Postprint: Supply-Demand Balance of Ecological Carrying Capacity of Cultivated Land in Karst Regions

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Abstract

Focusing on the supply-demand relationship of cultivated land ecological carrying capacity in karst regions, this study utilizes GIS software and the cultivated land ecological footprint model to construct a supply-demand balance index for cultivated land ecological carrying capacity in karst areas based on revised cultivated land yield factors, and conducts an analysis and evaluation of the supply-demand balance status of cultivated land ecological footprint in Bijie City—a region dominated by karst landforms—in 2014. The results indicate: (1) The supply-demand of cultivated land ecological footprint in Bijie City exhibits a spatial distribution pattern characterized by surplus in the northern part and overload in the southern part; (2) A negative correlation exists between Gross Domestic Product (GDP) and the cultivated land ecological footprint supply-demand balance index; (3) The cultivated land ecological carrying capacity supply-demand balance index demonstrates a negative correlation with the area proportions of potential, mild, and moderate rocky desertification, while showing a positive correlation with the area proportion of severe rocky desertification; (4) Among the eight counties (districts) in the municipality, four counties (districts) exhibit cultivated land ecological surplus, two counties show cultivated land ecological balance, and two counties display cultivated land ecological deficit; approximately 75.28% of the municipal population resides in cultivated land ecological surplus and balance zones, whereas 24.72% inhabits cultivated land ecological deficit zones. These findings can provide a decision-making foundation for agricultural industrial structure adjustment, ecological security early warning, regional economic development, and the formulation of overall land use planning in Bijie City.

Full Text

Abstract

Taking the supply-demand relationship of cultivated land ecological carrying capacity in karst regions as the entry point, this study employs GIS software and the cultivated land ecological footprint model to construct a supply-demand balance index for cultivated land ecological carrying capacity in karst areas, based on corrected cultivated land yield factors. The current status of supply-demand balance of cultivated land ecological footprint in Bijie City—a region dominated by karst landforms—was analyzed and evaluated for 2014. The results indicate that: (1) The supply-demand balance of cultivated land ecological footprint in Bijie City exhibits a spatial distribution pattern of surplus in the north and overload in the south; (2) There exists a negative correlation between gross domestic product and the cultivated land ecological footprint supply-demand balance index; (3) The cultivated land ecological carrying capacity supply-demand balance index is negatively correlated with the proportion of potential, light, and moderate rocky desertification areas, but positively correlated with the proportion of severe rocky desertification area; (4) Among the eight counties in Bijie City, four possess ecological surplus, two maintain ecological balance, and two exhibit ecological deficit of cultivated land, with 75.28% of the city' s population living in areas of ecological balance and surplus, while 24.72% live in areas of ecological deficit. These findings provide a decision-making basis for agricultural industrial structure adjustment, regional economic development, and comprehensive land use planning in Bijie City, as well as for early ecological security warning systems.

Keywords: Karst; cultivated land; ecological carrying capacity; supply-demand balance; Bijie City

Introduction

With rapid industrialization and urbanization transforming regional ecological environments and economic structures, exploring pathways to sustainable development has become a focal issue in current landscape ecology research. For human society to develop sustainably, it must maintain the stock of natural assets to ensure their sustainable utilization [1]. If the pressure of human activities on natural ecosystems remains within the carrying capacity of those ecosystems, the development of human society is sustainable [2]. Scholars such as Wackernagel et al. [3-4] proposed the concept of ecological footprint and its evaluation indices in the 1990s, which measures the gap between human demand for natural ecological services and what natural ecosystems can supply. This indicator enables understanding of human utilization of natural ecosystems at global, national, and regional scales. Numerous scholars have conducted extensive empirical studies on different regions using the ecological footprint model [5-12], with many research results demonstrating that the ecological footprint model is an effective quantitative method for studying regional sustainability

[13-15].

Karst regions feature fragile ecological environments. While some scholars have conducted in-depth research on changes in ecosystem service function values and their influencing factors in these areas [16-19], regional studies on cultivated land ecological services in karst regions remain limited. Moreover, existing research outcomes have only explained estimation methods for cultivated land ecological service functions [20], ecological deficit-surplus relationships [21], and the composition of ecological carrying capacity and ecological footprint [22-24], without revealing the relationship between cultivated land ecological supply-demand balance status and varying grades of rocky desertification intensity or economic development levels. This study applies GIS technology and the cultivated land ecological footprint model to investigate the cultivated land ecological supply-demand balance in Bijie City, Guizhou Province—a region dominated by karst landforms. By analyzing the supply-demand relationship of cultivated land, this research examines cultivated land protection, ecological security, and the influence of different grades of rocky desertification intensity and economic development status in karst regions. The findings offer valuable guidance for maintaining the sustainable use of cultivated land ecological services, promoting rational development and utilization of cultivated land resources, and coordinating development between humans and the natural environment in karst regions. The study also provides a decision-making basis for agricultural industrial structure adjustment, regional economic development, and comprehensive land use planning in Bijie City, as well as for ecological security early warning systems.

1. Study Area Overview

Bijie City is located in northwestern Guizhou Province, at the junction of Yunnan, Guizhou, and Sichuan provinces, bordering Zhaotong and Qujing cities in Yunnan to the north, Luzhou City in Sichuan to the south, Guiyang City to the east, and Anshun City to the south. Geographically situated between 105°36 -106°43 E and 26°21 -27°46 N, Bijie lies in the sloping transition zone from the Yunnan-Guizhou Plateau to the low mountains and hills of eastern China. The city covers a total land area of 26,853 km², with cultivated land accounting for 21,297.17 km². The strata are complex and diverse, featuring both eroded stone mountains with caves and gullies and eroded mountains and valleys. Medium-high mountain land and hills constitute 46.36% of the total area.

The city experiences a north subtropical monsoon humid climate with distinct monsoon patterns, an average annual temperature of 10–15°C, and average annual precipitation of 849–1,399 mm. The main soil types include yellow-brown soil, lime soil, yellow soil, marsh soil, and fluvo-aquic soil, among which lime soil and yellow soil are the most widely distributed. According to 2014 monitoring surveys of rocky desertification by the State Forestry Administration, the exposed karst area in Bijie City is 21,129.7 km², accounting for 79.31% of the city's total land area. The total rocky desertification area is 9,894.8 km² (33.39% of total land area), potential rocky desertification area is 8,137.96 km^2 (29.03%), and the city' s total population in 2014 was 8.8079 million, with agricultural population of 8.1521 million (92.55% of total).

2. Methods

2.1 Demand Model

Cultivated land is one of the six major productive land types in the ecological footprint model. Cultivated land ecological footprint refers to the area of cultivated land required to produce the crops (such as grain, oil, etc.) consumed by a population and to absorb the waste generated from this consumption. According to the definition and calculation method of ecological footprint, cultivated land ecological footprint measures the gap between human demand for cultivated land ecological services and the supply capacity of cultivated land itself within a certain region. By comparing and analyzing this relationship, we can assess the intensity of human utilization of cultivated land resources. The calculation formula is as follows:

$$EF = N \times ef$$

where EF is the total cultivated land ecological footprint of the study area, N is the total population of the study area, and ef is the per capita cultivated land ecological footprint.

$$ef = r \times \sum_{i=1}^{n} A_i$$

where r is the cultivated land equivalence factor of the study area, A_i is the per capita productive cultivated land area converted for the ith consumption item, and i represents the consumption item. Since the main crops planted in Bijie City are corn, wheat, potatoes, rapeseed, cured tobacco, and vegetables, these are the biological products involved in the cultivated land ecological footprint and ecological carrying capacity calculations. Research indicates that cultivated land equivalence factors change only subtly over long time periods. The internationally recognized and corrected cultivated land equivalence factor by Wackernagel in 2006 is adopted in this study.

2.2 Supply Model

Cultivated land ecological carrying capacity refers to the area of biologically productive cultivated land within the study region, reflecting the degree of supply that cultivated land ecosystems can provide to meet human demand. The calculation formula is:

$$EC = N \times ec$$

$$ec = a \times r \times y$$

where EC is the total ecological carrying capacity of the study area, ec is the per capita cultivated land ecological carrying capacity, a is the per capita biologically productive land area, r is the equivalence factor, and y is the yield factor of cultivated land in the study area.

Most scholars reference yield factors calculated by Wackernagel et al. for China. However, since Bijie City is a karst region with fragile ecological environment and severe soil erosion, it is necessary to correct the cultivated land yield factor. The crop yield factor refers to the ratio of the crop' s average yield to the global average yield [28]. Based on 2014 data for Bijie City, this study corrects the cultivated land yield factor for karst regions. The original ecological footprint model reserves 12% of the total productive land area as biodiversity conservation area when calculating ecological carrying capacity [29].

shows the calculation results of cultivated land yield factors in Bijie City in 2014.

2.3 Supply-Demand Balance Model

Based on the analysis of cultivated land ecological supply-demand in Bijie City, this study selects the cultivated land ecological carrying capacity supply-demand balance index (EI) to analyze the cultivated land ecological supply-demand relationship in the study area. EI refers to the ratio between per capita cultivated land ecological footprint and per capita cultivated land ecological carrying capacity, reflecting the relationship between demand and supply of cultivated land ecological resources. Theoretically, when EI equals 1, it indicates regional cultivated land ecological service balance; when EI is greater than 1, it indicates regional cultivated land ecological deficit; and when EI is less than 1, it indicates regional cultivated land ecological surplus. However, in reality, the probability of EI equaling 1 is small. Combining the actual situation in karst regions, this study uses a $\pm 15\%$ fluctuation range as the ecological service balance zone, meaning EI between 0.85 and 1.15 is considered the cultivated land ecological service balance zone in karst areas. EI less than or equal to 0.85 is classified as ecological surplus zone, and EI greater than or equal to 1.15 is classified as ecological deficit zone.

According to the EI ranges for cultivated land ecological balance, surplus, and deficit zones in the study area, and combining their relationship with average values, the study further subdivides the cultivated land ecological supply status. The specific classification criteria are shown in .

3. Data Sources

Data on corn, wheat, and other crops in Bijie City were obtained from the *Guizhou Statistical Yearbook 2015*, *Bijie Statistical Yearbook 2015*, *2014 Bijie National Economic and Social Development Statistical Bulletin*, and *International Statistical Yearbook*. Per capita consumption data for crops were used in calculations. Landsat TM remote sensing images (1977, 1978, 1991) at 1:50,000 scale were obtained from the Chinese Academy of Sciences' Earth Observation and Digital Earth Science Center Earth Observation Data Sharing Program. Auxiliary data for remote sensing image interpretation include 1:200,000 hydrogeological maps (2014) and administrative division maps from Bijie City Land and Resources Bureau. Geographic status data were obtained from Bijie City Agricultural Bureau.

4. Rocky Desertification Classification Standards

Different classification standards for rocky desertification intensity exist depending on the perspective considered. This study references the research results of Xiong Kangning et al. [30], who graded rocky desertification based on bedrock exposure rate and vegetation coverage in karst regions. The classification includes five grades: non-rocky desertification, potential rocky desertification, light rocky desertification, moderate rocky desertification, severe rocky desertification, and extremely severe rocky desertification, based on multiple indicators including bedrock exposure rate, vegetation and soil coverage.

4.1 Rocky Desertification Information Extraction

Using ENVI5.0 software' s decision tree analysis module, remote sensing images were corrected and preprocessed. Based on the preprocessed data source, band calculations were performed to compute the Normalized Difference Soil Index (NDSI) and Normalized Difference Vegetation Index (NDVI), generating vegetation coverage and exposure rates [31]. With the aid of land use status maps and hydrogeological maps, rocky desertification and non-rocky desertification areas were identified. Using ENVI5.0's decision tree analysis module and classification standards, combined with field survey verification and patch information modification, distribution maps of different rocky desertification intensity grades in the study area were obtained.

[Figure 1: see original paper] shows the distribution map of different rocky desertification grades in Bijie City in 2014.

5. Results

5.1 Cultivated Land Ecological Footprint Assessment in Bijie City

In 2014, Bijie City' s total cultivated land ecological footprint was 1,726,869.17 hm^2, with a per capita ecological footprint of 0.20 hm^2. Based on the relationship between the ratio of each county' s cultivated land ecological footprint to the city average and the ratio of per capita cultivated land ecological footprint to the city average, this study divided these ratios into high, medium, and low value zones. The results show that both ratios are dominated by medium value zones.

The high-value zone for the ratio of county-level cultivated land ecological footprint to city average is located in Weining County in the west and Zhijin County in the south. The high-value zone for the ratio of per capita cultivated land ecological footprint to city average is located in Nayong County and Zhijin County in the south. The distribution patterns of these two ratios show good consistency because the magnitude of ecological footprint is directly related to total population—counties with larger populations have larger cultivated land ecological footprints.

[Figure 2: see original paper] shows the ratio of county-level cultivated land ecological footprint to city average. [Figure 3: see original paper] shows the ratio of county-level per capita cultivated land ecological footprint to city average.

5.2 Cultivated Land Ecological Carrying Capacity Assessment in Bijie City

The total cultivated land ecological carrying capacity of Bijie City in 2014 was 247,917.69 hm^2, with per capita ecological carrying capacity of 0.023 hm^2. The spatial distribution of the ratio between each county' s cultivated land ecological carrying capacity and the city average shows dispersed low-value zones and relatively concentrated medium-value zones. Similarly divided into three levels, low and medium value zones dominate. The ratio of per capita cultivated land ecological carrying capacity to city average is dominated by medium and high value zones with relatively concentrated distribution. The difference in cultivated land area is the main reason for the spatial mismatch between per capita and total cultivated land ecological carrying capacity.

[Figure 4: see original paper] shows the ratio of county-level cultivated land ecological carrying capacity to city average. [Figure 5: see original paper] shows the ratio of county-level per capita cultivated land ecological carrying capacity to city average.

5.3 Supply-Demand Balance Assessment and Influencing Factors Analysis

Based on the analysis of cultivated land ecological supply-demand balance in Bijie City and the supply-demand balance index, the study evaluated the cultivated land ecological carrying status. Bijie City has 4 counties with ecological surplus, 2 counties with ecological balance, and 2 counties with ecological deficit. In terms of population distribution, the ecological surplus and balance zones accommodate 4.8013 million people (55.09% of total population), while the ecological deficit zone accommodates 2.1541 million people (24.72%). The ecological balance zone has the smallest population of 1.7602 million (20.20%).

In terms of land area, the ecological surplus zone covers the largest area of 597,662.5 hm² (60.03% of total cultivated land), the ecological deficit zone covers 199,979.6 hm² (20.09%), and the ecological balance zone covers the smallest area of 85,594.8 hm² (19.89%). The spatial distribution of cultivated land ecological carrying capacity supply-demand in Bijie City shows significant imbalance, characterized by surplus in the north and overload in the south. The ecological surplus and balance zones, with 79.91% of the city' s cultivated land area, support 75.28% of the population, while the ecological deficit zone, with only 20.09% of cultivated land area, supports 24.72% of the population.

shows the evaluation of cultivated land ecological carrying capacity supply-demand balance in Bijie City based on EI.

To analyze the relationship between cultivated land ecological carrying capacity supply-demand balance status and different grades of rocky desertification intensity and economic development, this study selected gross domestic product and the proportion of different rocky desertification intensity grades for correlation analysis with EI. Since the extremely severe rocky desertification area is very small in each county, it was merged with severe rocky desertification in calculations.

The results show a significant negative correlation between EI and the proportion of potential, light, and moderate rocky desertification areas, but a positive correlation with the proportion of severe rocky desertification area. Counties with higher GDP have better cultivated land ecological carrying capacity supply-demand balance status, while counties with lower GDP show overload or severe overload trends. This is because counties with higher GDP have a larger proportion of tertiary industry, reducing human activity damage to cultivated land and ecological environment, thereby alleviating human-land conflicts to some extent. In contrast, counties with lower GDP have high proportions of primary and secondary industries. For example, Nayong County' s industrial development focuses on agriculture and industry, creating strong dependence on land and mineral resources, prominent human-land contradictions, and overload trends in cultivated land ecological carrying capacity.

In karst regions, potential and moderate rocky desertification areas can still be used for agricultural production. However, in severe rocky desertification areas, severe soil erosion, soil degradation, and fertility depletion have completely lost cultivation conditions, creating prominent human-land contradictions. Therefore, counties with high proportions of severe rocky desertification area show overload trends in cultivated land ecological carrying capacity.

[Figure 6: see original paper] shows the spatial distribution pattern of cultivated land ecological carrying capacity supply-demand balance in Bijie City. [Figure 7: see original paper] shows the relationship between county-level cultivated land ecological carrying capacity balance index and gross domestic product. [Figure 8: see original paper] shows the relationship between different grades of rocky desertification proportion and cultivated land ecological carrying capacity balance index at county level.

6. Conclusions and Discussion

Karst regions have fragile ecological environments and prominent human-land contradictions. Issues of ecological service function degradation and rocky desertification have become hot topics in academia. However, research on the relationship between cultivated land ecological supply-demand balance status and different grades of rocky desertification intensity and economic development level in karst regions remains limited. This study, taking the supply-demand relationship of cultivated land ecological carrying capacity in karst regions as the entry point and using the cultivated land ecological footprint model, investigates the supply-demand balance of cultivated land ecological carrying capacity in Bijie City in 2014. The main findings are: (1) The supply-demand of cultivated land ecological carrying capacity in Bijie City shows obvious spatial imbalance, generally presenting a pattern of surplus in the north and overload in the south; (2) There is a negative correlation between gross domestic product and the cultivated land ecological carrying capacity supply-demand balance index. While studies by Shi Kaifang et al. [1] and Liu Dong et al. [9] show a positive correlation between cultivated land ecological carrying capacity supply-demand balance index and economic development level in non-karst regions, this negative correlation represents a characteristic distinguishing karst regions from other areas; (3) The cultivated land ecological carrying capacity supply-demand balance index is negatively correlated with the proportion of potential, light, and moderate rocky desertification areas, but positively correlated with the proportion of severe rocky desertification area; (4) Among the eight counties, four have ecological surplus, two have ecological balance, and two have ecological deficit, with 75.28% of the population living in ecological surplus and balance zones and 24.72% living in ecological deficit zones.

In recent years, with the implementation of the industrial strengthening strategy and accelerated urbanization, the degree of cultivated land ecological deficit in this region will inevitably intensify. Bijie City is the most severely rocky desertified area in Guizhou Province, and improvement of its cultivated land ecological carrying capacity supply-demand balance status plays a decisive role in improving the province' s ecological environment. In formulating comprehensive land use planning, Bijie City should coordinate the relationship between economic construction and cultivated land protection. Counties with cultivated land ecological carrying capacity above balance status should maintain existing cultivated land area indicators during land use planning adjustments to achieve human-land harmony. Zhijin County, with severe overload in cultivated land ecological carrying capacity, should reserve other land as reserve cultivated land and strictly restrict conversion of existing cultivated land to other uses during planning adjustments.

The supply-demand balance of cultivated land ecological carrying capacity in karst regions is a dynamic process closely related to local economic development level, population size, and changes in different grades of rocky desertification area. Existing research results show that the expansion trend of rocky desertification in Southwest China' s karst regions has been initially curbed, but the prevention situation remains severe [32]. Additionally, the national two-child policy will inevitably intensify cultivated land ecological supply-demand contradictions in karst regions, which will become a focus of subsequent research.

7. Poverty Alleviation Recommendations

Scientifically implement comprehensive land zoning and consolidation by integrating agricultural industry development with land remediation and rural comprehensive improvement to enhance villagers' living environments and production conditions. Considering Bijie City' s poverty status and planning requirements, focus on linking land remediation planning with various other plans, bundling layout with new rural construction, increasing remediation of idle and inefficiently used cultivated land, and actively promoting rural collective land circulation. Guide farmers to actively carry out collective land circulation through media publicity and field research, introduce leading enterprises for large-scale agricultural cultivation and breeding, and advocate for villagers to seek employment locally to promote poverty alleviation.

Implement quality improvement of 1 mu of high-quality cultivated land per poor person. Relying on Guizhou Provincial Department of Land and Resources' implementation plan for improving 1 mu of high-quality cultivated land per capita for 1 million local poverty alleviation populations, actively seek central and municipal land remediation project funds, encourage local land remediation and quality improvement work, and implement ecological relocation in batches. Research shows that areas with deteriorating ecological environments in karst regions often belong to economically underdeveloped areas. Cultivated land ecological carrying capacity in Bijie City generally shows a trend of surplus in the north and overload in the south, with particularly severe overload in southern Zhijin County and extremely fragile ecological environment. Improve villagers' living conditions and transportation access, and implement planned, batch-by-batch ecological migration.

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