Spatiotemporal Evolution Characteristics of the Coupling between High-Quality Development and Ecosystem Services at the County Level in Shanxi Province (Postprint)

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Abstract

Based on data from 107 counties and districts in Shanxi Province for the years 2000, 2005, 2010, and 2018, this study constructs an evaluation index system for high-quality development in Shanxi Province, employs the InVEST model to quantify ecosystem services at the county level, and utilizes the coupling coordination degree model and elasticity coefficient method to analyze the spatiotemporal coupling characteristics between the county-level high-quality development system and ecosystem services. The results indicate: (1) The hierarchical effect of cities exerts a significant influence on high-quality development levels, with pronounced spatial differentiation patterns in high-quality development, roughly forming three-level cores in the northern, central, and southern regions, and prominent polarization effects in the central region. (2) Ecosystem services exhibit a lock-in effect across both temporal and spatial dimensions, with spatiotemporal evolution characteristics consistent with the topographic distribution of the study area, presenting a stable "mirror-image L-shaped" spatial distribution pattern. (3) Ecosystem services overall lag behind high-quality development; temporally, the coupling level demonstrates an upward trend, while spatially, it exhibits a shift from an east-west orientation to a northeast-southwest coordination principal axis. (4) The coupling types between high-quality development and ecosystem services are primarily characterized by divergent changes, with a "polarization" pattern emerging where recessionary and lagging types counteract each other, forming a convergent "S-shaped" attenuation zone; as the ideal coupling type, the growth type rarely appears in the study area.

Full Text

Temporal and Spatial Evolution Characteristics of the Coupling between County High-Quality Development and Ecosystem Services in Shanxi Province

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Abstract

Based on data from 107 counties and districts in 2000, 2005, 2010, and 2018, this study constructs an evaluation index system for high-quality development in Shanxi Province, employs the InVEST model to quantify ecosystem services across counties, and analyzes the spatiotemporal coupling characteristics between the high-quality development system and ecosystem services using the coupling coordination degree model and elasticity coefficient method. The results reveal four key findings. First, urban hierarchical effects significantly influence high-quality development levels. The spatial differentiation of high-quality development is pronounced, forming a three-tier core structure (north, central, and south) with prominent polarization effects in the central region. Second, ecosystem services exhibit locking effects in both temporal and spatial dimensions. Their evolution patterns align with the topographic distribution of the study area, manifesting as a stable "mirror L-shaped" spatial configuration. Third, ecosystem services generally lag behind high-quality development. Temporally, the coupling level shows an upward trend, while spatially, the coordination axis shifts from east-west to northeast-southwest. Fourth, the coupling type between high-quality development and ecosystem services is dominated by divergent changes, showing an overall regressive trend. A polarization pattern emerges where recession and lag types compete, forming a convergent "S-shaped" attenuation zone. The growth type, representing an ideal coupling pattern, rarely appears in the study area.

Keywords: high-quality development; ecosystem services; coupling coordination degree model; counties in Shanxi Province

1. Introduction

The 19th National Congress of the Communist Party of China report proposed that China' s economy has shifted from a high-speed growth phase to a high-quality development phase. Since this theoretical proposition, academic research on high-quality development has primarily focused on evaluating its connotations, including "high-quality economic development, high-level reform and opening-up, high-quality urban and rural construction, high-quality ecological environment, and high-quality people' s lives." Studies have also developed indicator systems based on "innovation, coordination, green development, openness, and sharing," and analyzed high-quality development levels and internal mechanisms at watershed, provincial, and county scales. However, analyses of the relationship between high-quality development and ecosystem services remain limited.

International scholars have long examined the relationship between economic development and ecological environment, including the Environmental Kuznets Curve hypothesis, the Green Solow model, and the "pressure-state-response" framework, all proposing interactive relationships between ecological environment and economic growth. Domestic research has focused on the intrinsic connections between ecological environment and socio-economic development, such as environmental pollution and economic development, environment and urbanization, and urban land expansion versus ecological protection. With the construction of high-quality development indicator systems, scholars have begun examining internal coupling measurements and interactions between high-quality development and ecological environment. In recent years, extensive economic growth has increasingly highlighted negative ecological impacts, and with growing national attention to regional high-quality development and ecological protection, analyzing the spatiotemporal coupling characteristics between high-quality development and ecosystem services holds important practical significance for socio-economic development and ecological civilization construction.

Traditional indicator systems cannot intuitively characterize regional ecological conditions. Therefore, scholars have employed the InVEST model to evaluate ecosystem services from the perspective of ecosystem service formation mechanisms, using remote sensing data. This approach better represents ecological reality and clarifies ecosystem service formation mechanisms and assessment results. Existing research has primarily focused on provincial and municipal scales, with weaker exploration at the county scale. County units have weaker attraction for talent and capital, and some counties still face insufficient drivers for economic development and green development. Analyzing from the county perspective can more precisely depict spatial differentiation patterns in the relationship between regional high-quality development and ecosystem services, facilitating exploration of underlying formation mechanisms and holding important significance for ensuring quality and quantity growth and optimizing resource allocation in county economies.

Shanxi Province is situated in the middle reaches of the Yellow River Basin, on the eastern Loess Plateau, with complex terrain, severe soil erosion, and poor natural endowments. The development concept dominated by resource exploitation in recent years has further deteriorated its fragile ecological environment. Therefore, this paper constructs a county-level high-quality development indicator system and employs the InVEST model to comprehensively evaluate high-quality development levels and ecosystem services in Shanxi counties from 2000 to 2018. Using the coupling coordination model and elasticity coefficient method, it reveals the spatiotemporal differentiation characteristics of coupling coordination degrees and coupling types between high-quality development and ecosystem services, providing scientific basis for policy formulation related to high-quality development and ecological civilization construction in the study area.

2. Study Area and Data

2.1 Study Area Overview

Shanxi Province is located in North China, covering a total area of 15.67$×10^{4}$ km^2. It is a typical loess-covered mountainous plateau dominated by mountains and hills, with terrain higher in the northeast and lower in the southwest. The climate is temperate continental monsoon, with annual average temperatures of 4.2–14.2°C and precipitation of 358–621 mm. By the end of 2018, the permanent resident population reached 37.18 million (98.2% of the national average), per capita GDP reached 45,324 yuan (73.7% of the national average), R&D expenditure reached 19.12 billion yuan (51.5% of the national average), and patent applications reached 26,784 (29.6% of the national average). The province faces serious ecological problems and prominent human-land contradictions, with per capita water resources of only 204 m^3 (9.8% of the national average), forest coverage of 22.79% (70.3% of the national average), and good air quality days ratio of 77.04% (16.6% of the national average).

2.2 Data Sources

All statistical data were obtained from the *China County Statistical Yearbook*, *China Science and Technology Statistical Yearbook*, *Shanxi Statistical Yearbook*, and corresponding annual statistical bulletins of Shanxi prefecture-level cities. Land use data were derived from the 30 m$×30mresolution*ChinaLandCover* griddatasetoftheChineseAcademyofSciencesResourceandEnvironmentalScienceDataCenter.Precipitatio AnnualVegetationIndex(NDVI)SpatialDistributionDataset*at30m×30mresolution.DigitalElevationMode ChinaSoilDataset * oftheWorldSoilDatabase(HWSD)at30m×$30 m resolution. Root depth and evapotranspiration coefficients were calculated based on reference literature.

3. Methods

3.1 High-Quality Development Evaluation Index System

Drawing on relevant research and considering data availability, rationality, and actual county conditions in Shanxi, this study constructs a county-level high-quality development measurement index system (Table 1). The system employs entropy weight method and analytic hierarchy process for comprehensive weighting: $w_i = (w_{ei} + w_{ai})/2$, where w_{ei} and w_{ai} represent weights from entropy and analytic hierarchy methods respectively, and n is the number of indicators. Due to limited data availability at the county level, industrial development level (measured by the ratio of secondary to tertiary industry output value) is used to measure industrial coordination. A smaller ratio indicates higher regional industrial level, and a declining trend suggests the regional economy is moving toward service orientation.

3.2 Ecosystem Services Assessment

The InVEST model is used to evaluate ecosystem services in Shanxi counties. This model avoids problems such as unclear formation mechanisms and poor assessment result applicability. Drawing on relevant research, four universally applicable modules are selected: water conservation, soil retention, grain production, and carbon sequestration and habitat quality (Table 2).

The water conservation module in InVEST calculates water conservation services, with specific formulas in reference [33-34]. The soil retention module calculates soil retention, with formulas in reference [33-34]. Zhao et al. [35] noted significant linear relationships between crop yield and NDVI. Therefore, this study uses ArcGIS mask extraction to allocate grain production service supply based on the ratio of NDVI to total NDVI in cultivated land, exporting raster data and calculating through grid statistics. Carbon storage is calculated by multiplying average carbon density of four carbon pools (aboveground, underground, soil, and dead organic matter) by different land use/cover type areas, with formulas in reference [23]. The habitat quality module calculates habitat quality index by assuming high habitat quality areas have high biodiversity. The index is derived from total threat levels of habitat types, with habitat degradation, habitat quality formulas, and parameters in reference [31].

3.3 Coupling Coordination Degree Model

The coupling coordination degree model quantitatively evaluates the interactive coupling coordination between high-quality development and ecosystem services. The calculation process follows reference [36], dividing county coupling degrees and coordination into five stages (Table 3). The model is constructed as:

$$D = \sqrt{C \times T}, \quad T = \alpha EH + \beta EC$$

where D is coupling coordination degree, C is coupling degree, T is comprehensive evaluation index, EH and EC represent high-quality development level and ecosystem service level respectively, and α and β are undetermined coefficients (both taken as 0.5).

3.4 Elasticity Coefficient Model

The elasticity coefficient method reveals spatiotemporal coupling characteristics and the direction and speed of coupled system changes. The elasticity coefficient between high-quality development and ecosystem services is constructed as:

$$\beta = \frac{ECR}{EHR}, \quad EHR = \frac{EH_t - EH_0}{EH_0}, \quad ECR = \frac{EC_t - EC_0}{EC_0}$$

where β is the elasticity coefficient; EHR and ECR represent change rates of high-quality development level and ecosystem service level during a period; EH_t, EH_0, EC_t, and EC_0 are high-quality development and ecosystem service levels in year t and base year respectively.

Based on changes in EH and EC and elasticity coefficient variations, coupling relationships are refined into six types (Table 4). The growth type indicates improved coupling, the extensive type suggests slow ecosystem service growth requiring enhancement, the stagnant and lag types indicate weakened coupling and asynchronous decoupling, while the recession and decline types show poor regional development coordination.

4. Results

4.1 Temporal and Spatial Evolution of High-Quality Development

4.1.1 Temporal Changes Overall, the high-quality development level in the study area showed a significant upward trend from 2000 to 2018 (Table 5). The comprehensive index increased from 0.138 to 0.243. The proportion of counties with levels above the mean rose from 15.4% to 35.8%, primarily benefiting from industrial structure adjustments that transformed growth from extensive to intensive. The variation coefficient first increased then decreased, indicating that inter-county differences first expanded then contracted. From 2000–2005, the "slow rise"phase saw levels increase from 0.138 to 0.150, but with slow growth. The 2005–2010 "pains" phase saw levels decline from 0.150 to 0.147, related to industrial structure changes where counties dominated by secondary industry reached 76.6%. The 2010–2015 rapid rise phase saw levels increase from 0.147 to 0.218, as the National Development and Reform Commission established the "Shanxi National Resource-Based Economic Transformation Comprehensive Reform Pilot Zone," reducing secondary industry-dominated counties to 54.2% and promoting technological innovation. The 2015–2018 stable rise phase saw levels increase from 0.218 to 0.243, with growth stabilizing under government macro-control.

4.1.2 Spatial Evolution Using ArcGIS 10.5 spatial statistics tools, the global Moran' s I index exceeded 0.3 and passed significance tests, indicating significant positive spatial correlation in high-quality development levels. Moran' s I showed a fluctuating but overall upward trend, with Z-scores rising from

6.87 to 9.84, demonstrating increasingly strong spatial agglomeration. Using natural breaks classification, the spatial distribution pattern shows: In 2000, high levels presented a "high in central-east, low in north-south" pattern, concentrated in central Taiyuan area and eastern Yangquan area. By 2005, the pattern showed "east-west swap" to "high in central-west, secondary high in north-south," with southern high levels spreading from Yuncheng to Jincheng areas and northern cores forming around Datong. By 2010, spatial polarization emerged with a "high in central" pattern centered on Taiyuan. By 2018, polarization became prominent with three core areas: northern (Datong area), central (Taiyuan-Jinzhong area), and southern (Yuncheng area). Overall, urban hierarchical effects significantly impacted high-quality development levels.

[Figure 1: see original paper]

4.2 Temporal and Spatial Evolution of Ecosystem Services

4.2.1 Temporal Changes From 2000–2018, ecosystem service levels rose from 0.484 to 0.552, with the proportion of counties above the mean increasing from 50.9% to 56.1% (Table 6). The variation coefficient increased, indicating expanding inter-county differences. The 2000–2005 slow rise phase saw levels increase from 0.484 to 0.495. The 2005–2010 decline phase saw levels drop from 0.495 to 0.481, as land use structure changes negatively impacted services: cultivated land decreased from 36.8% to 28.1%, grassland from 29.1% to 28.1%, and urban construction land expanded, occupying cultivated land and grassland. The 2010–2015 rapid rise phase saw levels increase from 0.481 to 0.536. The 2015–2018 stable rise phase saw levels increase from 0.536 to 0.552.

4.2.2 Spatial Evolution Moran' s I exceeded 0.4 and passed significance tests, indicating significant positive spatial correlation. Z-scores first decreased then increased, showing a shift from spatial dispersion to agglomeration. Spatially, ecosystem services show a "high in south, low in north; high in east, low in west" pattern influenced by topography (Figure 2). In 2000, high-value areas concentrated in the Taihang Mountains (Heshun, Zuoquan, Licheng, Pingshun, Huguan counties) with strong soil conservation. Low-value areas concentrated in the northwest (Datong, Yanggao, Tianzhen, Zuoyun counties) with poor soil conservation and severe wind-sand disturbance. By 2005, the "mirror L-shaped" pattern emerged. By 2010, southern Yuncheng area levels improved. By 2018, the pattern stabilized, forming supply clusters in southern (Ruicheng, Pinglu, Yuanqu, Yangcheng counties) and eastern (Heshun, Zuoquan, Licheng, Pingshun counties) areas, showing a stable "mirror L-shaped" distribution.

[Figure 2: see original paper]

4.3 Coupling Coordination Relationship

4.3.1 Temporal Changes The coupling coordination degree remained in the "barely coordinated" interval but showed an upward trend. The proportion of counties above basic coordination increased from 12.1% to 28.0% (Table 7). The variation coefficient decreased, indicating narrowing inter-county differences. The 2000–2005 rise phase saw basic coordination counties increase from 13 to 20. The 2005–2010 "fallback" phase saw them decrease from 20 to 17, related to high-quality development recession. The 2010–2015 "rebound" phase saw them increase from 17 to 27. The 2015–2018 stable rise phase saw them increase from 27 to 30.

4.3.2 Spatial Changes Coupling coordination degrees showed positive spatial correlation (Moran' s I > 0.3). Z-scores fluctuated upward, indicating fluctuating spatial agglomeration. Spatially (Figure 3), 2000 saw a "central bulge" pattern with basic coordination centered on Taiyuan. By 2005, a basic coordination horizontal axis formed from Liulin to Pingding counties, with southern concentrated areas in Yuncheng and Jincheng. By 2010, overall coordination declined, shifting from east-west to northeast-southwest axis. By 2015, the northeast-southwest coordination axis formed, extending north-south. Overall, the east-west "coordination axis" gradually formed during 2000–2010, then shifted to northeast-southwest after 2015.

[Figure 3: see original paper]

4.4 Coupling Types

4.4.1 Temporal Changes Elasticity coefficient analysis shows coupling types generally degenerated (Table 8). Growth-type areas decreased from 56.6% to 3.8%, extensive-type from 16.9% to 12.3%, stagnant-type from 16.0% to 30.2%, lag-type from 13.2% to 46.2%, and recession-type from 12.3% to 76.4%. The 2000–2005 phase showed "inferior flourishing and superior declining," shifting from growth/extensive dominance to recession dominance. The 2005–2010 recession dominance related to high-quality development "pains." The 2010–2015 phase showed "polarization" between recession and lag types, related to high-quality development "rebound" and ecosystem service "fallback" weakening coupling relationships.

4.4.2 Spatial Evolution Coupling types showed strong positive spatial correlation (Moran's I > 0.3, Table 9). Z-scores declined during 2000–2010, indicating weakening spatial agglomeration. Spatially (Figure 4), 2000 saw extensive-type dominance with recession-type clusters in Yangquan area. By 2005, decline-type dominated with "S-shaped" pattern emerging. By 2010, a "polarization" pattern formed between recession and lag types, with recession-type "S-shaped" areas contracting and surrounded by stagnant-type areas.

[Figure 4: see original paper]

5. Discussion

The analysis of high-quality development levels shows a growth trend but slow growth rate, consistent with Xu et al. [5]. According to Shanxi Provincial Energy Bureau data, as of March 2021, the province had 668 production coal mines [37]. Long-term high-intensity coal mining has created fragile ecological environments and low ecological carrying capacity, resulting in weak endogenous drivers for regional high-quality development. Urban hierarchical effects significantly impact high-quality development levels because municipal districts receive greater intensity of innovation environment, opening-up, and public service inputs than counties.

Ecosystem service levels are primarily influenced by topography, with better services concentrated in the Taihang and Lüliang Mountains. However, Lüliang Mountains show significantly lower capacity than Taihang Mountains because they are located in typical loess hilly-gully regions with severe soil erosion. Water conservation is only 320.9 $m^3 \cdot hm^{-2}$, below the provincial average. The mountains are also concentrated mineral resource areas with frequent human activities. By 2020, Lüliang area had 91 coal mines (13.62% of provincial total) [37], and outdated mining methods and inadequate governance measures have burdened ecosystem services. Northwest low-value areas relate to natural climate conditions and wind-sand disasters, located in mid-temperate continental semi-arid monsoon climate zones with strong winds and little rainfall. Soil retention capacity averages only 37.95 $t \cdot hm^{-2}$, 17.4% of the provincial average, determining weak ecosystem service capacity.

In analyzing coupling coordination relationships, eight counties in Xinzhou (Pianguan, Hequ, Baode, Wuzhai, Kelan, Shenchi, Ningwu, Jingle) and three in Lüliang (Xixian, Fushan, Yonghe) remained in barely coordinated stages. These areas have low economic input, weak factor flows due to terrain constraints, and poor innovation environments. However, their mountainous terrain, difficult development, and minimal human interference create "locking effects" where ecosystem service capacity exceeds high-quality development levels, maintaining persistent barely coordinated states.

This study reveals spatiotemporal differentiation patterns in the coupling between high-quality development and ecosystem services at the county scale, but limitations exist. First, some InVEST model parameters (root depth, evapotranspiration coefficients) were primarily referenced from literature, introducing some error. Second, this paper only reveals spatiotemporal differentiation patterns without exploring influencing factors. Future research should conduct field observations to improve model accuracy and investigate influencing factors to reveal more scientific development pathways.

6. Conclusion

This paper analyzes the spatiotemporal evolution of coupling between county high-quality development and ecosystem services in Shanxi Province from 2000–

2018, yielding four main conclusions.

First, high-quality development shows strong temporal accumulation effects and pronounced spatial differentiation. Levels gradually increased over time, shifting from dispersion to agglomeration spatially, forming north-central-south three-tier cores with prominent central region polarization. Urban hierarchical effects significantly influence high-quality development levels.

Second, ecosystem services exhibit locking effects in temporal and spatial dimensions. Their evolution aligns with topographic distribution, forming a stable "mirror L-shaped" pattern. Southern and eastern supply clusters emerged in Ruicheng, Pinglu, Yuanqu, Yangcheng counties and Heshun, Zuoquan, Licheng, Pingshun counties.

Third, ecosystem services generally lag behind high-quality development. Coupling levels rose temporally, while spatially shifting from east-west to northeast-southwest coordination axis.

Fourth, coupling types are dominated by divergent changes, showing regressive trends overall. A polarization pattern emerges where recession and lag types compete, forming a convergent "S-shaped" attenuation zone. The growth type, as an ideal pattern, rarely appears.

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