Impacts of Land Use and Landscape Pattern Dynamics on Ecosystem Service Values: A Postprint

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Abstract

Based on land use data and statistical yearbook data from 1990-2013, this study constructed ecosystem service value (ESV) coefficients revised by the Consumer Price Index (CPI), conducted spatiotemporal evolution analysis of land use structure and spatial patterns and ESV assessment in the upper reaches of the Huai River, and explored the response relationship between ESV and changes in land use structure and patterns. The results indicate that: (1) The overall ESV in the upper Huai River region exhibits an upward trend, with a fluctuating decline during 1995-2005, a significant increase around 2010, and the ESV increment during 2010-2013 exceeding that of other periods; (2) The ESV increment demonstrates a topographic gradient effect of mountainous areas > hilly areas > plain areas, with the ecological value increase primarily derived from contributions of forestland and water bodies; (3) ESV is significantly correlated with spatiotemporal changes in land use and changes in richness and aggregation of land landscape patterns, demonstrating that rational land use development approaches and appropriate development rates will contribute to ecosystem service improvement, and that the development process should account for land type advantages while avoiding excessive fragmentation of land patches; (4) The method of revising ESV coefficients using the CPI index can eliminate price fluctuation factors within the time series, rendering calculation results more reflective of actual ESV and enhancing the accuracy and comparability of ecosystem service assessments across multiple periods.

Full Text

Preamble

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The Effects of Land Use Structure and Landscape Pattern Change on Ecosystem Service Values

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Abstract

It is important to study the effect of land use change on ecosystem service value (ESV). Most previous studies have tended to directly use the ecosystem service equivalent value to calculate ESV and then compare multi-period ESVs. Because of the use of different price bases, even if the value of the same ecosystem is assessed using multi-period ESVs, the conclusions can be very different, which means there has to be a deviation evaluation. In order to improve the accuracy of these comparisons, we developed a Consumer Price Index (CPI) revised ESV coefficient method for multi-period ESV computation. The upper reaches of the Huaihe River were used as a case study to estimate the spatial distribution and dynamics of ecosystem services. In this study, we used the land use and statistical yearbook data to investigate how the spatial-temporal evolution of land use structure and spatial patterns affect the ESV. The results showed that: (1) The ESV generally showed an increasing trend in the study region. Between 1995 and 2005, the ESV decreased, but then increased significantly around 2010. Furthermore, the increase from 2010 to 2013 was higher than that for any other period. (2) The ESV increase was higher in mountain areas than in hilly areas, and the increase in hilly areas was higher than that in the plains, which shows a topographical gradient effect. The increase was mainly because of the contributions made by forest and water ecosystems. (3) There were significant correlations between the ESV and land use change and landscape pattern indexes, including the Aggregation Index (AI) and Number of Patches (NP). These correlations show that a reasonable model for land use development and an appropriate development rate will help enhance ecosystem services. The development process should take into account the advantages that different land types can offer so that excessive fragmentation of land type patches can be avoided. (4) A method that uses the CPI index to revise ESV coefficients means that the values more closely reflect the actual ESV and improve multi-period ecosystem service evaluation comparability and accuracy.

Keywords: ecosystem services value; land use change; landscape pattern; spatial-temporal heterogeneity; the upper reaches of the Huaihe River

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1. Introduction

Under the influence of rapid economic development, land resource transactions and occupation have become increasingly active, prompting rapid transformation of land use types and patterns, which has produced significant impacts on ecosystem service value (ESV). After understanding the principles and methods of ESV estimation, Chinese scholars began searching for evaluation methods more suitable for China. Ouyang Zhiyun et al. [5] comprehensively applied ecological and economic methods to explore the connotation and evaluation methods of large-scale ecological service functions. Xie Gaodi et al. [6] and Bi Xiaoli et al. [7] used the ecosystem type unit value proposed by Costanza et al. to conduct value assessments of China' s ecosystem functions and benefits. He Hao et al. [8] combined remote sensing technology to calculate ESV. Xie Gaodi et al. [9] referenced some results from Costanza et al., integrated ecological questionnaire survey results from Chinese professionals, established a service value table per unit area for China' s terrestrial ecosystems, and conducted surveys of 200 professionals with ecological backgrounds to derive a new ecosystem service evaluation unit price system [10]. Based on this, they revised the system in 2008 [11] and constructed a spatiotemporal dynamic equivalent factor table with monthly temporal resolution and provincial spatial resolution. Although subsequent scholars conducted improvement and application studies [12-13], the essence remained based on the unit area value equivalent table proposed by Xie Gaodi et al. in 2008.

Due to different price bases, calculation results based on unit area equivalents are often much higher than those based on unit area value [6,11,14], limiting application in land management practice [15]. The unit area value has become the main factor causing changes in ESV. Existing literature often uses the main grain crop output value per unit area in the study area as the unit area value [8,12,17]. This calculation does not consider inflation factors, causing subsequent temporal difference values in marginal change analysis to still have different bases, resulting in the phenomenon where the same actual ecosystem value shows different price-quantities when expressed in assessment year prices [11,14]. Zhang Zhou et al. [15] analyzed this and believed that marginal change methods could be used for ESV assessment. However, existing research based on land area focuses more on land resource area changes while ignoring structure and pattern changes caused by land use area changes [8,13]. Even when some scholars studied the costly losses of farmland conversion [18], they still did not analyze and discuss the relationship between land use spatiotemporal change processes and ESV impacts.

The Huaihe River Basin is located in China' s north-south climate transition zone and central plains, carrying 20.4% of the country' s rural population. With less than [missing percentage] of the nation' s cultivated land area, it produces [missing percentage] of national agricultural output value and provides [missing percentage] of agricultural output [19]. Against this background of natural resource sensitivity and urgent economic demand, this study selected the upper reaches of the Huaihe River to investigate the impact mechanism of land use and landscape pattern evolution on ESV. We propose a CPI-based revision method for unit area ecosystem service value coefficients, aiming to quantitatively assess the ecological effects triggered by land use changes from macro and micro spatial scales, and provide theoretical and methodological support for future sustainable land resource utilization and socio-economic development in the upper Huaihe River region.

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2. Study Area Overview

The upper reaches of the Huaihe River are located in China' s north-south climate transition zone. In climate zoning, with the Huaihe River and the Northern Jiangsu Irrigation Main Canal as the boundary, the north belongs to the warm temperate semi-humid zone, while the south belongs to the subtropical humid zone. The annual average temperature is 16°C, showing a gradual decreasing trend from south to north. Precipitation distribution characteristics are obvious, with more in the south than north, and mountains higher than plains. Precipitation within the basin has large inter-annual variation, with most occurring during flood seasons. From south to west are the Tongbai and Dabie Mountains, with mountainous and hilly areas dominating. The area of mountains above 1000m is approximately 30,000 km², while low mountains and hills below 1000m are nearly 2,000 km² [20]. The northern part is mainly plains, which are important grain and oil production bases in China with high agricultural production levels and land utilization rates. The upper Huaihe River basin includes Xinyang City, Nanyang City, and parts of Zhumadian City. For convenient access to socio-economic data, this paper includes counties with more than [missing threshold] of their administrative area within the upper Huaihe River basin boundaries.

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

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3. Data Sources

The watershed administrative boundary data and land use data for five years (1990, 1995, 2000, 2005, 2010, 2013) were obtained from the National Science and Technology Infrastructure Platform - Yellow River Lower Reach Scientific Data Center. Land use data sources are Landsat TM images with 30m resolution, obtained through human-computer interactive interpretation with accuracy reaching [missing value], meeting research needs. DEM data came from the Chinese Academy of Sciences Data Cloud Platform. Cultivated land data and grain output value data for calculating ecosystem service value per unit area were obtained from the Henan Statistical Yearbook. CPI data used to eliminate price inflation came from the National Bureau of Statistics website.

4. Data Processing Methods

Land use data processing primarily used the ENVI 5.1 and ArcGIS 10.2 platforms for image processing and spatial analysis calculations. Landscape indices were obtained using Fragstats 4.2 software. The raster data unit for calculation was 30m×30m. The land use change rate formula referenced literature [17], and the landscape pattern index calculation method was detailed in literature [21]. Correlation coefficients were calculated based on [missing software]. Below we focus on introducing the ecosystem service value revision and calculation methods.

The ecosystem service value (ESV) calculation formula is:

$$ESV = \sum_{k=1}^{n} A_k \times VC_k$$

where n is the number of land use types, A_k is the area of land use type k in the study area, and VC_k is the ecosystem service value coefficient for land use type k.

The profit and loss calculation formula for land use type conversion is:

$$P_{ij} = (VC_i - VC_j) \times A_{ij}$$

where P_{ij} is the ESV after conversion from land use type i to type j, A_{ij} is the conversion area from type i to type j, and VC_i and VC_j are the ESV coefficients for types i and j respectively.

The CPI revision formula for VC_k is:

$$VC_k = VC'_k \times \frac{CPI_{current}}{CPI_{base}}$$

where VC'_k is the original coefficient, $CPI_{current}$ is the current period CPI, and CPI_{base} is the base period CPI.

The unit area value is calculated as 1/7 of the main grain crop output value per unit area in the study area for the current year. Equivalent data reference [9].

5. Results

5.1 Temporal Characteristics of Land Use Structure

Land use change analysis focuses on two aspects: land use type area changes and change rates. Cultivated land area proportion in the study region continued to decline, while construction land area proportion continued to rise. Grassland area showed a decreasing trend. Cultivated land dominated the study area at 67.2%. Using the comprehensive change dynamic degree formula with 5-year intervals, land use change rates were calculated for each period: 0.48% (1990-1995), 0.36% (1995-2000), 0.09% (2000-2005), 0.38% (2005-2010), and 0.11% (2010-2013). The period before 1995 was a time of rapid land type conversion, which slowed after 2005 but gradually accelerated again after 2010.

Land use structure and changing rate of the upper reaches of the Huaihe River from 1990 to 2013

The land transfer matrix illustrates the mutual conversion among land types during 1990-2013. Cultivated land had the largest transfer-out area at 1801.11 km^2, followed by forest land at 379.82 km^2. Grassland had the highest transfer-out proportion at 34.52%, while construction land had the highest transfer-in proportion at 31.46%. Due to the small base of unused land, minor quantity changes cause large proportion differences. Except for a small amount of cultivated land converted to unused land, unused land did not undergo other changes and is therefore ignored in transfer analysis.

Land use transfer matrix of the upper reaches of the Huaihe River from 1990 to 2013

5.2 Spatial Characteristics of Land Use Change

Using ENVI 5.1 and ArcGIS, land use change detection mapping was performed on land use type maps for two periods to identify change areas. Statistical analysis of five slope categories shows that with increasing slope, the transfer amount of all land types significantly decreases, showing natural land type attributes. Cultivated land to forest land conversion occurs more on slopes >15°, while forest land to cultivated land conversion occurs more on slopes <6°. Cultivated land to construction land and grassland to forest land conversions occur more on 6-15° slopes.

Land transfer regional slope statistics of the upper reaches of the Huaihe River from 1990 to 2013

Continuous conversion of cultivated land in flat areas to construction land, with forest land supplementing cultivated land, causes cultivated land to continuously expand into mountainous areas, particularly evident before 2010. After 2010, cultivated land to forest land and cultivated land to water area conversions appeared, indicating a human ecological restoration and reconstruction process of returning farmland to forest and grassland.

5.3 Spatiotemporal Evolution of Landscape Patterns

Landscape indices highly condense landscape pattern information and can reflect landscape structure composition and spatial configuration characteristics [21], making them important methods for quantitatively describing landscape pattern evolution and ecological process impacts [22]. Since patch analysis is often land-type based, this paper selected class-level metrics including patch shape index (FRAC_AM) and patch aggregation index (AI), and landscape-level metrics including contagion (CONTAG), landscape diversity (SHDI), Shannon' s evenness (SHEI), and interspersion juxtaposition index (IJI) for landscape pattern change analysis in the study area.

At the landscape scale, SHDI and SHEI increased annually, while CONTAG showed a decreasing trend (68.10 to 67.59). Over time, cultivated land had the highest fractal dimension, indicating the most irregular patch shapes and high fragmentation, but its large area still showed high aggregation. Forest land patch shapes became increasingly irregular over time, while water and unused land showed opposite trends. The continuous increase in shape indices for grassland and other land types indicates that land type fragmentation continued during 1990-2013. The decrease in landscape dominance led to reduced connectivity and accessibility among landscapes, combined with increasing aggregation degrees, resulting in more complex land type distributions.

[Figure 2: see original paper] Changing analysis of different land use FRAC_AM and AI index at the upper reaches of the Huaihe River from 1990 to 2013

The landscape pattern index table of the upper reaches of the Huaihe River from 1990 to 2013

5.4 ESV Change Analysis

5.4.1 Temporal Variation Characteristics Referencing the Henan Statistical Yearbook, main grain crop sowing area and output value were calculated to obtain unit area value excluding inflation. Combined with ecosystem area data and formula (1), ESV was calculated. ESV showed an overall upward trend in the study region. After 2005, it showed a significant upward trend, with the 2010-2013 increase higher than other periods. All four ecosystem service functions showed the above inter-annual variation characteristics. Regulation service function increased the most, followed by support service function. Water area had the largest increase, followed by forest land. Water area and farmland are the main components of ESV. Wetland was the only negative growth item.

The time variation of ESV of the upper reaches of the Huaihe River from 1990 to 2013

Although water area and forest land account for only 3.26% and 17.62% of regional area respectively, their ESV contribution reaches 33.67% and 36.00%, indicating they are the main land use types causing ESV increase. This phenomenon occurs because the increase in main grain unit output value in the study area leads to increased ecosystem service value per unit area, offsetting negative effects from area reduction.

The ESV of each ecosystem in the upper reaches of the Huaihe River from 1990 to 2013

5.4.2 ESV Profit and Loss Analysis Based on the 1990-2013 land transfer matrix, ESV profit and loss analysis shows total profit of 205.93 and total loss of 178.52. ESV increase mainly consists of ecosystem service value added by farmland-to-forest land and farmland-to-water area conversions. All land type conversions to water area show positive flow. Losses are mainly caused by forest land and water area conversions to farmland, with forest-to-farmland conversion causing the most loss at 138.05. All conversions to construction land show negative flow, mainly caused by farmland-to-construction land conversion. Overall, profits exceed losses, with ecological value increase mainly from forest land and water area contributions.

The ecosystem services profit or loss matrix values of the upper reaches of the Huaihe River from 1990 to 2013

5.4.3 Spatial Variation Characteristics From the topographic distribution of the study area, ESV shows a stepwise change pattern: mountainous counties (Biyang County, Queshan County) > hilly counties (Huangchuan County, Gushi County) > plain counties (Xinxian County, Shangcheng County). Runan County in the plain area is higher than other plain counties due to abundant water resources. After 2005, ESV increased rapidly in mountainous counties while other counties showed slower growth. Zhumadian City was the only negative growth region. During 2005-2010, total ecosystem service value increased, with value added mainly from forest land and water area contributions. Since forest land and water area distribution depends on topographic factors, total ecosystem service value increase shows spatial imbalance. The negative effects from continuous conversion of cultivated land to construction land have already appeared, indicating future attention should focus on natural resource protection and spatial equalization of ecological service values.

[Figure 3: see original paper] The spatial distribution of ESV in each county of the upper reaches of the Huaihe River from 1990 to 2013

5.5 Response Relationship Between ESV and Land Use/Landscape Changes

5.5.1 Correlation Analysis Between Land Use Change and ESV Change Using first-level land type areas and corresponding ESVs from five years (1990, 1995, 2000, 2005, 2010) for correlation analysis, the correlation coefficient is 0.35, reaching significance at the 0.05 level, indicating certain correlation between large land type areas and their ESVs. Correlation analysis between land use area change amounts and ESV change amounts for two periods (1990-1995 and 2005-2010) shows a correlation coefficient of 0.38, reaching significance at the 0.05 level. The correlation degree is significantly higher than that between two totals, indicating ESV is mainly affected by spatial distribution of land type areas.

5.5.2 Correlation Analysis Between Landscape Pattern Change and ESV Change Using Fragstats 4.2 software, six landscape indices were calculated: Number of Patches (NP), Largest Patch Index (LPI), Mean Patch Area (AREA_MN), Mean Shape Index (SHAPE_MN), Mean Fractal Dimension Index (FRAC_MN), and Aggregation Index (AI) for six land types (farmland, forest land, grassland, water area, wetland, and wasteland). Correlation analysis between each index and ESV for each period shows significant correlations between ESV and landscape richness and land type aggregation, but weak correlation with land type patch size. Strong negative correlations exist with patch shape complexity, indicating landscape fragmentation impacts ESV spatiotemporal changes.

The relevance of landscape pattern index and ESV at the upper reaches of the Huaihe River from 1990 to 2013

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6. Discussion

Correlation analysis is an important method and effective means for quantitatively studying spatial relationships. Using correlation coefficients to quantify the relationship between land use indicators and ESV helps highlight dynamic change patterns and explore construction of more reasonable ecosystem spatial patterns. The significant correlation between ESV and land type spatial distribution is consistent with research results from Hu and Bing et al. [28] and Ouyang Zhiyun et al. [5], showing that areas with good hydrothermal conditions favorable for vegetation growth (affected by topography) have higher ecosystem service value per unit area, and these areas also have better landscape diversity and ecological integrity.

ESV shows high correlation with inter-annual land type changes. During 1995-2005, land type transfer was most frequent, with large areas of cultivated land converted to construction land, and forest land and grassland transferred to supplement cultivated land, causing ESV to fluctuate and decrease. After 2010, some cultivated land was transferred to forest land and grassland, and ESV showed a clear upward trend, with consistent timing of changes. Although forest land and water area have small area proportions, they contribute significantly to total value. The conclusion that ESV has weak correlation with land type change rate is consistent with Hao Fanghua et al. [30].

During 1990-2013, landscape fragmentation intensified yearly, and landscape dominance decreased yearly. This phenomenon was most obvious around 2010, when regions were continuously damaged. The significant negative correlation between ESV and FRAC_MN also indicates that human activities affect land landscape patterns, and urban expansion-induced reduction of ecological land is often the main cause of total ESV loss [31]. This study analyzed land type structure and pattern spatiotemporal evolution characteristics, refined land type structures, and 梳理 the correlation degree with ESV, providing a beneficial attempt to explore ecosystem service response characteristics under land use changes, overcoming previous problems of overly large evaluation scales and insufficiently targeted conclusions.

7. Conclusions

(1) ESV shows the most significant correlation with land type spatial distribution attributes, weak correlation with land type change rate, significant correlation with land landscape heterogeneity and fragmentation, and weak correlation with landscape shape characteristics.

(2) The ecosystem value profit and loss analysis method focuses value changes on transitional losses of natural resources, compensating for deficiencies in existing ecosystem service process change evaluations and facilitating application of evaluation results in actual land use management.

(3) Using CPI to revise ESV coefficients can eliminate value changes caused by price inflation within time series, avoiding inconsistent research results under price influence and making calculation results more closely reflect actual ecosystem values, improving accuracy and comparability of multi-temporal ecosystem service evaluations.

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