Spatiotemporal Characteristics of Ecosystem Services and Ecological Function Zoning in the Guanzhong Plain Urban Agglomeration Postprint

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Abstract

Quantifying the spatiotemporal distribution patterns of regional ecosystem services, analyzing trade-off/synergy relationships, identifying ecosystem service bundles, and delineating ecological function zones based on the functional characteristics within each bundle are conducive to strengthening regional ecosystem management. Taking the Guanzhong Plain Urban Agglomeration as an example, five ecosystem services from 2000 to 2020 were quantified, K-means cluster analysis was employed to identify service bundles, dominant service functions were determined, and ecological function zoning was implemented. The results indicate that: (1) Grain production and soil retention exhibited a trend of initial increase followed by decrease; water yield showed a trend of rapid initial increase followed by gradual increase; both habitat quality and carbon sequestration displayed a slight decreasing trend. High-value areas of grain production were mainly concentrated in the central and northeastern parts of the study area; high-value areas of soil retention were primarily located in the southern and western regions; high-value areas of habitat quality and carbon sequestration were mainly distributed in the southern region. (2) Grain production showed trade-off relationships with all other services, while synergy relationships were observed between soil retention and habitat quality, soil retention and carbon sequestration, and habitat quality and carbon sequestration; the strength of correlations among different services varied over time. (3) Ecological function zones were identified as grain production areas, ecological conservation areas, important urban areas, and ecological balance areas. The research findings are crucial for maintaining ecosystem balance and sustainable economic development, and provide guidance for promoting ecosystem management across different ecological function zones in the Guanzhong Plain Urban Agglomeration.

Full Text

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Abstract

Quantifying the spatiotemporal distribution patterns of regional ecosystem services, analyzing trade-off and synergy relationships, identifying ecosystem service clusters, and delineating ecological functional zones based on the functional characteristics within each cluster are essential for strengthening regional ecosystem management. This study calculates five ecosystem services in the Guanzhong Plain urban agglomeration, employs K-means clustering analysis to identify service clusters, and determines dominant service functions to achieve ecological functional zoning. Results indicate: (1) Grain production and soil retention exhibit a trend of initial increase followed by decrease, while water yield shows a pattern of rapid increase followed by slow growth. Both habitat quality and carbon sequestration display relatively mild decreasing trends. High-value areas for grain production are concentrated in the central and northeastern parts of the study area; high-value zones for soil retention are mainly in the southern and western regions; and high-value areas for habitat quality and carbon sequestration are primarily in the south. (2) Grain production shows trade-off relationships with all other services, while soil retention demonstrates synergy with habitat quality, soil retention with carbon sequestration, and habitat quality with carbon sequestration. The strength of correlations between different services varies over time. (3) Ecological functional zones are identified as primary grain-producing areas, ecological conservation zones, important urban areas, and ecological balance zones. These findings are crucial for maintaining ecosystem balance and sustainable economic development, providing guidance for ecosystem management across different functional zones in the Guanzhong Plain urban agglomeration.

Keywords: ecosystem service clusters; trade-offs; synergies; K-means clustering; Guanzhong Plain urban agglomeration

1. Introduction

Ecosystem services represent the natural environmental conditions and utilities upon which human survival depends, comprising various benefits obtained directly or indirectly from ecosystems. Complex interactions exist among ecosystem services, including trade-offs and synergies. Trade-offs occur when the enhancement of one service leads to the reduction of another, while synergies refer to simultaneous enhancement or reduction of multiple services. Urban agglomerations serve as crucial carriers for future productivity distribution and primary forms of urbanization development. Unreasonable management measures will intensify conflicts between humans and nature. Ecosystem service clusters refer to combinations of multiple ecosystem services that repeatedly appear in space or time. With advancing urbanization, excessive development and utilization have exacerbated ecosystem service degradation, intensifying conflicts between human activities and ecosystems. Quantitative assessment of ecosystem services within a region, clarification of relationships between different services, and identification of service clusters can enhance understanding of current regional ecosystem status and optimize ecosystem layout, thereby achieving high-quality regional development.

The Guanzhong Plain urban agglomeration, centered on Xi'an City, is the second-largest urban agglomeration in western China and the only national-level urban agglomeration in the middle reaches of the Yellow River. It holds a unique strategic position in national modernization and the overall pattern of opening-up. However, the region faces weak ecological carrying capacity, water scarcity in some areas, and soil erosion and pollution caused by extensive mineral resource extraction. Despite these challenges, research on ecosystem service trade-offs, synergies, and ecological functional zoning in the Guanzhong Plain urban agglomeration remains relatively limited. Therefore, this study quantitatively assesses ecosystem services from 2000 to 2020, visualizes the spatiotemporal characteristics of grain production, soil retention, water yield, habitat quality, and carbon sequestration at the county scale, reveals trade-off and synergy relationships between different services using Spearman correlation analysis, identifies ecosystem service clusters through K-means clustering analysis, and determines dominant service functions as the basis for urban agglomeration ecological functional zoning. Investigating relationships among different ecosystem services and delineating ecological functional zones is significant for resolving contradictions between ecological protection and economic construction.

1.2 Data Sources

The study's foundational data include land use, meteorological, digital elevation model (DEM), normalized difference vegetation index (NDVI), soil, and socioeconomic data, obtained from the following sources: Land use data were acquired from the Resource and Environmental Science and Data

Center of the Chinese Academy of Sciences (https://www.resdc.cn/) and reclassified into cropland, forestland, grassland, water bodies, construction land, and unused land. DEM data were obtained from the Geospatial Data Cloud (https://www.gscloud.cn/). Meteorological data were sourced from the National Earth System Science Data Center (http://www.geodata.cn). NDVI data, derived from NASA's MODID13Q1 product, were processed using the maximum value composite method. Soil data were obtained from the World Soil Database's Chinese soil dataset (http://westdc.westgis.ac.cn). Relevant socioeconomic data were collected from provincial statistical bureaus and statistical yearbooks. Data from different sources were standardized in terms of resolution and coordinate system, unified to WGS 1984.

1.3.1 Grain Production

Grain production exhibits a significant linear correlation with NDVI. This study employs MODIS NDVI data and statistical grain yield data to assess grain production at the raster scale within the study area. The calculation formula is:

$$FP_i = \frac{NDVI_i}{NDVI_{sum}} \times FP_{sum}$$

where FP_i represents the grain yield of pixel i ($\mathrm{t \cdot km^{-2}}$), $NDVI_i$ is the NDVI value of pixel i, FP_{sum} denotes the total grain yield, and $NDVIsum$ represents the sum of NDVI values.

1.3.2 Soil Retention

Soil retention refers to the ecosystem's capacity to prevent soil loss. This study employs the Universal Soil Loss Equation to assess soil retention, which is calculated as the difference between potential and actual soil erosion:

$$SR = R \times K \times LS \times (1 - C \times P)$$

where SR is soil retention ($\mathrm{t \cdot hm^{-2}}$), R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the slope length and steepness factor, C is the vegetation cover and management factor, and P is the soil and water conservation practice factor.

1.3.3 Water Yield

Water yield serves as the foundation for various ecological processes and services. Regional water yield is generally defined as precipitation minus actual evapotranspiration. This study utilizes the InVEST water yield module for quantification:

$$WY_x = P_x - AET_x$$

where WY_x represents water yield at grid cell x (mm), AET_x is actual evapotranspiration at grid cell x (mm), and P_x is annual precipitation at grid cell x (mm).

1.3.4 Habitat Quality

The InVEST habitat quality module is used to assess regional habitat quality. The habitat quality index is a dimensionless comprehensive indicator that evaluates habitat suitability and degradation levels of different land use types, reflecting habitat quality 优劣 and thereby assessing biodiversity maintenance services:

$$Q_{xj} = H_{xj} \times \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}\right)$$

where Q_{xj} is habitat quality in grid cell x for land use type j, H_{xj} is habitat suitability in grid cell x for land use type j, D_{xj} is the level of habitat threat in grid cell x for land use type j, k is the half-saturation constant, and z is a normalized constant. Habitat quality values typically range between [0, 1], with higher values indicating better habitat quality.

1.3.5 Carbon Sequestration

The InVEST carbon module is employed to calculate ecosystem carbon sequestration capacity. Carbon sequestration ($C_{i-total}$) is calculated by combining land use data and includes four basic carbon pools: aboveground, belowground, soil, and dead organic matter:

$$C_{i-total} = \sum_i (C_{i-above} + C_{i-below} + C_{i-soil} + C_{i-dead}) \times S_i$$

where $C_{i-total}$ represents total carbon sequestration in terrestrial ecosystems (t), $C_{i-above}$ is aboveground carbon density for land use type i ($\mathrm{t \cdot hm^{-2}}$), $C_{i-below}$ is belowground carbon density for land use type i ($\mathrm{t \cdot hm^{-2}}$), C_{i-soil} is soil carbon density for land use type i ($\mathrm{t \cdot hm^{-2}}$), C_{i-dead} is dead organic carbon density for land use type i ($\mathrm{t \cdot hm^{-2}}$), and S_i is the area of land use type i ($\mathrm{hm^2}$).

1.4 Ecosystem Service Trade-off/Synergy Analysis

To quantitatively analyze synergies and trade-offs among ecosystem services in the Guanzhong Plain urban agglomeration, this study employs Spearman correlation analysis to examine relationships among grain production, soil retention, water yield, habitat quality, and carbon sequestration. If the correlation coefficient (r) is positive and significance test $P < 0.01$, it indicates an extremely significant synergy; if r is positive and $0.01 < P < 0.05$, it indicates a significant synergy. If r is negative and $P < 0.01$, it indicates an extremely significant trade-off; if r is negative and $0.01 < P < 0.05$, it indicates a significant trade-off. If $P > 0.05$, it indicates no significant relationship between the two services.

1.5 Identification of Ecosystem Service Clusters

Ecosystem service clusters are identified by measuring and evaluating similarities among different ecosystem services, grouping regions with high similarity into the same cluster and regions with high dissimilarity into different clusters. K-means clustering analysis is an unsupervised clustering method with advantages of small computational load, fast operation speed, clear clustering structure, and simple process, making it widely applicable in spatial pattern research. Therefore, this study first uses K-means clustering analysis to identify and classify service clusters. The data for the five ecosystem services are standardized, and the optimal number of clusters is determined using the within-cluster sum of squared errors. Based on the optimal number of clusters, the clusters are delineated and visualized spatially using ArcGIS to analyze the composition structure and dominant service types within different clusters.

2. Results

2.1.1 Temporal Variation Characteristics of Ecosystem Services

From 2000 to 2020, ecosystem services in the Guanzhong Plain urban agglomeration showed noticeable temporal changes (Table 1). Grain production and soil retention displayed a trend of initial increase followed by decrease. From 2000 to 2010, the annual average grain production increased by 37.35%, and soil retention increased by 44.00%. From 2010 to 2020, grain production decreased by 9.13%, and soil retention decreased by 29.29%. Water yield showed a pattern of rapid increase followed by slow growth, with the annual average increasing by 39.69% from 2000 to 2010 and by 0.71% from 2010 to 2020. Both habitat quality and carbon sequestration exhibited relatively mild decreasing trends.

2.1.2 Spatial Variation Characteristics of Ecosystem Services

From 2000 to 2020, various ecosystem services displayed distinct spatial distribution patterns (Figure 2). High-value areas for grain production were concentrated in Xianyang City, Weinan City in the central part of the urban agglomeration, and Yuncheng City and Linfen City in the northeastern part. These areas feature flat terrain, fertile soil, favorable hydrothermal conditions, and are dominated by cropland, making them suitable for agricultural production. Temporal analysis reveals that unit area grain production in Xianyang, Weinan, Yuncheng, and Linfen increased significantly from 2000 to 2020. Low-value areas for grain production were mainly in Baoji City, Xi'an City, and Shangluo

City, where mountainous and hilly terrain dominates, forestland and grassland are extensive, and cultivation is unsuitable, resulting in lower unit area grain production.

High-value zones for soil retention were concentrated in the southern part of the study area, including Baoji City, Xi'an City, and Shangluo City. These mountainous and hilly regions are dominated by forestland and grassland with high vegetation coverage, providing strong soil retention functions that effectively prevent and reduce soil erosion. Low-value areas for soil retention were mainly distributed in the central part of the study area, including the municipal districts of Xianyang, Weinan, and Xi'an, and Yuncheng City in the northeast, where cropland is the primary land use type and sediment interception capacity is limited.

Water yield generally decreased from south to north, corresponding to the topographic characteristics of the study area. Temporal analysis shows that soil retention and water yield in Xi'an, Shangluo, and southern Xianyang counties displayed an initial increase followed by a decrease, closely related to precipitation patterns. High-value areas for carbon sequestration and habitat quality showed similar spatial distributions, concentrated in southern Baoji, Danfeng and Zhashui counties of Shangluo, Zhouzhi County of Xi'an, Yijun County of Tongchuan, and Xia and Jiang counties of Yuncheng. These regions have high forest coverage, extensive vegetation, relatively high habitat quality levels, and serve as important carbon sinks. The districts of Xincheng, Beilin, Lianhu, and Yanta in Xi'an consistently showed the lowest values for habitat quality and carbon sequestration services, being the most urbanized areas dominated by construction land.

2.2 Trade-off/Synergy Relationships Among Ecosystem Services

At the county scale, different ecosystem services in the Guanzhong Plain urban agglomeration exhibited distinct trade-off and synergy relationships, with synergy intensities varying over time (Table 2). Correlations between grain production and soil retention, habitat quality, and carbon sequestration all passed significance tests at the $P < 0.01$ level, indicating extremely significant trade-off relationships. Correlations between grain production and water yield passed significance tests at the $0.01 < P < 0.05$ level, indicating significant trade-off relationships. Temporally, correlations between grain production and soil retention, habitat quality, and carbon sequestration gradually weakened, indicating diminishing extremely significant trade-off relationships. Conversely, the significant trade-off relationship between grain production and water yield gradually strengthened.

Correlations between soil retention and habitat quality, soil retention and carbon sequestration, and habitat quality and carbon sequestration all passed significance tests at the $P < 0.01$ level, indicating extremely significant synergies. Temporally, these correlations fluctuated, showing an initial increase followed by a decrease. The correlation between soil retention and water yield changed from a significant synergy in 2000 ($0.01 < P < 0.05$) to no significant correlation in 2010 and 2020 ($P > 0.05$). No significant differences existed in correlations between water yield and habitat quality or between water yield and carbon sequestration.

2.3 Ecological Function Zoning

Following existing research, K-means clustering analysis was applied to the 65 county-level administrative units in the Guanzhong Plain urban agglomeration. The standardized multi-year average values of ecosystem services were analyzed, and the optimal number of clusters was determined based on the relationship between within-cluster sum of squared errors and different cluster numbers (Figure 3). Four service clusters were extracted.

The composition structure of ecosystem services within each cluster was expressed by determining the average value of all ecosystem services as 0. If a particular ecosystem service value exceeds 0, it indicates that the functional zone's service is above the average level; if below 0, it is below average.

Based on ecosystem service functions within each cluster, the Guanzhong Plain urban agglomeration is divided into four functional zones: primary grain-producing areas, ecological conservation zones, important urban areas, and ecological balance zones (Figure 5). Primary grain-producing areas are concentrated in Yuncheng, Weinan, southern Xianyang, and southern Tongchuan, comprising 31 counties (23.80% of the study area). These areas feature flat terrain, fertile soil, and sufficient irrigation conditions, with cropland as the dominant land use type. They represent important grain production bases ensuring regional food security. However, frequent agricultural activities and increasing human disturbance result in soil retention far below average, with water yield, habitat quality, and carbon sequestration slightly below average.

Ecological conservation zones are concentrated in southern Xi'an, Shangluo, Weinan, and Baoji, and eastern Tianshui, comprising 40 counties (30.54% of the study area). These regions belong to the Qinling mountainous area in the southern part of the urban agglomeration, with high vegetation coverage and forestland and grassland as the main land use types. These land cover types provide climate regulation, soil erosion prevention, and carbon sequestration enhancement, though the ecological environment is fragile. Soil retention is particularly prominent in these zones, with water yield, habitat quality, and carbon sequestration also above average, while grain production is below average due to limited cropland and extensive mountainous terrain unsuitable for cultivation.

Important urban areas include four districts—Xincheng, Beilin, Lianhu, and Yanta—comprising only 0.23% of the urban agglomeration's total area. These areas are densely populated and economically developed, dominated by construction land. Grain production, soil retention, habitat quality, and carbon sequestration are at the lowest levels in the urban agglomeration, making it impossible to fulfill grain production and ecological protection functions. However, water yield is far above the regional average due to extensive impervious surfaces that rapidly convert precipitation into runoff, combined with relatively high precipitation levels.

Ecological balance zones are concentrated in Tianshui, Pingliang, Qingyang, Tongchuan, Linfen, northern Baoji and Xianyang, and eastern Yuncheng, comprising 45.44% of the study area. These regions are located in the western and northern parts of the urban agglomeration, with cropland, grassland, and forestland as the main land use types. They provide lower supply services than primary grain-producing areas and lower regulating and supporting services than ecological conservation zones. Grain production is roughly at the regional average, while soil retention, habitat quality, and carbon sequestration are slightly above average, and water yield is slightly below average.

3. Discussion

The ecosystem service assessment results accurately reflect the value and changes of ecosystem services for human social development within the urban agglomeration. Grain production and soil retention in the Guanzhong Plain urban agglomeration showed an initial increase followed by a decrease. The increase in grain production from 2000 to 2010 is primarily related to improved agricultural technology and increased unit area yields, while the decrease from 2010 to 2020 is mainly due to the implementation of the Grain for Green Program, which significantly reduced cropland area—consistent with findings from Wang Shimei et al. Soil retention and water yield trends align with research by Xu Xingchao et al., with the Grain for Green Program demonstrating clear effects on soil retention. The decomposition of vegetation litter can effectively improve soil structure and enhance soil erosion resistance, while plant roots fix soil and reduce water erosion. The decrease in soil retention levels after 2010 is mainly due to reduced rainfall erosivity during this period. With minimal changes in actual evapotranspiration, continued increases in precipitation lead to increasing water yield.

Identifying regional ecosystem service clusters provides the basis for ecological functional zoning. Based on ecosystem service functions within clusters, the Guanzhong Plain urban agglomeration is divided into four functional zones: primary grain-producing areas, ecological conservation zones, important urban areas, and ecological balance zones. Similar studies by Zhao Xiaoqing et al. in karst mountainous areas and Shen Jiashu et al. in Xiong'an New Area have used dominant ecosystem service functions for zoning, demonstrating that analyzing service cluster composition structures enhances zoning rationality.

Future development requires reasonable ecological planning to promote coordinated development among ecosystem services. For primary grain-producing areas, construction of high-standard farmland should be strengthened, cropland protection redlines strictly observed, planting structures optimized, and farmland ecosystem multifunctionality enhanced. For ecological conservation zones, nature reserves should be appropriately established, natural forests and water source protection areas maintained, and unique tourism and biological resources reasonably developed. For important urban areas, green infrastructure construction should be strengthened to reduce impervious surface coverage. For ecological balance zones, priority should be given to maintaining ecosystem service stability without sacrificing soil retention, habitat quality, or carbon sequestration.

At the methodological level, this study innovates urban agglomeration ecological functional zoning methods by identifying ecosystem service clusters through K-means clustering analysis. However, cultural services have not been addressed. Existing research indicates that cultural services exhibit trade-off and synergy relationships with ecosystem supply, regulating, and supporting services, and future studies should strengthen assessments of multiple ecosystem services. This study quantifies ecosystem services at the raster scale but processes them at the county administrative unit level for relationship analysis convenience, without comparative analysis at raster or township scales. Future research should consider analyzing trade-off and synergy relationships among ecosystem services in the Guanzhong Plain urban agglomeration at different scales to enrich regional ecosystem service research.

4. Conclusion

(1) Ecosystem service assessment results accurately reflect the level and changes of ecosystem service value for human social development within the urban agglomeration. In the Guanzhong Plain urban agglomeration, grain production and soil retention showed initial increase followed by decrease, water yield exhibited rapid increase followed by slow growth, and habitat quality and carbon sequestration showed relatively mild decreasing trends. Mountainous and hilly areas with high vegetation coverage have higher soil retention, habitat quality, and carbon sequestration; flat plains with extensive cropland have higher grain production; and areas with high precipitation and urbanization levels have higher water yield.

(2) Extremely significant trade-off relationships exist between grain production and soil retention, habitat quality, and carbon sequestration. A significant trade-off relationship exists between grain production and water yield. Extremely significant synergy relationships exist between soil retention and habitat quality, soil retention and carbon sequestration, and habitat quality and carbon sequestration. No significant differences exist between water yield and habitat quality or between water yield and carbon sequestration. Temporally, correlations between grain production and soil retention, habitat quality, and carbon sequestration are weakening, while the correlation between grain production and water yield is strengthening. Correlations among soil retention, habitat quality, and carbon sequestra-

tion show initial increase followed by decrease.

(3) Based on ecosystem service functions within clusters, the Guanzhong Plain urban agglomeration is divided into four functional zones: primary grain-producing areas, ecological conservation zones, important urban areas, and ecological balance zones. Primary grain-producing areas are dominated by grain production services; ecological conservation zones are dominated by soil retention, with relatively high water yield, habitat quality, and carbon sequestration. Important urban areas have soil retention, grain production, habitat quality, and carbon sequestration far below average, requiring improved living environments and increased green space. Ecological balance zones have grain production roughly at the regional average, with soil retention, habitat quality, and carbon sequestration slightly above average and water yield slightly below average.

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