Impacts of Land Use Change on Ecosystem Services in Hengyang City, 2000–2013: A Postprint

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Abstract

One important approach to applying ecosystem services assessment to regional ecological conservation decision-making is ecosystem services mapping. This study interpreted multi-temporal remote sensing imagery of Hengyang City, employing the equivalent factor method to estimate its ecosystem services value (ESV) and the value gains and losses caused by land use pattern transformations. With the support of ArcGIS 10.0 software, spatial statistical methods including spatial autocorrelation, high-low clustering, and centroid analysis were utilized to conduct mapping simulation of the spatiotemporal variation of ESV in Hengyang City, aiming to provide decision support for ecological conservation planning and management in Hengyang City. The research results indicate that: 1) The ESV of Hengyang City decreased slightly from 2000 to 2013, dropping from 241 billion yuan in 2000 to 239.4 billion yuan in 2013; transition matrix analysis revealed that the conversion of forestland and cropland to construction land, as well as the conversion of forestland to cropland, were the primary causes of ESV reduction in Hengyang City. 2) High-value ESV areas in Hengyang City exhibited an encircling pattern around low-value areas; from 2000 to 2013, ESV loss areas were mainly distributed in the urban district and its eastern regions, while gain areas were primarily located in the western regions of the urban district. 3) The spatial autocorrelation and high-low value clustering phenomena of ESV in Hengyang City were significant, with their intensity tending to strengthen; the ESV centroid migrated 245.73 m in the direction 9° north of west. Measures such as restricting the conversion of forestland and cropland to construction land, implementing "stock" or "reduction" land use policies, and maintaining and strengthening the continuity of the regional overall ecosystem pattern could be considered to enhance the ecosystem services value of the study area.

Full Text

Preamble

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Abstract: Ecosystem services mapping represents a critical pathway for integrating ecosystem services assessment into regional ecological protection decision-making. This study interprets multi-temporal remote sensing imagery of Hengyang City, employing the equivalent factor method to estimate ecosystem services value (ESV) and quantify gains and losses resulting from land use pattern transformations. Supported by ArcGIS 10.0, spatial statistical methods including spatial autocorrelation, high-low clustering, and gravity center analysis are utilized to simulate the spatiotemporal dynamics of ESV, thereby providing decision support for ecological protection planning and management in Hengyang. The results indicate: (1) From 2000 to 2013, Hengyang' s ESV decreased slightly from 241.0 billion yuan to 239.4 billion yuan. Transfer matrix analysis reveals that conversion of forestland and cultivated land to construction land, along with forestland conversion to cultivated land, constituted the primary drivers of ESV decline. (2) High-ESV areas in Hengyang exhibited an encircling pattern around low-ESV areas. Between 2000 and 2013, ESV loss zones were concentrated in urban districts and eastern regions, while value-added areas were predominantly located in western districts. (3) Spatial autocorrelation and high-low value clustering of ESV were pronounced and intensifying over time. The ESV gravity center migrated 245.73 meters in a west-northwest direction (9°). Recommended measures to enhance regional ecosystem services include restricting forestland and cultivated land conversion to construction land, implementing "stock" or "reduction" land use policies, and maintaining and strengthening the continuity of the overall regional ecosystem pattern.

Keywords: Ecosystem services value; Land use; Spatial statistical methods; Hengyang City

Introduction

Ecosystem services refer to the conditions and processes provided by natural ecosystems and their species that satisfy and sustain human needs [1-2]. Quantitative valuation of these services facilitates efficient and rational allocation of competing environmental resources [3] and supports the scientific formulation of ecological compensation policies [4]. Costanza et al. [5] pioneered the quantitative assessment of ecosystem services value (hereafter "ESV"), establishing a foundation for international research on sustainable development. Chinese scholars such as Ouyang et al. [6-7] and Fu et al. [8-9] elaborated on the concepts, utilities, and valuation methods of ESV. Xie et al. [10-12] repeatedly refined Costanza's methodology, developing ESV equivalent coefficients suitable for China's national context. The equivalent factor method has since been widely adopted by domestic and international researchers for regional ESV assessment. Additionally, approaches integrating ecological parameters with value equivalents and assessments from ecological asset perspectives have demonstrated good applicability and development potential [13-14].

Land use/cover change (LUCC) influences ecosystem structure and function [15] and plays a decisive role in maintaining ecosystem service functions [16]. Consequently, numerous scholars have investigated ESV changes induced by land use transformations across various temporal and spatial scales using diverse methods [17-18]. With advances in 3S technology (Remote Sensing, Geographic Information Systems, and Global Positioning Systems), researchers have combined remote sensing data with eco-physiological models, employing equivalent factors for ESV assessment and mapping spatial distributions to support regional protection decision-making and management planning [19-20]. However, research utilizing 3S technology to simulate the spatial distribution of regional ESV gains and losses, and applying spatial statistical analysis to reveal spatiotemporal patterns and characteristics of ESV change, remains insufficient.

This study examines Hengyang City in Hunan Province. Supported by ArcGIS 10.0 and based on multi-year remote sensing imagery and socioeconomic statistics, we assess ESV, map the spatial distribution of ESV and its gains/losses, and employ spatial statistical methods to explore the spatiotemporal dynamic evolution characteristics of ESV in Hengyang. The findings provide essential references for regional ecological security management and eco-economic development in Hengyang.

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1. Study Area Overview

Hengyang City is located in central-southern Hunan Province, along the middle reaches of the Xiang River and south of Mount Heng. It serves as a sub-central city of Hunan Province, an important industrial city in central-south China, and a regional logistics center. The city jurisdiction comprises five districts (Shigu, Yanfeng, Zhuhui, Zhengxiang, and Nanyue), five counties (Hengyang, Hengnan, Hengshan, Hengdong, and Qidong), and two county-level cities (Leiyang and Changning). Geographically situated at 110°32 16 -113°16 32 E and 26°07 05 - 27°28 24 N, Hengyang covers a total area of approximately 15,310 km². In recent years, rapid economic and social development has substantially altered land use types and spatial structures, consequently impacting regional ecosystem services value.

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2. Methods

2.1 Data Sources and Processing

LandSat TM remote sensing images from 2000, 2005, 2010, and 2013 were acquired for the Hengyang region, with a spatial resolution of 30 m × 30 m. Through visual interpretation, land use types were classified into seven categories: cultivated land, forestland, grassland, wetland, water bodies, construction land, and unused land [Figure 1: see original paper]. The overall classification accuracies were 85.2%, 86.5%, 88.7%, and 87.4% respectively, with Kappa values exceeding 0.8, meeting research requirements. Relevant economic and social development data were obtained from Hengyang Statistical Yearbooks.

2.2.1 ESV Accounting for Land Use Pattern Transformation

The equivalent factor method based on per-unit-area value coefficients was employed to account for ESV changes resulting from land use pattern transformation in Hengyang. An ESV equivalent factor represents the relative contribution rate of ecosystem service provision. According to Xie et al. [10], the economic value of one ESV equivalent factor in China equals one-seventh of the national average market price of grain yield in the corresponding year. To reflect regional characteristics, the study calculated ESV equivalent factors using local grain yields and introduced biomass-based adjustment factors [11] to modify the ESV coefficients.

Land use transfer matrices were calculated to quantify gains and losses in ESV. Traditional ESV analysis models based on land use type areas only consider numerical changes in ESV during monitoring periods, failing to reflect the sources and destinations of ESV gains and losses. Transfer matrix analysis simultaneously considers both the spatial distribution of ESV transfers and quantitative change directions for each land use type, providing deeper insights into ESV change characteristics. The calculation formulas are presented in Table 1 .

2.2.2 Spatial Statistical Analysis of ESV Evolution

Geographic data exhibit interdependence among different spatial locations due to spatial interaction and diffusion, a phenomenon known as spatial autocorrelation. Analyzing the degree of mutual influence and dependency of ESV across different spatial units within a geographic range is crucial for understanding its evolution characteristics and patterns. This study employs Global Moran' s I and Getis-Ord General G to detect spatial autocorrelation and high/low clustering of ESV at specific scales. The Getis-Ord General G statistic specifically tests for spatial clustering of high or low values. Gravity center analysis, a method for investigating spatial differentiation and dynamic changes in geographic phenomena, utilizes the gravity center concept to analyze ESV movement direction and distance, thereby reflecting regional ESV spatial disparities and revealing dynamic evolution processes.

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3. Results

3.1.1 Changes in ESV Structure

Based on the interpreted remote sensing data [Figure 1: see original paper] and the ESV estimation model described above, we calculated Hengyang' s ESV for 2000, 2005, 2010, and 2013 and generated an average ESV distribution map for the 2000–2013 period [Figure 2: see original paper].

The results reveal several key patterns: First, regarding ESV composition, the relative proportions of individual ecosystem service functions in Hengyang ranked as follows: biodiversity conservation > water conservation > soil formation and protection > climate regulation > gas exchange > raw materials > waste treatment > entertainment/culture > food production. Biodiversity conservation, water conservation, soil formation and protection, climate regulation, and gas exchange collectively accounted for 15.16%, 14.99%, 14.37%, 13.75%, and 13.74% of total functional value respectively. Raw materials and waste treatment represented the next tier, each comprising 9.23% and 9.12% of total value. Food production and entertainment/culture exhibited the lowest values at 2.94% and 6.71% respectively. Second, in terms of ESV changes, Hengyang' s total ESV declined gradually from 2000 to 2013, with all individual service functions showing slight decreases and an overall reduction of 0.67%. Between 2000 and 2005, Hengyang' s ESV increased by 0.62 billion yuan due to modest increases in waste treatment (0.54%), water conservation (0.25%), climate regulation (0.18%), and entertainment/culture (0.12%). However, during 2005–2010 and 2010–2013, all individual ESV components showed decreasing trends.

The average ESV distribution pattern reveals that high-value areas are generally located in mountainous forestlands near the municipal boundary, while low-value areas are concentrated in more central regions with gentler terrain suitable for urban development and agricultural cultivation. Overall, both high-value and low-value areas demonstrate good integrity and continuity, with high-value areas encircling low-value zones. The low-value areas spread outward from the urban core toward county seats, a pattern that aligns with Hengyang' s basin topography.

3.1.2 ESV Gains and Losses from Land Use Pattern Transformation

Based on [Figure 1: see original paper], we calculated the land use transfer matrix for Hengyang and derived the ESV gains and losses resulting from land use pattern transformation . Using raster calculator and interpolation tools in ArcGIS, we generated spatial distribution maps of ESV profit and loss for each study period [Figure 3: see original paper].

The analysis yields three key findings: (1) During 2000–2005, land use transformation resulted in ESV gains of 0.513 billion yuan and losses of 0.451 billion yuan, yielding a net gain of 0.062 billion yuan. The primary contributions to gains came from four transformation types: cultivated land to forestland, cultivated land to water bodies, forestland to water bodies, and water bodies to wetland, which accounted for approximately 86% of total gains. Conversely, conversion of cultivated land and forestland to construction land was the main cause of ESV losses, responsible for 73% of total losses. (2) During 2005–2010, ESV gains reached 5.627 billion yuan while losses amounted to 6.637 billion yuan, resulting in a net loss of 1.009 billion yuan. This period exhibited more dramatic land pattern changes than the other two intervals. Gains were predominantly generated by conversions from cultivated land to forestland and water bodies, which contributed 70% of total gains. Meanwhile, forestland conversion to cultivated land and construction land constituted the primary cause of losses, accounting for 87% of total losses. (3) During 2010–2013, ESV gains were 0.585 billion yuan and losses 1.241 billion yuan, yielding a net loss of 0.657 billion yuan. The mutual conversion between cultivated land and forestland produced roughly balanced gains and losses. The main cause of ESV loss was conversion of forestland and cultivated land to construction land, which generated losses of 0.61 billion yuan.

The spatial distribution patterns of ESV gains and losses show distinct characteristics across periods: (1) During 2000–2005, loss zones were concentrated in urban districts, northern Hengdong County seat, and slightly southeast of Leiyang County seat. Value-added areas were primarily located in eastern Hengyang County, western Qidong County, southwestern Hengnan County, and eastern Changning City. (2) During 2005–2010, the profit-loss distribution was more complex than in other periods. Loss zones were mainly found in areas adjacent to urban districts in eastern Hengyang County, southwestern Hengnan County, areas along railways and highways in southern Leiyang, southern and northern Hengdong County, southern Hengshan County, and slightly northwestern Nanyue District. Value-added regions were concentrated in northeastern Hengnan County bordering urban districts, northwestern Hengyang County, northwestern Qidong County, eastern Hengdong County, northwestern Changning City, and northeastern and southeastern Leiyang City. (3) During 2010–2013, loss zones were primarily distributed in eastern Hengnan County, southern Hengdong County, and southeastern Changning City, with notable losses also occurring in urban districts and areas where Hengyang, Hengdong, and Hengnan counties border the urban core. Value-added areas were mainly located in northern Hengyang County, northwestern Hengshan County, western Hengyang County, southern Qidong County, and southern Leiyang City.

3.2 Spatial Autocorrelation and High/Low Clustering Analysis of ESV

The statistical results demonstrate several important trends: First, in spatial autocorrelation analysis, the Moran' s I values for all four years were relatively high. Standardized statistical measures Z(I) were applied to test significance levels, calculated as $Z(I) = [I - E(I)]/\sqrt{Var(I)}$, where E(I) and Var(I) represent the theoretical expectation and variance of index I respectively. The results show that all Z(I) values exceeded the 1% significance threshold, indicating strong spatial autocorrelation in Hengyang' s ESV distribution and a clustered spatial pattern. Additionally, the I index and Z(I) values exhibited a decreasing-then-increasing trend across the four periods, suggesting that spatial autocorrelation first weakened then strengthened.

Second, in high/low clustering analysis, the G index values for all four years were not significantly greater than E(G), but Z(G) values were notable, indicating the presence of both high-value and low-value clustering patterns in Hengyang' s ESV distribution. The Z(G) values showed a decreasing-then-increasing trend, revealing that clustering intensity of both high and low values weakened during 2000–2005, then continuously strengthened thereafter, eventually surpassing 2000 levels.

3.3 Migration Trajectory of ESV High-Value Area Gravity Center

Using Formula 4 from Table 2, we calculated the weighted gravity centers of ESV for the four years and generated a migration trajectory map [Figure 4: see original paper], along with statistics on migration distances [Figure 5: see original paper]. The results show that from 2000 to 2013, Hengyang' s ESV gravity center consistently fell near Changweichong in Zhuhui District. The migration was extremely slow, moving primarily in a west-northwest direction with a general "U-shaped" pattern. The migration exhibited distinct phases, following a "slow—rapid—slow" trajectory. The total linear migration distance during 2000–2013 was approximately 247 meters. Specifically, the 2005–2010 period represented the most dynamic phase, with the longest average annual migration distance, while the other two phases showed similar, relatively minor movement.

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4. Discussion and Conclusions

This study, based on the equivalent factor method, interpreted remote sensing imagery to identify seven land use types in Hengyang. Using biomass indicators to adjust the ESV equivalent factors, we estimated annual ESV values, mapped spatial distributions of ESV and its gains/losses, and applied spatial statistical methods including spatial autocorrelation, high-low clustering, and weighted gravity center calculation to explore spatiotemporal dynamic evolution characteristics. The findings provide references for decision-makers to formulate realistic land use structures and implement environmental protection and ecosystem management, thereby promoting coordinated economic, social, and ecological development in Hengyang.

Key findings include: (1) From 2000–2005, Hengyang' s total ESV increased slightly, likely due to Hunan Province' s afforestation program initiated in 2000. The continuous decline from 2005–2013 probably represents an inevitable consequence of urbanization encroaching on forestland and cultivated land. (2) The average ESV distribution pattern of high values in peripheral areas and low values in the center primarily reflects Hengyang' s basin topography, a factor previously shown to significantly influence regional ecological quality [21-23]. (3) The main drivers of ESV change were interactive conversions among forestland, cultivated land, and construction land. Profit-loss analysis maps show that loss zones occurred mainly in urban districts and county seats, where extensive conversion of cultivated land and forestland to construction land took place. Satellite imagery confirms that construction land area in Hengyang increased by 18,504.72 hectares between 2000 and 2013. (4) The ESV gravity center migrated west-northwest, possibly reflecting uneven economic development and population growth among districts and counties. Hengyang Statistical Yearbooks [24] indicate spatial differentiation in economy and population, with Leiyang, Changning, and Hengnan counties experiencing faster growth than Qidong, Hengdong, and Hengshan counties, showing an east-west development gradient that corresponds with the ESV gravity center trajectory.

Several limitations warrant acknowledgment: First, different ESV estimation methods may yield substantially different results. Current approaches can be broadly categorized into "service price-based methods" and "equivalent factor-based methods." The equivalent factor method was chosen for its intuitiveness, minimal data requirements, and particular suitability for regional and global-scale ESV assessments integrated with GIS analysis. Second, the equivalent factor method has inherent limitations. For instance, when the area of a particular land use type remains unchanged but its landscape metrics (e.g., patch number, mean patch area, aggregation index) change, ESV will be affected. While the biomass method provides some correction, it cannot fully resolve this issue, prompting calls for multi-level, multi-scale ESV assessment case studies [10,25]. Third, besides biomass correction, some scholars have adjusted food production ESV coefficients based on actual conditions of farmland ecosystems [26] or applied catastrophe theory to modify per-unit-area ESV coefficients for China' s terrestrial ecosystems [27]. Different regional correction methods inevitably produce different final ESV estimates. Fourth, finer land use classifications and higher-resolution raster analysis would enhance result reliability. Additionally, due to space constraints, this study focused on mapping average ESV distribution and profit-loss patterns along with spatial statistical analysis, without examining driving mechanisms of ESV spatiotemporal differentiation—

an aspect to be addressed in future research.

The main conclusions are as follows:

1) From 2000 to 2013, Hengyang' s ESV decreased from 241.0 billion yuan to 239.4 billion yuan. Biodiversity conservation, water conservation, soil formation and protection, climate regulation, and gas exchange represented the most prominent service functions, while food production and entertainment/culture exhibited the lowest values. High-ESV areas encircled low-ESV areas, with high values distributed in mountainous forestlands around the municipal boundary and low values in the central region with gentler terrain suitable for agriculture and construction, consistent with Hengyang' s basin topography.

2) Conversion of forestland and cultivated land to construction land, along with forestland conversion to cultivated land, constituted the primary causes of ESV decline. Loss zones were mainly distributed in urban districts, eastern Hengnan County, eastern Hengyang County, southern Leiyang City, and southeastern Changning City.

3) Hengyang' s ESV demonstrated pronounced spatial autocorrelation and high/low value clustering. Although total ESV declined from 2000–2013, its spatial autocorrelation and clustering intensity increased, indicating reduced spatial fragmentation. The ESV gravity center consistently fell near the junction of southern urban districts and Chejiang Town in Hengnan County, migrating very slowly in a west-northwest direction following a "slow—rapid—slow" pattern.

Based on these conclusions, the following measures are recommended for effective ecosystem services management in Hengyang:

1) Restrict conversion of forestland and cultivated land to construction land; encourage afforestation and restoration of farmland to lakes to offset ESV losses from construction land expansion.

2) Implement intensive monitoring in ESV loss zones and enforce "stock" or "reduction" land use policies to strictly control their expansion, while guiding transitions from low-ESV to high-ESV land use types.

3) In regional land use master planning, maintain and strengthen the continuity of the overall ecosystem pattern and enhance protection of forestland, wetlands, and water bodies to improve regional ESV.

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