Spatial Evolution of Coordinated Development between Economy and Ecological Environment in Terrestrial China (Postprint)

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Abstract

Based on GDP data from 2,853 counties (districts) across China and national 1km grid land use data, this study constructs ESV, YEEH, and EEHC models to calculate the coordination degree between China' s terrestrial economy and ecological environment based on per unit area changes in ESV and GDP. Spatial analysis of YEEH and EEHC raster data is performed using the ArcGIS 10.1 platform to reveal the correlation and evolutionary characteristics between China' s terrestrial economic development and ecological environment systems. The findings demonstrate: (1) The coordinated development degree between China' s terrestrial economy and ecological environment is gradually improving, manifesting a spatial pattern wherein Northeast China outperforms Western China, which in turn outperforms Central and Eastern China. This reflects that the relationship between current socioeconomic activities and the natural ecological environment is generally progressing toward sustainability; (2) The spatial distribution pattern of coordinated development between China' s terrestrial economy and ecological environment has evolved from a below-mean clustering pattern in 1980 to a co-distribution of high-low clustering patterns in 2010; (3) While the coordination degree between socioeconomic and ecological environment development in China is improving overall, pronounced spatial disparities exist in regional distribution. Western China must vigorously develop its economy while protecting the ecological environment, whereas Central and Eastern China should emphasize ecological conservation and restoration alongside economic development. China' s economic development and ecological environment construction remains a long and arduous undertaking.

Full Text

Preamble

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Spatial Evolution of Coordinated Development between Economy and Eco-environment in China' s Terrestrial Areas

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Abstract

Based on Gross Domestic Product (GDP) data and 1 km × 1 km land use grid data for 1980, 1990, 2000, and 2010, and using 2,853 counties or districts as basic units, this study employed models including Ecosystem Service Value (ESV), Year of Economy-Environmental Harmonize (YEEH), and Economy-Environmental Harmonize Change (EEHC) to calculate the coordination degree between China's terrestrial economy and eco-environment according to per-unit-area changes in ESV and GDP. The YEEH and EEHC indices were used to reflect the relationship between economic development and eco-environmental systems in China and their evolution. The results showed that: (1) The coordination between economy and eco-environment continuously improved from 1980 to 2010. The EEHC in northern China was better than that in the western region, and the EEHC in western China was better than that in the central and eastern regions, reflecting that the relationship between current socio-economic activities and the natural ecological environment is generally developing in a sustainable direction. (2) The spatial distribution pattern of coordination between economy and eco-environment in China appeared as an aggregated model with values lower than the average in 1980, but it developed into a pattern with both high and low aggregation coexisting by 2010. (3) The coordination degree between economic society and ecological environment is currently improving overall, though significant spatial differences exist across regions. Western re-

gions need to vigorously develop their economies while protecting the ecological environment, whereas central and eastern regions must emphasize ecological conservation and restoration while developing their economies. China' s economic development and ecological environment construction still have a long way to go.

Keywords: Economic and ecological coordination; spatial evolution pattern; China

Introduction

Sustainable development has become a societal consensus in contemporary China, with its fundamental connotation being the coordinated development of socio-economy and ecological environment. Coordinated development between economy and ecological environment is widely recognized as the optimal approach to managing the relationship between economic growth and environmental protection, as well as the necessary path to achieving sustainable development strategic goals for human society [1]. Quantitative evaluation of coordinated development can provide relevant theoretical foundations for achieving these objectives, facilitating timely regulatory measures based on changes in coordination degree and promoting stable development of both socio-economic and natural ecological systems.

In recent years, research on ecological environment and economic coordination has become a hotspot in sustainability studies. Foreign scholars have primarily introduced land use changes into coordination studies, employing methods such as multi-scale evaluation models [2], spatiotemporal variation analysis [3], market value approaches [4], land function-economic development integration [5], and sustainability assessment methods [6-7]. In practice, research has focused on establishing eco-industrial parks, analyzing policies, and evaluating internal economic cycles. In terms of application, scholars have conducted extensive research on quantitative evaluation theories and models, including comprehensive indicator evaluation [8], ecological footprint analysis [9], material flow analysis [10], and system dynamics modeling [11].

Domestic scholars have shown greater attention to theory and evaluation models. Given the comprehensive and complex nature of ecological environment-economic coordination issues, which require integrating geography, ecology, economics, and other disciplines, current evaluation studies still require new approaches for deeper investigation [13]. Existing research has concentrated on three aspects: regional economic coordination theory, eco-economic coordination evaluation, and practical applications. Theoretically, scholars emphasize that economic development should adapt to natural ecology, forming a sustainable virtuous cycle. In evaluation, research has focused on variation coefficient coordination [14], order parameter efficacy function coordination [15], and fuzzy membership function coordination [16]. Currently, evaluation methods tend toward integrated approaches, while practical applications in China have mainly explored eco-agriculture, eco-industry, and eco-tourism as leading sectors for developing ecological economies.

In terms of scale, this study examines national economic development and ecological environment changes at the county level. Methodologically, it employs the Getis-Ord G*i index from spatial statistics to investigate spatial correlation and patterns between ecology and economy.

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1. Study Area and Data Sources

This paper uses county-level units as the basic unit for studying regional economic and ecological environment differences and their spatial patterns. According to administrative divisions, the basic units include counties, county-level cities, and municipal districts. Cities without districts (Dongguan and Zhongshan in Guangdong Province, Sanya in Hainan Province, and Jiayuguan in Gansu Province) are incorporated as basic research units, resulting in a total of 2,853 basic units. The study period spans 1980, 1990, 2000, and 2010.

The research data consist of 1 km × 1 km grid land use data. Land use data for 1980, 1995, and 2000 were obtained from the Chinese Academy of Sciences' Resource and Environment Database. The 2010 land use data were derived from the European Space Agency' s GlobCover global land cover dataset. The original GlobCover data were generated from Envisat MERIS (Medium Resolution Imaging Spectrometer) sensor imagery, primarily using high-quality image data received between December 2004 and June 2006 for image synthesis. Each grid contains land type codes and area proportions for categories including cropland, forest, grassland, water bodies, urban/rural settlements, and unused land, with a data format of 300 m resolution TIFF files.

Statistical data were mainly obtained from the "China Economic and Social Development Statistical Database" on CNKI, "China Regional Economic Statistical Yearbook," "China Urban Statistical Yearbook," provincial and municipal yearbooks, and national economic and social development statistical bulletins from various cities and counties.

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2. Data Processing

2.1 Ecological Environment Data Processing

This study utilized China' s terrestrial land use data from different periods to calculate Ecosystem Service Value (ESV). The four-phase data (1980, 1995, 2000, 2010) were unified according to China's land resource classification system, reclassifying land types into six primary categories: cropland, forest, grassland, water bodies, construction land, and unused land for ESV calculation. All four-phase land use types were merged into these six categories. The data projection was unified to Krasovsky1940_Lambert Conformal Conic for analysis and mapping.

2.2 Economic Data Processing

GDP data for the four time points were obtained directly from databases and statistical yearbooks. For counties lacking statistical data, two interpolation methods were employed: (1) for counties with per capita GDP data, total GDP was calculated using population data and per capita GDP; (2) for counties with economic growth rate data, GDP was extrapolated using growth rates. These interpolated data were verified to meet the accuracy requirements of this study (see reference [17]).

To facilitate matching with ESV grid data for studying spatial patterns of coordination degree changes, the four-phase county-level GDP data were rasterized. The rasterized data were then classified using the Natural Breaks (Jenks) method in ArcGIS 10.1 Surface Modeling Tools (Spline) for mapping.

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3. Methods

3.1 Ecosystem Service Value Calculation

Numerous methods exist for assessing ecosystem service quantity and value domestically and internationally, but none have gained universal acceptance among the public and academia. This study adopts the calculation models proposed by Costanza et al. [18] and Xie Gaodi et al. [19], which are the most widely used baseline unit values for ecosystem service valuation in China. The formula is:

$$ESV = \sum_{j=1}^{n}(A_j \times E_{ij})$$

where A_j is the area of ecosystem type j ($j = 1, 2, ..., n$), and E_{ij} is the baseline unit value of ecosystem service function i for ecosystem type j.

Xie Gaodi et al. [19] developed an equivalent factor table for terrestrial ecosystem service value per unit area in China based on expert questionnaires. Building upon this table and considering research actualities, this study made appropriate adjustments to some equivalents, incorporating functions such as gas regulation and climate regulation to obtain terrestrial ecosystem service equivalents suitable for national-scale research.

3.2 Economic-Ecological Coordination Evaluation Method

There is no unified standard for coordinated development between economy and environment; the coordination degree between the two systems is a relative indicator. Chinese scholars Wang Zhen [20] and Qiao Biao et al. [21] utilized the ratio between ecosystem service value and GDP in constructing environment-economy coordination indicators.

Based on analysis of ecological environment-economic coordination development and its connotation, this study constructed the Yearly Economy-Environment Harmonize (YEEH) index and Economy-Environment Harmonize Change (EEHC) index.

YEEH refers to the ratio of per-unit-area ecosystem service value to per-unit-area GDP at a research time node, characterizing the coordination relationship between current economic development and the inherent environment:

$$YEEH = \frac{ESV_{ea}}{GDP_{ea}}$$

EEHC is defined as the ratio of the change rate of per-unit-area ecosystem service value to the change rate of per-unit-area GDP during the study period, better reflecting the degree of mutual influence, constraint, or promotion between environmental change and economic development:

$$EEHC = \frac{ESV_{pr}}{GDP_{pr}}$$

where: - ESV_{ea} and GDP_{ea} represent per-unit-area ecosystem service value and GDP, respectively - $ESV_{pr} = \frac{ESV_{pj} - ESV_{pi}}{ESV_{pi}}$ and $GDP_{pr} = \frac{GDP_{pj} - GDP_{pi}}{GDP_{pi}}$ - ESV_{pi}, ESV_{pj} and GDP_{pi}, GDP_{pj} are the per-unit-area values at the start and end years of different periods

The coordination states are interpreted as follows: 1. When $ESV_{pr} > 0$ and $GDP_{pr} > 0$, the system develops in a positive direction 2. When $ESV_{pr} < 0$ and $GDP_{pr} > 0$, economic development may be exerting increasing pressure on the ecological environment 3. When $ESV_{pr} > 0$ and $GDP_{pr} < 0$, natural vegetation is growing well or human intervention is improving the ecological environment 4. When $ESV_{pr} < 0$ and $GDP_{pr} < 0$, the eco-economic system is in an uncoordinated state

Classification and mapping are conducted according to the magnitude of these ratios based on coordination standards.

4. Classification of Economic-Ecological System Coordination Degree

During the research process, YEEH values were classified according to the following standards: 0 < YEEH 0.3 (high deterioration zone), 0.3 < YEEH 0.6 (deterioration zone), 0.6 < YEEH 0.9 (deterioration-coordination transition zone), 0.9 < YEEH 1.2 (coordination zone), 1.2 < YEEH 1.5 (high coordination zone), 1.5 < YEEH 1.8, and YEEH > 1.8.

Based on calculation results, China' s terrestrial areas were divided into five categories for analyzing spatiotemporal distribution patterns and change rules. For EEHC, the following classification was applied:

1. **EEHC 1**: The eco-economic system is coordinated, indicating a harmonious and mutually promoting natural state between ecology and economy, or that natural ecological environment is harsh and economic development is lagging but undergoing natural or artificial restoration
2. **0 EEHC < 1**: The economy and ecological environment remain coordinated, though economic growth may be facing increasing ecological pressure; smaller values indicate lower coordination levels
3. **-1 EEHC < 0**: Economic development has negatively impacted the ecological environment, with the eco-economic relationship entering an uncoordinated state
4. **EEHC < -1**: Terrestrial ecosystem service value has decreased significantly, ecological environment has deteriorated, and economic development conflicts with ecological protection and restoration, showing severe incoordination

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5. Spatial Statistical Methods

Based on the above classification results, EEHC values for different periods (EEHC , EEHC , EEHC , EEHC) were divided into persistent deterioration zones (EEHC < -1), initial deterioration zones (-1 EEHC < 0), stable coordination zones (0 EEHC < 0.6), initial coordination zones (0.6 EEHC < 1), and persistent coordination zones (EEHC 1.2). As different regionalized variables, their spatial evolution patterns across different periods can be analyzed using spatial statistical methods.

The Getis-Ord G*i index, a local indicator of spatial association, calculates the correlation degree between each spatial unit and its neighbors for a given attribute [23]. Spatial pattern analysis can test whether the value of a spatial variable is related to its neighboring values. When a variable' s value at a location and its neighbors show the same trend, it is called spatial positive correlation; otherwise, it is spatial negative correlation [24]. The G*i index can identify hot and cold spots of China's economic development and ecological environment coordination, revealing potential spatial distribution relationships.

The formula is:

$$G_i^* = \frac{\sum_{j=1}^{n} W_{ij} X_j}{\sum_{j=1}^{n} X_j}$$

where W_{ij} is the spatial weight matrix (1 for adjacent spaces, 0 otherwise) and X_i is the observed value of region unit i. A significantly positive G_i^* indicates relatively high values around region i, classifying it as a hot spot; conversely, it is a cold spot.

6. Results

6.1 County-Level Changes in Economic-Ecological Coordination Across Study Periods

Statistical analysis revealed that in the 1980-1990 period, 352 counties were in deterioration zones (12.33% of national total), with 259 in high deterioration zones (9.07%). Meanwhile, 344 counties were in coordination zones (12.05%), but only 280 were in high coordination zones (9.81%). The gap between deterioration and coordination zones was small.

By 1990-2000, counties in coordination zones increased to 1,314 (46.05% of national total), with 1,186 in high coordination zones (41.57%). Counties in deterioration zones decreased significantly to 1,539, with high deterioration zones dropping to 293 (10.27%). This trend continued improving after 2000, with coordination zones further increasing and deterioration zones decreasing markedly, indicating an overall improving trend in China' s terrestrial economic-ecological coordination.

shows the classification and statistics of YEEH categories across different periods.

6.2 Annual Economic-Ecological Coordination Characteristics

The annual coordination degree between economic development and ecological environment was calculated for each study year. YEEH reflects the per-unit-area coordination relationship. Comparison results show that high deterioration and deterioration zones decreased from 1980 to 2010, particularly in central Inner Mongolia, northern Shaanxi, and central Shanxi, which transitioned from high deterioration to deterioration zones. Eastern Heilongjiang and Jilin shifted from deterioration zones to deterioration-coordination transition zones, indicating ecological improvement alongside economic development.

In 2010, spatial distribution showed clear aggregation effects. High deterioration zones were mainly in central Inner Mongolia, northern Shaanxi, central Shanxi, Beijing-Tianjin region, Shandong, and Jiangsu, covering 22.12% of China' s terrestrial area. Deterioration zones covered 27.98% (northeastern Inner Mongolia, Hubei, Anhui). Deterioration-coordination transition zones covered 19.24% (Shaanxi, Shanxi, Jiangxi). Coordination and high coordination zones were mainly distributed across Tibet, southwestern Qinghai, central-eastern Sichuan, and northeastern Inner Mongolia, covering 32.3% of the total area.

From 1980 to 2010, deterioration zones decreased from 58.43% to 50.25% of total area, while coordination zones increased from 12% to 16.34%, demonstrating significant improvement in China' s economic-ecological coordination.

shows the YEEH classification statistics for China' s terrestrial areas from 1980 to 2010.

6.3 Spatial Evolution Patterns of Economic-Ecological Coordination

To further investigate spatial changes in coordination degree during development, EEHC values were analyzed. From 1980-1990, most of China showed low coordination, with persistent deterioration zones in central-western Sichuan, Zhejiang, and Jiangxi. Tibet and western Sichuan had slower economic development, while eastern regions like Zhejiang overemphasized economic growth, causing economic expansion to exceed ecosystem service value evolution.

From 1990-2000, persistent deterioration zones decreased significantly, while initial coordination and persistent coordination zones began to increase. Western Gansu, western Inner Mongolia, and central-western Qinghai shifted from initial coordination to initial deterioration zones. Most of Sichuan and Tibet transitioned from persistent deterioration to initial deterioration and stable coordination zones.

From 2000-2010, persistent deterioration zones further decreased while initial coordination and persistent coordination zones increased. Western Xinjiang, Guizhou, and parts of Heilongjiang were in initial coordination and persistent coordination zones, while central-eastern Xinjiang, central Inner Mongolia, Henan, and others were in stable coordination zones. Only small areas like central Inner Mongolia and southern Jiangsu were in persistent coordination zones.

Overall, China' s terrestrial economic development and ecological environment are gradually improving. The benefits of ecological restoration projects since 2000 are becoming evident, though deterioration zones still far exceed coordination zones in area and show uneven regional distribution with polarization phenomena.

[Figure 1: see original paper] shows the spatial evolution of annual economic-environmental coordination (YEEH) in China from 1980 to 2010.
[Figure 2: see original paper] shows the spatial evolution of EEHC in China from 1980 to 2010.

6.4 Provincial-Level EEHC Change Characteristics

To more clearly demonstrate regional changes, provincial EEHC values were extracted and compared between adjacent periods. From 1980-1990, most provinces showed decreases, with western regions decreasing most significantly. From 1990-2000, Beijing, Shanghai, and Zhejiang showed the largest increases, while Henan showed the largest decrease. From 2000-2010, western regions (except Xinjiang, Ningxia, and Inner Mongolia) generally increased, while most eastern provinces decreased.

Overall, most provinces in central and eastern China showed varying degrees of decrease, while western provinces mostly increased with significant growth trends, particularly in the Beijing-Tianjin-Hebei region. This confirms the gradual improvement in China' s economic-ecological coordination, presenting a spatial pattern of Northeast > West > Central-East.

[Figure 3: see original paper] shows the provincial EEHC change characteristics in China from 1980 to 2010.

6.5 Spatial Evolution Patterns

Spatial statistical analysis clearly shows that coordination development forms highly aggregated distribution patterns. The G*i Z-score analysis reveals that in 1980, the spatial distribution was relatively uniform, with high-value clusters only in southwestern and northeastern Tibet. By 1990, large high-value aggregation areas emerged in southwestern, eastern, and northeastern Tibet, and northeastern Inner Mongolia—regions with major EEHC fluctuations.

By 2000, hot spots further concentrated in central-eastern Tibet, southern Qinghai, and western Xinjiang, while cold spots (low-value clusters) were widely distributed in eastern Tibet and western Sichuan. By 2010, cold spots aggregated in central-eastern Tibet, southern Qinghai, and western Yunnan, while hot spots were mainly in western Xinjiang, southern Qinghai, and border areas between Tibet and Xinjiang. Below-mean clusters also showed clear aggregation in Anhui and Shanghai.

This demonstrates that China' s economic-ecological coordination spatial distribution evolved from a below-mean aggregation pattern in 1980 to coexisting high and low aggregation patterns by 2010, showing characteristics of highly aggregated hot spots and lowly aggregated cold spots. This indicates the development model is polarizing toward both high and low directions, fluctuating simultaneously in southwestern and southeastern China.

[Figure 4: see original paper] shows the hot and cold spot distribution of EEHC research units in China from 1980 to 2010.

7. Discussion

7.1 Accuracy of Ecosystem Service Value Calculations

Current domestic research on economic-ecological coordination is mainly limited to specific regions or evaluation units [25-26], with few studies at the national scale. Therefore, direct comparison of final coordination results is not feasible. This study compares two influencing factors: statistical data accuracy and ESV calculation accuracy. Statistical data were obtained from officially released Chinese statistics, meeting research accuracy requirements.

For ESV, this study calculated China' s terrestrial total ESV for 1980, 1990, 2000, and 2010 as 6.591, 6.575, 6.817, and 6.749 trillion yuan, respectively. These values are basically consistent with: Shi Yao et al.' s [27] calculation of 6.568 trillion yuan for 2008; Chen Zhongxin et al.' s [29] results; and Pan Yaozhong et al.' s [28] remote sensing-based measurement of 6.958 trillion yuan (slightly higher). The spatial distribution pattern of higher values in central-eastern regions and lower values in western regions aligns with Bi Xiaoli [30] and He Hao [31]. The finding that western China had faster ESV growth than central-eastern regions is also consistent with Ran Shenghong et al. [32].

Differences arise because: (1) This study is based on land use/cover classification, while Pan Yaozhong and Chen Zhongxin used vegetation data, potentially causing discrepancies in land type areas; (2) Their estimates were based on 1980s vegetation remote sensing data, differing from this study' s data sources and time nodes.

7.2 Driving Factors of Economic-Ecological Development Evolution

Economic-ecological development results from the combined effects of human activities and natural environment. Natural environment determines regional ecological conditions, while human activities and socio-economic development can either nurture or destroy original ecological environments. Overall, China' s socio-economic activities and natural ecological environment are developing toward greater sustainability.

China' s economic-ecological coordination has gradually improved, with western regions performing better than eastern regions. This is primarily because China' s reform and opening-up since 1980 emphasized economic development through industrial revitalization and urban expansion while neglecting ecological civilization construction, leading to ecosystem service growth lagging behind economic growth. Since 2000, national awareness of ecological construction importance has grown, launching large-scale ecological restoration projects (returning farmland to forest/grassland, ecological barrier construction, soil erosion control), which expanded forest and grassland areas and improved ecosystem service functions while promoting better socio-economic development.

7.3 Uncertainties in Research Results

Given the complexity, comprehensiveness, and ambiguity of socio-economic and ecological environment coordination, current evaluation technologies cannot yet achieve fully comprehensive, scientific, and accurate assessment. This study provides a preliminary evaluation based on previous research, with limitations in more scientific estimation methods:

1. When using land use/cover data for ESV assessment, different resolutions yield different land cover types, and different classification systems produce different categories. Mixed pixels affect classification accuracy when land cover patches are smaller than image resolution. Future research should enhance effective spatial resolution, whether through direct remote sensing extraction or correction.
2. This study explores coordination based on economic development and ecosystem service functions, considering spatial and temporal factors. However, this approach requires further validation for objectivity, and improvements are needed in indicator selection and classification systems.

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8. Conclusions

1. China' s terrestrial economic-ecological coordination degree has gradually improved from 1980 to 2010. No large-scale coordination loss has occurred between economic development and ecological environment, reflecting that socio-economic activities and natural ecological environment are generally developing sustainably. However, deterioration zones currently exceed coordination zones in area, with uneven regional distribution and polarization phenomena in some regions.
2. The spatial distribution pattern evolved from a below-mean aggregation model in 1980 to coexisting high and low aggregation patterns in 2010, showing highly aggregated hot spots and lowly aggregated cold spots. This indicates the development model is polarizing toward both high and low directions, fluctuating simultaneously in southwestern and southeastern China.
3. Overall coordination is improving, but significant spatial differences exist across regions. Western regions need vigorous economic development while protecting ecological environments, whereas central and eastern regions must emphasize ecological conservation and restoration while developing economies. China' s economic development and ecological environment construction still face a long and arduous task.

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