_n - Y_m)^2}$$

where $c = 111.11$ km is the conversion coefficient from geographic coordinates to planar distance.

The transfer angle θ_{n-m} from year m to n is:

$$\theta_{n-m} = \arctan\left(\frac{Y_n - Y_m}{X_n - X_m}\right)$$

where the positive north direction is 0°, east is 90°, south is ±180°, and west is −90°. Typically, $-180° < \theta < -90°$ indicates northwest movement, $-90° < \theta < 0°$ indicates northeast movement, $0° < \theta < 90°$ indicates southeast movement, and $90° < \theta < 180°$ indicates southwest movement.

3.4 Analysis of Driving Factors

Grey correlation analysis was used to analyze driving factors of cultivated landscape evolution and ecological security gravity center transfer. This method determines the contribution of factors to system behavior through grey correlation degree, based on the similarity of sequence geometric shapes. It is applicable regardless of sample size or pattern and avoids inconsistencies between quantitative and qualitative results.

The grey correlation coefficient is expressed as:

$$\varepsilon_i(k) = \frac{\min\min|x_i(k) - x_0(k)| + \rho\max\max|x_i(k) - x_0(k)|}{|x_i(k) - x_0(k)| + \rho\max\max|x_i(k) - x_0(k)|}$$

where ρ is the resolution coefficient (typically 0.5) introduced to enhance significant differences between correlation coefficients. The correlation degree r_i is:

$$r_i = \frac{1}{n}\sum_{k=1}^{n}\varepsilon_i(k)$$

Due to different data dimensions among system sequences, range standardization was applied for dimensionless processing before analysis:

For positive indicators (larger is better):

$$X'_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})}$$

For negative indicators (smaller is better):

$$X'_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})}$$

where X_{ij} is the original data for the jth indicator in year i, and X'_{ij} is the standardized value.

4. Results

4.1 Evolution Characteristics of Cultivated Landscape Patches

From 2000 to 2014, the patch density and shape index of cultivated landscape in Chishui City showed significant changes. Both dry land and paddy field areas decreased substantially, with patch density declining and patch shape index increasing, indicating increasingly complex shapes and more uniform spatial distribution. Dry land patch density decreased from 0.27 to 0.08, while paddy field patch density decreased from 0.25 to 0.09. Although both decreased, dry land maintained higher complexity than paddy fields. The patch shape index of dry land increased from 11,211.33 to 20,280.58, and paddy fields from 8,034.99 to 16,543.09, demonstrating increasingly irregular patch shapes.

Changes of cultivated land landscape characteristic indices in the study area in 2000 and 2014

4.2 Spatial Configuration Characteristics of Cultivated Landscape

To reflect spatial position and morphological characteristics of cultivated landscape elements, fractal dimension and stability coefficient were introduced. Fractal dimension magnitude is closely related to human landscape management. From temporal and spatial perspectives, larger fractal dimensions indicate more complex cultivated land morphology and spatial expansion, while smaller values indicate simpler morphology and spatial contraction [40].

From 2000 to 2014, the fractal dimension of cultivated land in all townships and streets generally decreased, except for Shibao Township' s dry land and Lianghekou Town' s paddy field landscapes, which showed increased fractal dimensions, indicating increasingly complex patch morphology and unordered expansion trends. Spatially, Tiantai Town' s fractal dimension exceeded 1.45 while other townships were below 1.45, with large spans between dry land and paddy field fractal dimensions. In 2014, Baoyuan Township' s fractal dimension exceeded 1.45 while others were below 1.45, with smaller inter-township spans.

The spatial structure stability index of cultivated land in all townships showed an overall upward trend from 2000 to 2014, except in Lianghekou Town and Shibao Township. In 2000, dry land stability indices were generally higher than paddy fields, but by 2014, paddy field stability indices exceeded dry land, indicating decreasing paddy field stability while dry land stability gradually increased.

Fractal dimension of landscape types of cultivated land in various towns and streets in 2000 and 2014
Stability index of cultivated land in towns and streets in 2000 and 2014

4.3 Cultivated Landscape Ecological Security Status

The overall landscape pattern index of cultivated land in Chishui showed a declining trend. The average ecological security index of dry land landscape decreased from 0.822 in 2000 to 0.695 in 2014, while paddy field landscape decreased from 0.767 to 0.743, indicating continuously decreasing ecological security for both.

Landscape pattern index of cultivated land in different towns and streets in 2000
Landscape pattern index of cultivated land in different towns and streets in 2014

Classification of the results reveals significant differences in cultivated landscape security status among townships. In 2000, Level III (safe) dry land landscapes were mainly located in Changqi Town in the southeast, while Level I (dangerous) areas were primarily in the eastern region. By 2014, the Level III area shifted to Datong Town in the north, with the Level I area moving to Wenhua Office in the west, and the Level II range expanded to include Tiantai Town. Paddy field landscape ecological security showed Level III areas in the east (including Changqi Town and Guandu Town) and Level II areas in Wanglong Town and Hushi Town in 2000. By 2014, the Level III area reduced, excluding Wanglong Town, with more dispersed distribution.

The main characteristics of ecological security pattern changes from 2000 to 2014 include: dangerous zones expanded significantly from central to southeastern areas; safe zones transitioned to relatively safe zones, which in turn became dangerous zones; relatively safe zones showed fragmented changes; safe zone scale continuously compressed, decreasing from southwest to southeast.

[Figure 2: see original paper] Grading map of ecological security of dry land and paddy field in study area

4.4 Gravity Center Transfer of Cultivated Landscape Ecological Security

Based on gravity center coordinates of dry land and paddy field landscape ecological security from 2000 to 2014, the transfer characteristics were analyzed. Both dry land and paddy field landscape ecological security gravity centers shifted northwest, but dry land showed greater variation in longitude and latitude than paddy fields. The dry land landscape ecological security gravity center moved 219.335 km northwest from Xinchun Village in Wanglong Town to Sankuai Village in Tiantai Town at an angle of 129.341°. The paddy field gravity center moved 94.124 km northwest within Xinchun Village in Wanglong Town at an angle of 135.096°.

The characteristics of barycenter diversion in the study area during 2000 to 2014
[Figure 3: see original paper] Gravity center transferring map of landscape ecological security in study area during 2000 to 2014

4.5 Analysis of Driving Factors

Cultivated landscape changes from 2000 to 2014 were influenced by natural, social, economic, and production technology factors. To identify primary driving factors of landscape change and gravity center transfer, ten indices were selected based on scientific principles, availability, and measurability, combined with regional characteristics: population density, agricultural population proportion, regional construction land proportion, grain yield, unit cultivated land fertilizer application, arable area, agricultural gross output value, per capita disposable income of farmers, crop sown area, and number of rural practitioners.

Grey correlation analysis was performed using 2000–2014 changes in these indices as comparison sequences and changes in landscape ecological security indices as reference sequences. The correlation coefficients were calculated and sorted to determine primary driving factors for each land use type.

For dry land landscape ecological security evolution and gravity center transfer, the correlation coefficients ranked as: agricultural gross output value (2.111) > grain yield (2.096) > crop sown area (2.048) > regional construction land proportion (1.990) > population density (1.933) > agricultural population proportion (1.878) > unit fertilizer application (1.740) > rural practitioners (1.614) > per capita disposable income (1.604).

For paddy field landscape ecological security evolution and gravity center transfer, the ranking was: grain yield (1.920) > unit fertilizer application (1.903) > population density (1.895) > agricultural population proportion (1.855) > agricultural gross output value (1.801) > rural practitioners (1.759) > per capita disposable income (1.723) > crop sown area (1.673) > regional construction land proportion (1.489).

Statistics on the change of statistical indicators of township and street offices in Chishui from 2000 to 2014
Correlation coefficients between comparison and reference sequences of dry land during 2000 to 2014
Correlation coefficients between comparison and reference sequences of paddy field during 2000 to 2014

The analysis shows that in areas where ecological security status changed significantly (e.g., Guandu Town shifting from safe to dangerous, Changqi Town from relatively safe to safe, Datong Town from safe to relatively safe), the changes corresponded with substantial variations in driving factors such as agricultural output value, grain yield, and crop sown area, confirming the reliability of the grey correlation method.

5. Conclusions and Discussion

Based on land use data and statistical information from 2000 to 2014, this study analyzed the evolution process of cultivated landscape ecological security in karst mountainous counties using ArcGIS 10.2, Fragstats 4.2, and SPSS 19.0, and further examined driving factors of evolution direction and gravity center transfer. The main conclusions are:

1. **Patch Evolution and Spatial Configuration**: From 2000 to 2014, patch density of both dry land and paddy fields decreased, fragmentation reduced, and spatial distribution became more uniform, though patch shapes became increasingly irregular. The fractal dimension of cultivated land in all townships generally decreased, with larger spans between dry land and paddy field values in 2000 than in 2014. Spatial structure stability indices generally increased, with dry land stability exceeding paddy fields in 2000 but the reverse in 2014.

2. **Ecological Security Status**: Ecological security of both dry land and paddy field landscapes continuously declined. The dangerous zone expanded southeastward, the relatively safe zone changed from concentrated

to divergent distribution, and safe zone scale continuously shrank. Dry land landscape shifted from 1 safe state to 1 relatively safe state, while paddy fields shifted from 2 safe states to 2 relatively safe states.

3. **Gravity Center Transfer**: Both dry land and paddy field landscape ecological security gravity centers moved northwest, with dry land showing greater movement distance (219.335 km) than paddy fields (94.124 km).
4. **Driving Factors**: Grey correlation analysis revealed different driving factors for dry land versus paddy fields. Agricultural gross output value, grain yield, and crop sown area most strongly influenced dry land evolution, while grain yield, unit fertilizer application, and population density most strongly affected paddy fields.

This study demonstrates that using landscape ecological security evaluation models and gravity center transfer analysis provides a comprehensive reflection of spatiotemporal layout characteristics and ecological evolution directions of county-level cultivated landscapes in karst mountainous areas. Grey correlation analysis effectively reveals evolution mechanisms, with results consistent with actual conditions in the study area. However, due to data availability limitations, the study' s basic database scale is relatively small and driving factor indicators are not fully comprehensive. Future research should strengthen studies with larger scales and higher precision.

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Note: Figure translations are in progress. See original paper for figures.