Postprint: Optimization of Ecological Function Zoning in Gansu Province Based on Ecosystem Service Trade-offs and Synergies

Authors: Li Xiaofei, Gong Jian, Ye Jing, Fang Hongjia, Zhang Shizhen, Lin Jiasheng

Date: 2025-03-14T00:00:00+00:00

Abstract

Taking Gansu Province in the ecologically fragile region of northwestern China as the study area, based on physical geography and socio-economic data, this study employs methods such as the InVEST model, CASA model, and ArcGIS spatial analysis to analyze the ecological service functions of Gansu Province and their trade-off and synergy relationships, and explores optimization schemes for ecological function zoning under these relationships. The results show that: (1) From 2000 to 2020, due to large-scale ecological restoration projects such as the Grain for Green Program, land types with strong ecological functions in Gansu Province, including forestland, grassland, river water surfaces, and lake water surfaces, have increased, and the four ecological services of carbon sequestration, habitat quality, soil conservation, and water yield have all exhibited a fluctuating upward trend. (2) In terms of trade-off and synergy relationships, habitat quality-water yield, carbon sequestration-water yield, and soil conservation-habitat quality show moderate synergy, while soil conservation-carbon sequestration, soil conservation-water yield, and habitat quality-carbon sequestration show strong synergy. (3) Using K-means clustering, Gansu Province is divided into six ecological zones: economic-cultural development zone, habitat quality-carbon sequestration priority zone, soil conservation-carbon sequestration priority zone, biodiversity-soil conservation zone, comprehensive soil and water conservation zone, and comprehensive ecological service conservation zone. By incorporating trade-off and synergy relationships into the optimization of ecosystem service bundle zoning, the area requiring optimization accounts for 3.07% of the province' s total area. Through comprehensive analysis of the similarity and difference of ecological services, after forming ecosystem service bundles, the trade-off and synergy relationships within each zone are fully considered to optimize and adjust traditional ecological zoning, proposing spatially differentiated governance measures to enhance synergies and mitigate trade-offs.

Full Text

Abstract

Using physical geographic and socioeconomic data, we analyzed the ecological service functions and their trade-off synergistic relationships in Gansu Province, an ecologically fragile region in northwest China. By applying InVEST spatial analysis and other methods, we examined the spatiotemporal evolution of ecosystem services and explored optimization schemes for ecological function zoning under trade-off synergistic relationships. The results indicate: (1) From 2000 to 2020, large-scale ecological construction projects such as the Grain-for-Green Program increased the area of land cover types with strong ecological functions (forestland, grassland, river surfaces, and lake surfaces) in Gansu Province. Four ecosystem services—carbon sequestration, habitat quality, soil conservation, and water yield—all exhibited fluctuating upward trends. (2) In terms of trade-off synergistic relationships, habitat quality-water yield, carbon sequestration-water yield, soil conservation-habitat quality, and carbon sequestration-water yield showed medium to high levels of ecological services. Habitat quality-soil conservation demonstrated a moderate synergistic relationship, while soil conservation-carbon sequestration, soil conservation-water yield, and habitat quality-carbon sequestration showed strong synergistic relationships. (3) Using K-means clustering, Gansu Province was divided into six ecological zones: economic-cultural development zone, habitat quality-carbon sequestration priority zone, soil conservation-carbon sequestration priority zone, biodiversity-soil conservation zone, soil and water comprehensive conservation zone, and ecological service comprehensive conservation zone. By incorporating trade-off synergistic relationships into the optimization of ecosystem service cluster zoning, the area requiring optimization accounted for 3.07% of the province' s total area. Through comprehensive analysis of the similarities and differences in ecosystem services and forming ecosystem service clusters with full consideration of internal trade-off synergistic relationships, traditional ecological zoning was optimized and adjusted, and spatially differentiated governance measures were proposed to enhance synergies and mitigate trade-offs.

Keywords: ecosystem services; ecological zoning; trade-offs and synergies; Gansu Province

1.1 Study Area Overview

Gansu Province is located at the intersection of three major plateaus—the Loess Plateau, Tibetan Plateau, and Inner Mongolia Plateau—and three natural regions: the arid northwest, the alpine Tibetan region, and the eastern monsoon zone, resulting in complex and diverse ecosystems. As shown in [Figure 1: see original paper], the study area features interwoven distributions of mountains, plateaus, plains, valleys, deserts, and Gobi landforms. The terrain slopes from southwest to northeast and can be broadly divided into six distinct geomorphic regions: the Longnan Mountains, Longzhong Loess Plateau, Gannan Plateau, Hexi Corridor, Qilian Mountains, and the area north of the Hexi Corridor. The "Three Barriers and Four Zones"represents the ecological function zoning scheme for Gansu Province based on its major function-oriented zoning. This includes the upper reaches of the Yellow River ecological barrier, upper reaches of the Yangtze River ecological barrier, upper reaches of the Hexi inland river ecological barrier, Longdong Loess Plateau hilly-gully soil conservation ecological function zone, lower Shiyang River ecological protection and management zone, Dunhuang ecological environment and cultural heritage protection zone, and the northern desert ecological protection zone in Subei. These areas constitute the key focus for ecological protection under current provincial policies.

1.2 Data Sources

The research data comprised continuous time-series datasets from 2000 to 2020, including land use data, meteorological data, elevation data, and socioeconomic data, along with relevant auxiliary information. Based on research requirements, land use types from the European Space Agency were reclassified into six categories: cropland, forestland, grassland, water bodies, construction land, and unused land. All spatial datasets were projected to the WGS_{{{1984}}{{UTM}}}{47N} coordinate system. Specific data sources are detailed in .

1.3.1 Research Framework

This study quantified the spatiotemporal evolution characteristics of ecosystem services and their trade-off relationships in Gansu Province from 2000 to 2020. We conducted functional zoning of ecosystem services and proposed differentiated ecological management recommendations for each functional zone, providing a scientific basis for ecological protection and territorial spatial management. The United Nations Sustainable Development Goals provide a practical framework for global ecological civilization construction (see [Figure 2: see original paper]). Considering Gansu' s position as a severely ecologically fragile province with serious soil erosion and its national strategic role in the "Dual Carbon" initiative, we selected four ecosystem services closely related to the region: habitat quality, carbon sequestration, soil conservation, and water yield. Using the InVEST and CASA models, we assessed the temporal evolution of ecosystem services in Gansu Province. To reduce interference from anomalous years, we employed pixel-wise partial correlation analysis to map the spatial patterns of ecosystem service trade-off relationships. In the ecological function zoning phase, K-means clustering was first used to classify regions with similar ecosystem services into ecosystem service clusters. Based on the similarities and differences in ecological functions, we optimized and adjusted the zoning, proposing differentiated management measures for ecologically fragile areas to enhance regional ecological efficiency and maintain ecological sustainability.

1.3.2 Ecosystem Service Assessment

Among current mainstream research, habitat quality, soil conservation, water yield, carbon sequestration, and grain production are key focus areas. As a typical ecologically fragile region in northwest China, Gansu Province has relatively weak grain production capacity, which is not a priority in regional development planning. However, the other four ecosystem services can fully reflect the ecological importance and ecological issues faced by the fragile region. Considering the difficulty in obtaining and abstract nature of cultural service data at the provincial scale, we quantified habitat quality, carbon sequestration, soil conservation, and water yield.

Habitat Quality: Biodiversity conservation is closely related to habitat quality. We used the biodiversity module of the InVEST model to assess habitat quality. The calculation formula is as follows:

$$HQ_{xj} = H_j \times \left(1 - \frac{D_{xj}^z}{D_{xj}^z + K^z}\right)$$

where HQ_{xj} is the habitat quality index for pixel x in land use type j; H_j is the habitat suitability of habitat type j, ranging between 0 and 1; D_{xj} is the habitat degradation index for pixel x in land use type j; K is the half-saturation constant, generally set to 0.5; and z is a normalized constant, typically set to 2.5.

Carbon Sequestration: Net Primary Productivity (NPP) reflects carbon sequestration capacity. The calculation formula is as follows:

$$NPP = APAR \times \varepsilon$$

where $APAR$ is the photosynthetically active radiation absorbed by the pixel, and ε is the actual light use efficiency.

Soil Conservation: Soil conservation can be quantified using the Revised Universal Soil Loss Equation (RUSLE) to estimate soil erosion. The calculation formula is as follows:

$$A = R \times K \times LS \times C \times P$$

where A is the soil loss ($\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$); R is the rainfall erosivity factor ($\mathrm{MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot a^{-1}}$); K is the soil erodibility factor; LS is the slope length and steepness factor; C is the vegetation cover factor; and P is the soil conservation practice factor.

Water Yield: Water yield represents water supply capacity and is often assessed using the InVEST water yield module, which calculates the difference between precipitation and actual evapotranspiration for each unit based on water balance principles. The calculation formula is as follows:

$$Y(x) = P(x) - AET(x)$$

where $Y(x)$ is the water yield for pixel x; $P(x)$ is the annual precipitation for pixel x; and $AET(x)$ is the actual evapotranspiration for pixel x.

1.3.3 Temporal Change Analysis of Ecosystem Services Based on Sen' s Trend and Hurst Index

Ecosystem service temporal changes represent long-term dynamic processes that require analysis of trends and stability through long time series. Sen's slope uses a linear regression method to identify trends in ecosystem services, calculated as follows:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \quad \forall i < j$$

where β is the median slope, representing the change rate of ecosystem service variable x; x_i and x_j are the values of ecosystem service x in years i and j, respectively. If $\beta > 0$, the ecosystem service function shows an upward trend; if $\beta < 0$, it indicates degradation.

The Hurst index quantitatively describes the persistence and dependency of ecosystem service development, calculated through the rescaled range analysis of time series subsequences. A threshold of 0.5 is used: values less than 0.5 indicate future trends will oppose past trends, while values greater than 0.5 indicate continued trends with strong persistence.

1.3.4 Analysis of Ecosystem Service Trade-off and Synergy Relationships

Understanding the trade-off and synergy relationships among ecosystem services is crucial for promoting sustainable regional development. Decision-making processes must study these effects to avoid reducing one service while increasing another, ultimately achieving "win-win" outcomes. We used partial correlation analysis to examine pixel-wise relationships among habitat quality, carbon sequestration, soil conservation, and water yield, effectively excluding the influence of third variables to analyze correlations between any two services. Results can be interpreted based on correlation coefficients and significance levels (see). Significant negative correlations indicate trade-offs, while significant positive correlations indicate synergies.

1.3.5 Ecological Function Zoning

To improve refined ecological governance, this study used K-means clustering to identify ecosystem service clusters at the pixel level. Since different cluster numbers produce different zoning results, we determined the optimal number based on the principle of minimizing within-group sum of squares. After comparing with Gansu' s "Three Barriers and Four Zones" ecological construction zones through qualitative and quantitative analysis, we identified the cluster number that reached a threshold while showing high overlap with existing ecological construction zones. Using ArcGIS visualization, we spatially overlaid ecosystem service clusters to form ecological function zones, following the principle that dominant functions within a service cluster should avoid trade-off effects while allowing synergistic relationships. This approach integrates patch-level partitions to create an ecological function zoning scheme. Differentiated ecological management strategies were proposed for each functional zone based on its dominant characteristics, providing important references for ecological protection and territorial spatial management in other ecologically fragile provinces.

2.1 Characteristics of Ecosystem Service Function Changes

2.1.1 Temporal Evolution of Ecosystem Services

From 2000 to 2020, carbon sequestration, habitat quality, soil conservation, and water yield in Gansu Province all showed fluctuating upward trends (see [Figure 3: see original paper]). Large-scale ecological projects such as the Grain-for-Green Program increased the area of land cover types with strong ecological functions, leading to continuous ecological quality improvement. Specifically, habitat quality and carbon sequestration showed rapid growth after 2005, with growth rates slowing and fluctuating after 2010 before stabilizing and increasing again. Soil conservation and water yield services, influenced by meteorological data fluctuations, showed significant volatility between 2010 and 2015, presenting a "first increase then decrease, then increase again" pattern.

2.1.2 Spatial Distribution of Ecosystem Services

The spatial distribution of ecosystem services in Gansu Province (see [Figure 4: see original paper]) reveals that the soil conservation pattern remained relatively stable, dominated by low-value areas with a general "high in the south, low in the north" distribution. Increasing soil conservation areas were concentrated in the Longnan Mountains and along the Yellow River, where forest and grassland densities are high, as soil conservation depends on vegetation root systems to stabilize soil. Water yield showed significant spatial differentiation, with high values in the Gannan Plateau and Longnan Mountains within the monsoon and semi-humid zones, while arid regions showed low water yield due to low precipitation and high evapotranspiration. Habitat quality and carbon sequestration showed weak spatial changes, both presenting a "high in central-south, low in northeast" pattern, with high-value areas mainly distributed in the "Two Rivers and One Water" basin of the upper Yangtze River, along the Yellow River, and in the Gannan Plateau and Longnan Mountains, where dense forests and grasslands are located. Habitat quality was relatively high along the Qilian Mountain glaciers, though carbon sequestration was relatively low in these areas.

2.1.3 Trend Analysis of Ecosystem Service Changes

Overall, ecosystem services showed diverse change trends with significant differences among functions (see and [Figure 5: see original paper]). Habitat quality mainly showed decreasing trends, with anti-persistent significant decrease areas accounting for 42.02%—indicating that while habitat quality increased in the past, it will decrease in the future. Significant increase areas accounted for only 9.05%. Carbon sequestration mainly showed increasing trends, with persistent significant increase areas accounting for 26.75% and significant decrease areas accounting for 25.10%. Soil conservation and water yield showed similar trends, both increasing, with persistent significant increase areas accounting for 30.38% and 50.80%, respectively, while significant decrease areas accounted for less than 10%. Spatially, habitat quality future decrease trends were extensive, radiating outward from construction land centers, while increase areas were sporadically distributed along the Hexi Corridor. Carbon sequestration future decrease areas were small, concentrated along the Qilian Mountains, while future increase areas were widespread. Soil conservation and water yield future change trends were similar, with increase areas mainly located along the Hexi Corridor, Gannan Plateau, and Longnan Mountains.

2.2 Trade-off and Synergy Relationships of Ecosystem Service Functions

The correlation coefficients between ecosystem services were all greater than 0, passing significance tests at the $P < 0.01$ level, indicating significant synergistic relationships (see). In terms of correlation strength, habitat quality-water yield, carbon sequestration-water yield, soil conservation-habitat quality, and carbon sequestration-water yield showed moderate synergistic relationships, while soil conservation-carbon sequestration, soil conservation-water yield, and habitat quality-carbon sequestration showed strong synergistic relationships. The temporal trends of these relationships were relatively stable, with soil conservation-habitat quality, soil conservation-carbon sequestration, and habitat quality-carbon sequestration showing steady increases from 2000 to 2020, while habitat quality-water yield showed significant fluctuations.

The strong synergistic relationship between soil conservation and carbon sequestration in Gansu Province arises because high carbon sequestration areas are mainly forestland and grassland, which have higher vegetation coverage. Root systems reduce soil loss, enhance rainfall interception, and increase soil conservation capacity, thus showing significant positive correlation. Habitat quality-carbon sequestration also shows strong synergy, as high habitat quality areas concentrate in forested regions of southern Gansu and the Qilian Mountains with minimal human disturbance, where high ecosystem service functionality corresponds to higher carbon sequestration and soil conservation. In this arid and semi-arid region, forested areas receive abundant rainfall, increasing total water yield. Soil conservation and water yield are both influenced by soil texture, rainfall, and land use, showing strong synergistic relationships.

Spatial differentiation of trade-offs and synergies (see [Figure 6: see original paper]) shows that soil conservation-habitat quality exhibits non-significant trade-off and synergy effects, accounting for 59.79% and 26.03% of the area, respectively. Soil conservation-water yield shows non-significant trade-off and synergy effects, accounting for 38.92% and 20.11%, respectively, with significant trade-off areas mainly in western Hexi Corridor and significant synergy areas concentrated in the Loess Plateau region. Carbon sequestration-water yield shows non-significant trade-off and synergy effects, accounting for 44.09% and 26.30%, respectively, with significant trade-off areas distributed along the Hexi Corridor and scattered significant synergy areas. Habitat quality-carbon sequestration shows extremely significant trade-off and synergy effects, accounting for 29.6% and 63.66%, respectively, with trade-off areas mainly along the central Hexi Corridor and synergy areas in northwestern Gansu.

2.3 Ecosystem Service Zoning Optimization and Management

2.3.1 Ecosystem Service Zoning Optimization

Using ecosystem service values as training samples for K-means clustering, we performed ecological function clustering for all grid cells in Gansu Province based on ecosystem service functional similarity. By analyzing within-group sum of squares across different classification numbers and combining this with Gansu' s "Three Barriers and Four Zones" ecological construction zones through qualitative and quantitative analysis, we determined that when the number of service clusters is 6, the within-group sum of squares reaches a threshold while showing high overlap with existing ecological construction zones. Based on the distribution characteristics of four ecosystem services within each cluster, we identified dominant ecological functions for different ecosystem service clusters and named the zones accordingly, resulting in six partition types: economic-cultural development zone, habitat quality-carbon sequestration priority zone, soil conservation-carbon sequestration priority zone, biodiversity-soil conservation zone, soil and water comprehensive conservation zone, and ecological service comprehensive conservation zone.

We updated service cluster zoning using ecosystem trade-off and synergy effects to ensure that dominant functions within clusters did not exhibit trade-off inhibition. Trade-off restrictions for each service cluster are shown in . The economic-cultural development zone (Cluster 1) shows no prominent ecosystem services and is mainly desert and Gobi unused land. Considering the "Belt and

Road" construction and Dunhuang desert cultural development, no trade-off restrictions were set for this cluster. Conversely, the ecological service comprehensive conservation zone (Cluster 6) shows high ecological capacity across all four services, and this high-quality ecological area also has no restrictions. Other clusters require zoning optimization based on dominant function trade-offs.

The comparison before and after ecosystem service zoning adjustment (see [Figure 7: see original paper]) shows that the total area requiring optimization based on ecosystem service trade-offs is 13,092 km^2, accounting for 3.07% of the province' s area, where significant trade-off relationships exist in dominant functions. Specifically, the areas showing significant trade-offs in dominant functions are: habitat quality-carbon sequestration priority zone (6,466 km^2), soil conservation-carbon sequestration priority zone (155 km^2), biodiversity-soil conservation zone (5,686 km^2), and soil and water comprehensive conservation zone (785 km^2).

2.3.2 Ecosystem Service Zoning Control Path

Ecosystem service zoning management should reflect dominant functions while considering Gansu' s reality as an ecologically fragile province. By leveraging regional resource advantages through functional zoning, overall ecological quality improvement and coordinated win-win outcomes can be achieved in ecologically fragile areas.

Economic-Cultural Development Zone: This zone has low ecosystem service functions, is located in arid and semi-arid desert areas with scarce rainfall, and mainly consists of Gobi and desert unused land unsuitable for development. The ecological environment is extremely fragile. Comprehensive water conservation measures should be implemented, using major ecological water transfer projects to adjust water resource utilization structures and reduce disorderly resource development while tapping into Dunhuang' s cultural heritage potential. As a national ecological barrier, this zone requires continued afforestation, increased vegetation coverage, reduced desertification, and ecological restoration for high-quality development.

Habitat Quality-Carbon Sequestration Priority Zone: Dominant functions are habitat quality and carbon sequestration, located along the Hexi Corridor and central Longzhong region. Centered on the provincial capital Lanzhou, this zone should balance ecological and economic development, avoid destroying forest and grassland habitats during construction, and promote biodiversity conservation. The central Hexi Corridor shows some dominant function trade-offs, requiring balanced development.

Soil Conservation-Carbon Sequestration Priority Zone: Dominant functions are soil conservation and carbon sequestration, located in central Gansu and near the Qilian Mountains. Strict ecological control measures should be implemented to restore and precisely repair soil conservation functions. This zone shows gradually decreasing ecological quality and intensifying soil erosion on the Loess Plateau, requiring urgent protection to prevent human destruction.

Biodiversity-Soil Conservation Zone: Dominant functions are carbon sequestration, habitat quality, and soil conservation, with scattered spatial distribution. To reduce land fragmentation and increase vegetation coverage, afforestation should be promoted relying on national ecological management zones to achieve ecological restoration and high-quality development.

Soil and Water Comprehensive Conservation Zone: Dominant functions are water yield and soil conservation, located in southwestern Gansu on the northeastern edge of the Tibetan Plateau. This zone has concentrated forest and grassland resources and developed traditional animal husbandry with important ecological functions. Future development should prioritize ecology, balancing protection and development to build an ecological barrier in the upper Yellow River through continued Grain-for-Green policies and enhanced ecological restoration.

Ecological Service Comprehensive Conservation Zone: Dominant functions include water yield, soil conservation, carbon sequestration, and habitat quality, located in southeastern Gansu. With vast forest areas, humid climate, and high vegetation coverage, this zone is a major area for the Grain-for-Green Program. The strictest ecological protection system should be maintained, continuing national ecological management projects and strengthening ecological conservation.

3 Discussion

Regarding spatiotemporal characteristics of ecosystem services, large-scale ecological projects like Grain-for-Green have increased forestland, grassland, and other land cover types with strong ecological functions in Gansu Province, continuously improving ecological quality—consistent with findings from Xu et al. Carbon sequestration and habitat quality increased rapidly after policy implementation but subsequently slowed and fluctuated, indicating significant initial effects that may be influenced by climate change and land use transitions in the long term. Soil conservation and water yield, affected by precipitation and evaporation fluctuations, showed a "first increase then decrease, then increase again" pattern, highlighting the significant impact of climate change requiring long-term monitoring. Cultural services, though difficult to quantify at the grid level, were identified as key in desert areas through policy interpretation, though this requires more detailed theoretical support. Compared with other studies, our long-term data analysis comprehensively reflects dynamic changes, though the 20-year time span may be affected by anomalous climate events or human activities, causing data uncertainty. Future research should use longer time series and multi-dimensional ecological, cultural, and social data to quantify regional ecological functions from different perspectives.

Regarding trade-off and synergy relationships, these represent complex dynamic processes. Multiple ecosystem services in the study area generally show synergistic relationships, consistent with related research. However, the absence of provisioning services may affect trade-off/synergy results. Our pixel-wise analysis using long-term data reveals significant spatial differentiation in trade-off/synergy relationships, which are influenced by research scale and regional contexts. While we used trade-off relationships to characterize internal contradictions and mutual exclusivity among ecosystem services, future research should use multi-scale big data to identify more precise relationships for refined governance.

Regarding ecological function zoning optimization, maximizing "high synergy" or even "full synergy" is the ultimate goal of ecosystem management. However, most regions exhibit some trade-off relationships that hinder maximization of ecological benefits. Through human intervention and management, converting trade-off areas into synergy areas can effectively prevent future ecological degradation risks and maintain territorial spatial stability in ecologically fragile provinces. Future research should assess differences in impacts on decision-makers and stakeholders before and after zoning optimization to better apply zoning decisions within practical frameworks.

4 Conclusions

(1) From 2000 to 2020, carbon sequestration, habitat quality, soil conservation, and water yield in Gansu Province all showed fluctuating upward trends, with continuous ecological quality improvement due to large-scale ecological projects like Grain-for-Green.

(2) Reflecting functional differences through trade-off relationships, habitat quality-water yield, carbon sequestration-water yield, soil conservation-habitat quality, and carbon sequestration-water yield showed medium to high ecological service levels. Habitat quality-soil conservation showed moderate synergistic relationships, while soil conservation-carbon sequestration, soil conservation-water yield, and habitat quality-carbon sequestration showed strong synergistic relationships with significant spatial differentiation.

(3) Reflecting functional co-occurrence through ecosystem service clusters, Gansu Province can be divided into six ecosystem service clusters: economic-cultural development zone, habitat quality-carbon sequestration priority zone, soil conservation-carbon sequestration priority zone, biodiversity-soil conservation zone, soil and water comprehensive conservation zone, and ecological service comprehensive conservation zone.

(4) By comprehensively considering the co-occurrence and differences in ecosystem service functions, trade-off areas requiring optimization account for 3.07% of Gansu' s area. Significant trade-off relationships in dominant functions were identified in habitat quality-carbon sequestration priority zone (6,466 km^2), soil conservation-carbon sequestration priority zone

(155 km^2), biodiversity-soil conservation zone (5,686 km^2), and soil and water comprehensive conservation zone (785 km^2).

References

[1] Su Boru, Liu Moucheng. Research progress in ecosystem management strategies based on ecosystem services trade-offs[J]. Journal of Natural Resources, 2023, 38(7): 1848-1862.

[2] Huang Y T, Wu J Y. Spatial and temporal driving mechanisms of ecosystem service trade-off/synergy in national key urban agglomerations: A case study of the Yangtze River Delta urban agglomeration in China[J]. Ecological Indicators, 2023, 154: 110800, doi: 10.1016/j.ecolind.2023.110800.

[3] Li S, Zhu C M, Deng X D. Exploring the urban-rural gradient effects of construction land expansion processes on land use function trade-off/synergy in rapidly urbanizing areas[J]. Land Degradation & Development, 2024, 35(1): 46-61.

[4] Liu Song, Zhang Haopeng, Pei Xinsheng, et al. Drivers of ecosystem service trade-off and synergy in long-term sequence: A case study of the extremely important ecosystem service function area in Wuhu City[J]. Acta Ecologica Sinica, 2024, 44(5): 1780-1790.

[5] Zhao Xiaoqing, Shi Xiaoqian, Li Yuhao, et al. Spatio-temporal pattern and functional zoning of ecosystem services in the karst mountainous areas of southeastern Yunnan[J]. Acta Geographica Sinica, 2022, 77(3): 736-756.

[6] Li J L, Hu D W, Wang Y Z, et al. Study of identification and simulation of ecological zoning through integration of landscape ecological risk and ecosystem service value[J]. Sustainable Cities and Society, 2024, 107: 105442, doi: 10.1016/j.scs.2024.105442.

[7] Yuan Haiwei, Gong Jianzhou, Chen Yating, et al. Recognition and analysis of ecosystem service cluster patterns in Guangdong Province based on region division[J]. Acta Ecologica Sinica, 2023, 43(22): 9384-9401.

[8] Ouyang Zhiyun, Wang Xiaoke, Miao Hong. A primary study on Chinese terrestrial ecosystem services and their ecological-economic values[J]. Acta Ecologica Sinica, 1999, 19(5): 19-25.

[9] Xu J Y, Chen J X, Liu Y X. Partitioned responses of ecosystem services and their tradeoffs to human activities in the Belt and Road region[J]. Journal of Cleaner Production, 2020, 276: 123205, doi: 10.1016/j.jclepro.2020.123205.

[10] Dai Erfu, Wang Xiaoli, Zhu Jianjia, et al. Progress and perspective on ecosystem services trade-offs[J]. Advances in Earth Science, 2015, 30(11): 1250-1259.

[11] Peng H J, Zhang X S, Ren W, et al. Spatial pattern and driving factors of cropland ecosystem services in a major grain-producing region: A production-

living-ecology perspective[J]. Ecological Indicators, 2023, 155: 111024, doi: 10.1016/j.ecolind.2023.111024.

[12] Shen Jiashu, Liang Ze, Liu Laibao, et al. Trade-offs and synergies of ecosystem service bundles in Xiong' an New Area[J]. Geographical Research, 2020, 39(1): 79-91.

[13] Mo W B, Zhao Y L, Yang N, et al. Ecological function zoning based on ecosystem service bundles and trade-offs: A study of Dongjiang Lake Basin, China[J]. Environmental Science and Pollution Research, 2023, 30(14): 40388-40404.

[14] Pan Dongrong, Yan Haowen, Han Tianhu, et al. Evaluation of the service function value of grassland ecosystems in Gansu Province using the equivalence factor method[J]. Pratacultural Science, 2021, 38(9): 1860-1868.

[15] Zhang Chunyue, Bai Yongpin, Yang Xuedi, et al. Identification of ecosystem service bundles in Ningxia Plain under multi-scenario simulation[J]. Geographical Research, 2022, 41(12): 3364-3382.

[16] Wang Z L, Dong C, Dai L D, et al. Spatiotemporal evolution and attribution analysis of grassland NPP in the Yellow River source region, China[J]. Ecological Informatics, 2023, 76: 102135, doi: 10.1016/j.ecoinf.2023.102135.

[17] Pranav D S, Anna K, Paweł H, et al. Possibility of spatial estimation of soil erosion using revised universal soil loss equation model and generalized additive model in post-hard coal mining spoil heap[J]. Land Degradation & Development, 2023, 35(3): 923-935.

[18] Wang C, Li K M, Yuan C X. Study of the effects of land use change on water yield in the Qilian Mountains in western China[J]. Ecological Indicators, 2024, 158: 111464, doi: 10.1016/j.ecolind.2023.111464.

[19] Lal M, Ismail M, Jatisankar B, et al. Assessment of spatio-temporal trends of satellite-based aerosol optical depth using Mann-Kendall test and Sen' s slope estimator model[J]. Geomatics, Natural Hazards and Risk, 2022, 13(1): 1270-1298.

[20] Sun Guojun, Li Weihong, Zhu Chenggang, et al. Spatial-temporal characteristics of vegetation cover in Ili River Valley from 2000 to 2015[J]. Arid Land Geography, 2020, 43(6): 1551-1558.

[21] Li Qianru, Jia Yanlong, Wang Huijun, et al. Analysis of trade-off and synergy effects of ecosystem services in Hebei Province from the perspective of ecological function area[J]. Acta Geographica Sinica, 2023, 78(11): 2833-2849.

[22] Wang Binyu, Wang Ling, Chen Junchen, et al. Identification of ecological functional zoning and its influencing factors in the Sihu Lake Basin, China[J]. Chinese Journal of Applied Ecology, 2023, 34(10): 2757-2766.

[23] Li Y G, Liu W, Feng Q, et al. Quantitative assessment for the spatiotemporal changes of ecosystem services, trade-off-synergy relationships and drivers

in the semi-arid regions of China[J]. Remote Sensing, 2022, 14(1): 239, doi: 10.3390/rs14010239.

[24] Deng Yuli, Wang Dan, Xu Han. Trade-offs and synergies relationships of ecosystem services and their socio-ecological driving factors under different spatial scales in Shaoguan City, Guangdong, China[J]. Chinese Journal of Applied Ecology, 2023, 34(11): 3073-3084.

[25] Xu Xingchao, Zhao Xueyan, Song Xiaoyu. Impacts of the returning farmland to forest (grassland) project on ecosystem services in the Weihe River Basin, China[J]. Chinese Journal of Applied Ecology, 2021, 32(11): 3893-3904.

[26] Yuan Hongwei, Cai Jun, Zhang Lei. Temporal and spatial changes of human activities and habitat quality in national key ecological function areas and their spatial effects[J]. Arid Land Geography, 2023, 46(6): 934-948.

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