Response of Ecosystem Services to Land Use Pattern Changes in Central Shanxi Urban Agglomeration: A Postprint

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Abstract

The Shanxi Central Urban Agglomeration represents the region with the most robust economic development in Shanxi Province; however, this economic growth has been concomitant with varying extents of ecosystem degradation. Based on land use pattern evolution, this study employs methods including the InVEST model, ArcGIS technology, pixel statistical analysis, and the four-quadrant model to evaluate the spatiotemporal patterns and trade-off/synergy relationships of water yield, food supply, soil conservation, and carbon storage services from 2000 to 2020, and conducts an in-depth analysis of the effects of land use patterns on ecosystem services. The results demonstrate that: (1) Water yield, food supply, and soil conservation demonstrated increasing trends, whereas carbon storage showed a gradual decreasing trend, with significant differences existing in ecosystem service provision capacities across different land-use types and administrative districts. (2) Spatially, ecosystem services were predominantly characterized by synergistic relationships, with food supply, water yield, and soil conservation demonstrating mutual synergistic relationships, while all three exhibited trade-off relationships with carbon storage. (3) Expansion of construction land had a positive impact on water yield services, increases in forestland promoted soil conservation, whereas reductions in forestland and grassland had negative impacts on carbon storage; land use intensity showed an overall positive correlation with water yield, food supply, and soil conservation, yet its influence on carbon storage showed a negative trend. These findings provide important references for ecological security construction and sustainable development in the Shanxi Central Urban Agglomeration and other comparable regions.

Full Text

Response of Ecosystem Services to Land Use Pattern Changes in the Shanxi Central Urban Agglomeration

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Abstract: The Shanxi central urban agglomeration represents the region with the strongest economic development momentum in Shanxi Province. However, this economic growth has been accompanied by varying degrees of ecosystem degradation. Based on land use pattern evolution, this study employs the InVEST model, ArcGIS, pixel statistical analysis, and the four-quadrant model to evaluate the spatiotemporal patterns and trade-off/synergy relationships of water yield, food provision, soil conservation, and carbon storage services from 2000 to 2020, and to analyze in depth the impacts of land use patterns on ecosystem services. The results indicate that: (1) Water yield, food provision, and soil conservation in the Shanxi central urban agglomeration increased year by year, while carbon storage decreased slowly, with significant differences in ecosystem service provision capacity across different land types and administrative regions. (2) Spatially, ecosystem services were dominated by synergistic relationships, with food provision, water yield, and soil conservation mutually synergistic, while all showed trade-off relationships with carbon storage. (3) Built-up land expansion positively impacted water yield services, forestland increase promoted soil conservation, while forestland and grassland reduction negatively affected carbon storage. Land use intensity showed positive correlations with water yield, food provision, and soil conservation, but exhibited negative trends in its impact on carbon storage. These findings provide important references for ecological security construction and sustainable development in the Shanxi central urban agglomeration and similar regions.

Keywords: ecosystem services; InVEST model; land use intensity; trade-offs and synergies; Shanxi central urban agglomeration

Introduction

Since the concept of ecosystems providing "services" to humanity was proposed, and particularly following the release of international ecosystem assessment reports and the implementation of ecosystem service policies by governments and international organizations, ecosystem services have become a frontier research area in environmental protection and sustainable development. Ecosystem services refer to the direct and indirect benefits and resources that natural systems provide to human society, such as food production, climate regulation, and biodiversity maintenance. Trade-off and synergy relationships exist among ecosystem services, meaning that an increase in one service may lead to a decrease in another, or two services may increase or decrease simultaneously. Land use change is a crucial driver of ecosystem change, directly affecting ecosystem services by altering ecosystem types and patterns. Therefore, correctly understanding the impacts of land use on ecosystem services facilitates rational land resource allocation and coordinated regional economic development.

Numerous studies have explored the effects of land use on ecosystem services with important achievements. For example, Kreuter et al. emphasized the importance of land cover in time-series studies of ecosystem services, while Xie Gaodi et al. established an ecosystem service valuation method more suitable for China' s national conditions based on expert knowledge, promoting rapid development of related research domestically. Recent domestic research on land use impacts on ecosystem services has focused primarily on land use transfer matrices and dynamics, with fewer studies examining land use intensity effects. However, in-depth investigation of the relationship between land use intensity and ecosystem services can reveal the influence patterns of human activities on ecosystems, which is significant for coordinating human-nature relationships.

The Shanxi central urban agglomeration is the region with the largest population, highest economic development level, and most active land use intensity in Shanxi Province. Increased urbanization levels lead to greater socioeconomic activity, which subsequently affects ecosystems and reduces ecosystem service levels. This study selects the Shanxi central urban agglomeration as a case study, integrating multi-source data including remote sensing, meteorological, and socioeconomic data, along with various analytical methods such as InVEST and spatial analysis, to systematically evaluate the spatiotemporal variation characteristics and interrelationships of four key ecosystem services in the region from 2000 to 2020, and to explore the response of ecosystem services to land use pattern changes. The research results provide important reference values for scientifically adjusting land use development strategies and achieving ecological and economic sustainable development goals.

1.1 Study Area Overview

The Shanxi central urban agglomeration (110°20 E–114°05 E, 36°40 N–39°50 N) serves as the political, economic, cultural, and technological center of Shanxi Province, encompassing five prefecture-level cities: Taiyuan, Jinzhong, Lüliang, Xinzhou, and Yangquan [Figure 1: see original paper]. The region features diverse topography and a warm temperate continental monsoon climate. The Shanxi Central Urban Agglomeration High-Quality Development Plan explicitly proposes measures for coordinated protection and governance, strengthened ecological conservation and restoration, and construction of green, low-carbon, and livable cities to promote high-quality development. However, as a typical resource-based urban region, long-term irrational industrial structures and intensive energy extraction have severely damaged the ecological environment, constraining ecosystem service construction and high-quality development.

1.2 Data Sources

The primary data used in this study include land use, meteorological, digital elevation, and grain yield data. Land use data were obtained from the multi-temporal land use/land cover remote sensing monitoring dataset of the Chinese Academy of Sciences' Resource and Environmental Science and Data Center (https://www.resdc.cn). Based on the classification system and characteristics of land use types in the Shanxi central urban agglomeration, the study area was divided into six types: cropland, forestland, grassland, water bodies, built-up land, and unused land. Meteorological data such as precipitation and potential evapotranspiration were sourced from the China Meteorological Data Network (http://data.cma.cn). Digital elevation data were obtained from the Geospatial Data Cloud platform (https://www.gscloud.cn). Socioeconomic data such as grain production were derived from statistical yearbooks of Shanxi Province and its prefecture-level cities.

1.3 Methods

1.3.1 Land Use Intensity

Land Use Intensity (LUI) measures the degree of human disturbance on land use patterns. Value assignments reference the research results of Han Zenglin et al. .

1.3.2 Ecosystem Service Assessment Methods

Referencing ecosystem service studies in metropolitan areas, this study selected water yield (WY), food provision (FP), soil conservation (SC), and carbon storage (CS) services. Selection criteria are as follows: the study area is located in a critical water source conservation zone of the Fenhe River Basin, making water yield assessment crucial for regional water resource management and regulation; urban expansion and cropland reduction issues are increasingly prominent, making food provision assessment important for regional food security; given the dominant forestland and grassland areas, assessing soil conservation capacity is vital for maintaining ecosystem stability; and under global carbon neutrality goals, studying carbon storage changes facilitates advancing carbon neutrality construction.

Water Yield Service: The InVEST model' s Water Yield module was used to assess water yield services in the Shanxi central urban agglomeration. The specific calculation method is as follows:

$$WYx = \mathrm{AET}x\mathrm{AET}x\mathrm{P}x = 1 + P\mathrm{ET}x\mathrm{PET}x\mathrm{P}x - \mathrm{K}cx \times \mathrm{A}WCx\mathrm{PET}x = Px + 1.25ETOx$$

Where WY x and P x represent annual water yield (mm) and mean annual precipitation (mm) for pixel x, respectively; PET x and AET x denote potential evapotranspiration (mm) and actual evapotranspiration (mm) for pixel x; Kc x is the crop evapotranspiration coefficient for pixel x; AWC x is plant available water content for pixel x; Wx is an empirical parameter; and Z is a seasonal constant ranging from 1 to 30. Based on actual water yield data from the Shanxi Statistical Yearbook and Shanxi Water Resources Bulletin, the model outputs were continuously validated.

Soil Conservation Service: The Sediment Retention module in the InVEST model, based on the Revised Universal Soil Loss Equation (RUSLE), was used to calculate soil conservation capacity in the Shanxi central urban agglomeration:

$$RUSLEUSLEx = RKLSx - Rx \times Kx \times USLExKx \times Px \times LSx \times SRx = RKLSx = Rx \times$$

Where SR x is soil retention ($\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$) for pixel x; RKLS x and USLE x represent potential soil erosion ($\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$) and actual soil erosion ($\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$) for pixel x, respectively; R x, K x, and LS x are rainfall erosivity factor, soil erodibility factor, and slope length-gradient factor for pixel x; P x and C x are water conservation measures factor and vegetation cover factor for pixel x, both dimensionless. The P, C, K factors and detailed calculation methods reference the InVEST model user guide.

Food Provision Service: Research demonstrates that the Normalized Difference Vegetation Index (NDVI) has a significant linear relationship with crop yield. Combining this with grain yield data from the Shanxi Statistical Yearbook, grain yields were spatially allocated to determine food provision at each pixel:

$$FPi = NDVIiNDVIsum \times FPsum$$

Where FPi is food provision service for pixel i ($\mathrm{t \cdot km^{-2}}$); FPsum is total grain production for the study area; NDVIi is the normalized difference vegetation index for pixel i; and NDVIsum is the sum of normalized difference vegetation indices for all pixels.

Carbon Storage Service: The Carbon Storage module in the InVEST model was used for assessment. Terrestrial ecosystem carbon density includes aboveground, belowground, soil, and dead organic matter carbon densities. Total carbon storage in the study area was obtained by multiplying each land type' s area by its carbon density across four carbon pools and summing the results, with carbon density data referencing existing research:

$$Ci-above+Ci-below+Ctotal=\sum iCi-dead+Ci-soil-2$$

Where Ci is total carbon density for land type i ($t \cdot hm^{-2}$); Ci-above, Ci-below, Ci-dead, and Ci-soil represent aboveground, belowground, dead organic matter, and soil carbon densities for land type i ($t \cdot hm^{-2}$); Ctotal is total carbon storage for all land types ($t \cdot hm^{-2}$); Ai is area of land type i (hm^2); and n is the number of land use types.

Trade-off and Synergy Analysis: This study employs Spearman correlation coefficients to assess trade-offs and synergies among ecosystem services across different periods, with significance testing applied to correlation coefficients, and uses ArcGIS software for spatial pattern analysis.

Four-Quadrant Model: Originally developed for real estate market analysis, the four-quadrant model' s application has gradually expanded to ecology. This study uses counties as research units, applying the four-quadrant model to analyze and spatially visualize correlations between ecosystem services and land use intensity.

2.1 Land Use Pattern Evolution in the Shanxi Central Urban Agglomeration

From 2000 to 2020, land use in the Shanxi central urban agglomeration was dominated by grassland and cropland, each accounting for over 30% of total area. Cropland area decreased most significantly, shrinking by 2239.74 km^2, while built-up land expanded most dramatically, increasing by 1530.43 km^2. Forestland and grassland showed "first decreasing then increasing" trends, with forestland decreasing by 320.82 km^2 and grassland increasing by 350.59 km^2. Spatially, cropland and built-up land were mainly distributed in densely populated areas around cities and towns, while forestland was concentrated in the Lüliang and Taihang Mountains, and grassland was primarily found around the Lüliang Mountains and Wutai Mountain [Figure 2: see original paper]. These changes primarily resulted from accelerated urbanization reducing cropland, grassland, and forestland while expanding built-up land.

2.2 Spatiotemporal Patterns of Ecosystem Services

2.2.1 Water Yield Service

Total water yield in the Shanxi central urban agglomeration was 56.78$×10^{8}$ m^3, 90.79$×10^{8}$ m^3, and 132.07$×10^{8}$ m^3 for 2000, 2010, and 2020, respectively, showing an overall growth of 132.49% and a particularly significant increase of 41.28$×10^{8}$ m^3 from 2010 to 2020 [Figure 3: see original paper]. Average annual water yields were 55.92 mm, 76.87 mm, and 46.77 mm, respectively. High water yield areas were primarily located in Xinzhou and built-up land in central regions. By 2020, high-value zones expanded to parts of Jinzhong and Yangquan, mainly due to increased precipitation and rapid urbanization with expanded impervious surfaces. Low-value areas were concentrated in the Xinzhou-Dingxiang Basin, Taiyuan Basin, and Fenhe River Valley, where gentle terrain dominated by cropland and built-up land, combined with dense populations, accelerated soil loss. Overall, water yield showed a gradually increasing trend with a spatial pattern of higher values in the south and lower values in the north.

2.2.2 Carbon Storage Service

Total carbon storage in the Shanxi central urban agglomeration showed a declining trend, with values of 942.19$\times10^{6}$ t, 930.25$\times10^{6}$ t, and 926.30$\times10^{6}$ t for 2000, 2010, and 2020, respectively. Spatially, high carbon storage areas aligned with forestland and grassland distribution, while low carbon storage areas coincided with built-up land expansion. In 2000, low carbon storage areas were mainly distributed in central basins and valley regions. As built-up land increased through 2020, low carbon storage areas also expanded. Regionally, carbon storage loss was concentrated around cities and in some grassland areas, particularly near urban centers, though most areas showed minimal change [Figure 4: see original paper].

2.2.3 Soil Conservation Service

Average annual soil conservation in the Shanxi central urban agglomeration was 25019 $t \cdot km^{-2}$, 25581 $t \cdot km^{-2}$, and 35649 $t \cdot km^{-2}$ for 2000, 2010, and 2020, respectively, showing a yearly increasing trend and overall growth of 42.49%. High-value areas were located in the Lüliang Mountains, Hengshan and Wutai Mountains in eastern Xinzhou, Taihang Mountains in central-eastern Jinzhong, and parts of the Taiyue Mountains in southeastern Lingshi County. These areas feature dense vegetation cover, primarily forest and grassland, with adequate water sources and strong interception and retention functions beneficial for soil conservation. Low-value areas were concentrated in the Xinzhou-Dingxiang Basin, Taiyuan Basin, and Fenhe River Valley, where flat terrain dominated by cropland and built-up land, combined with dense populations, accelerated soil erosion. Interannual changes showed slight decreases in soil conservation capacity in small eastern and central areas from 2000 to 2010, but increases from 2010 to 2020, except for slight declines in Pianguan County in northwestern Xinzhou and minimal changes in small watersheds of the Hutuo River and Fenhe Reservoir [Figure 5: see original paper].

2.2.4 Food Provision Service

Average food provision in the Shanxi central urban agglomeration was 160.57 $t \cdot km^{-2}$, 208.14 $t \cdot km^{-2}$, and 221.18 $t \cdot km^{-2}$ for 2000, 2010, and 2020, respectively, with total food supply increasing from 267.7$\times10^{4}$ t to 494.0$\times10^{4}$ t. This improvement benefited from agricultural incentive policies, comprehensive grain production capacity enhancement projects, and agricultural mechanization promotion implemented in Shanxi Province. Spatial distribution showed two concentration zones: one in the Xinzhou-Dingxiang Basin, Taiyuan Basin, and Jinzhong region with flat terrain suitable for agriculture; the other in western Lüliang, northwestern Xinzhou, and Yangquan areas with lower elevations dominated by cropland and grassland. From 2000 to 2010, food provision increased significantly in Jinzhong and Xinzhou, with some growth in Lüliang and Yangquan. The increase from 2010 to 2020 was less pronounced than in the previous period, though overall food provision continued rising [Figure 6: see original paper].

2.3 Differences in Ecosystem Service Capacity

2.3.1 By Land Type

Differences in ecosystem service capacity across land types in the Shanxi central urban agglomeration are displayed using rose diagrams showing standardized mean values [Figure 7: see original paper]. Built-up land and unused land showed the strongest water yield capacity, cropland performed best in food provision, forestland demonstrated the strongest soil conservation capacity followed by grassland, and carbon storage capacity ranked from high to low as forestland, grassland, cropland, unused land, built-up land, and water bodies. Water bodies provided nearly zero ecosystem services across all categories.

2.3.2 By Administrative Region

Based on ArcGIS zonal statistics and standardization of ecosystem services for each administrative unit (primarily prefecture-level cities), Xinzhou showed relatively high levels of various ecosystem services, while Taiyuan showed lower levels. Yangquan had high water yield but low levels of other ecosystem services [Figure 8: see original paper]. Decision-makers should focus on overall regional stability of ecosystem services.

2.4 Trade-offs and Synergies Among Ecosystem Services

2.4.1 Correlation Coefficients

At the static temporal scale, correlations among the four ecosystem services all passed significance tests at the 0.01 level, indicating significant trade-off or synergy relationships . Food provision and water yield, food provision and soil conservation, and soil conservation and water yield showed synergistic relationships, while carbon storage showed trade-off relationships with food provision, water yield, and soil conservation. Correlation coefficients first decreased then increased, with relatively stable overall changes.

2.4.2 Spatial Patterns

Based on pixel-scale spatial mapping of dynamic relationships among ecosystem services from 2000 to 2020 with significance testing, ecosystem services in the Shanxi central urban agglomeration overall showed synergistic relationships [Figure 9: see original paper]. Food provision and water yield, food provision and soil conservation, and soil conservation and water yield were primarily synergistic, accounting for 90.79%, 76.50%, and 74.88% of pixels, respectively, mainly distributed in southern regions. Carbon storage showed trade-off relationships with food provision, soil conservation, and water yield, primarily because carbon storage slowly declined while food provision, water yield, and soil conservation increased over the past 20 years.

2.5 Impact of Land Use on Ecosystem Services

Land use/cover changes significantly impacted ecosystem services in the Shanxi central urban agglomeration from 2000 to 2020 . Built-up land expansion had the greatest positive impact on water yield, while forestland and grassland slightly decreased, negatively impacting carbon storage. Forestland increase positively affected soil conservation. The four-quadrant model analyzed correlations between land use intensity and ecosystem services. Water yield, food provision, and soil conservation showed positive correlations with land use intensity in most areas, while carbon storage showed negative correlations. Quadrants 2 and 4 represented areas where ecosystem services improved or degraded with increasing land use intensity, while quadrants 1 and 3 showed the opposite pattern. Counties in quadrants 2 and 4 were more numerous, mainly distributed in Xinzhou and Lüliang, reflecting that ecosystem service degradation may be more influenced by non-human factors. However, quadrant 1 areas, as high land use intensity zones, require attention to adjusting human activities to promote overall regional ecosystem service levels [Figure 10: see original paper].

3 Discussion

Water yield and soil conservation services in the Shanxi central urban agglomeration increased from 2000 to 2020, while carbon storage decreased, consistent with related research findings. Under the Grain-for-Green Program and comprehensive soil erosion control, soil conservation capacity improved, as also shown by Yin Baoku et al. for the middle Yellow River region. Ecosystem services are closely linked to land cover types. This study used ecosystem service rose diagrams to clearly demonstrate capacity differences across land types, showing forestland' s advantage in carbon storage. Therefore, urban planning should prioritize increasing urban green space to enhance ecosystem regulation capacity. For regions with strong ecosystem service capacity, such as northern Xinzhou, the government should strengthen forestland protection and control built-up land expansion to ensure regional ecosystem service stability.

The four-quadrant model results for land use intensity better reflect ecosystem service spatial distribution under human activity influence. Although large areas of the study region' s water yield, food provision, and soil conservation services are influenced by non-human factors, small areas in quadrants 1 and 3 affected by human activities require focused attention. Strengthening or weakening land use intensity corresponds to ecosystem service degradation or improvement. Quadrant 1 areas, as high land use intensity zones, need human activity adjustment to promote overall regional ecosystem service levels. The four quadrants represent different ecosystem service change conditions under varying land use intensities. Future ecological protection and restoration in the study area should use quadrant 4 as a baseline, with corresponding countermeferences for other quadrants.

Ecosystem service trade-off/synergy relationships vary by perspective and scale. From a static temporal perspective, soil conservation and carbon storage showed relatively stable synergistic relationships. From a dynamic spatial perspective, they showed trade-off relationships because the former calculated correlation coefficients across the entire study area annually, while the latter explored spatial consistency and regional differences at the pixel scale. Spatially, carbon storage and soil conservation showed trade-off relationships, similar to findings in the middle Yellow River region by Ren Juan et al. Water yield and soil conservation, and food provision showed synergistic relationships, consistent with existing research, though some regional differences exist. For instance, Han Lei et al. found trade-off relationships between water yield and other ecosystem services in Yan' an City, possibly due to different precipitation and evapotranspiration influences. Future research should consider ecosystem service relationships from multiple angles and regional scales.

Land use impacts on ecosystem services manifest in two main aspects. First, land use type changes significantly affect ecosystem services: built-up land increase positively impacts water yield, while forestland and grassland reduction negatively impacts carbon storage. Second, land use intensity changes show positive correlations with water yield, food provision, and soil conservation in most areas, but negative correlations with carbon storage.

4 Conclusions

This study focuses on the Shanxi central urban agglomeration, comprehensively evaluating four ecosystem services based on land use pattern evolution using InVEST and pixel statistical analysis methods, and exploring the impacts of land use patterns on ecosystem services. The main conclusions are:

From 2000 to 2020, land use in the Shanxi central urban agglomeration changed significantly, with urbanization driving land use type conversion and regional increases in land use intensity. Grassland and cropland remained the dominant land types, with cropland area decreasing by 2239.74 km^2 while built-up land increased by 1530.43 km^2. Land use intensity increased slowly from 267.72 to 275.92 during the study period.

Water yield, food provision, and soil conservation services increased overall, while carbon storage slowly decreased. Different land types and administrative regions showed significant differences in ecosystem service provision capacity. Built-up land and unused land provided the highest water yield capacity, cropland excelled in food provision, forestland and grassland dominated carbon storage and soil conservation, while water bodies provided nearly zero services. Xinzhou showed relatively high ecosystem service levels, while Taiyuan and Yangquan showed lower levels.

Ecosystem services were dominated by synergistic relationships, with food provision, water yield, and soil conservation mutually synergistic, while all showed trade-off relationships with carbon storage. Built-up land expansion positively impacted water yield, forestland increase promoted soil conservation, while forestland and grassland reduction negatively affected carbon storage. Land use intensity was positively correlated with water yield, food provision, and soil conservation, but negatively affected carbon storage.

These results provide important references for ecological security construction and sustainable development in the Shanxi central urban agglomeration and similar regions.

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