Postprint of Identification of Priority Areas for Ecological Compensation for Soil and Water Conservation in Ningxia

Authors: Shen Cao, Ren Zongping, Li Peng, Wang Kaibo 2), Lu Kexin, Ren Zhengyan, Wei Xiaoyan

Date: 2024-03-01T00:00:00+00:00

Abstract

Research on identifying ecological compensation priority areas based on soil and water conservation service functions holds significant reference value for establishing a locally adapted ecological compensation system for soil and water conservation. Taking Ningxia as the study area, this study employs the InVEST model to evaluate three primary soil and water conservation services—water source conservation, soil retention, and carbon storage—and conducts their monetary valuation. By comprehensively considering the ecological compensation priority rankings and ecological vulnerability indices of various districts and counties, spatial identification of regional soil and water conservation ecological compensation priority areas is performed. The results indicate that the value of soil and water conservation in Ningxia for the years 2000, 2010, and 2020 was 2478.9$×108*yuan*, 2661.7×108*yuan*, *and*2958.5×$108 yuan, respectively, demonstrating a continuous increasing trend. Spatially, the values exhibit a distribution pattern of higher in the south and lower in the north, with the maximum located in Jingyuan County and the minimum in Jinfeng District. Over the past 20 years, dynamic variations in soil and water conservation priority compensation areas across the region have been relatively minor. Compensation priority areas are primarily situated in the southern regions characterized by high ecological value and economically underdeveloped conditions, while secondary ecological compensation priority areas are located in the central and northern regions with relatively lower ecological value and higher economic development levels. Compensating these priority areas can effectively enhance ecological compensation efficiency and promote sustainable development of the regional ecological environment and socio-economy.

Full Text

Identification of Priority Areas for Ecological Compensation for Soil and Water Conservation in Ningxia

SHEN Cao[1], **REN Zongping**[1], **LI Peng**[1], **WANG Kaibo**[2], **LU Kexin**[1], **REN Zhengyan**[3], **WEI Xiaoyan**[3]

[1]State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China, Xi' an University of Technology, Xi' an 710054, Shaanxi, China
[2]Institute of Earth Environment, Chinese Academy of Sciences, Xi' an 710061, Shaanxi, China
[3]Soil and Water Conservation Monitoring Station of Ningxia Hui Autonomous Region, Yinchuan 750000, Ningxia, China

Abstract

Identifying priority areas for ecological compensation under soil and water conservation services is crucial for establishing a locally adapted ecological compensation system. This study takes Ningxia as the research area, employing the InVEST model to evaluate three major soil and water conservation service functions—water retention, soil conservation, and carbon storage—and quantifies their economic values. By comprehensively considering the ecological compensation priority levels and ecological vulnerability indices of each district and county, we spatially identify priority areas for soil and water conservation ecological compensation across the region. The research demonstrates that from 2000 to 2020, the total value of soil and water conservation services in Ningxia increased steadily, reaching 247.89 billion yuan, 266.17 billion yuan, and 295.85 billion yuan respectively, showing an overall upward trend. Spatially, the distribution exhibits a pattern of high values in the south and low values in the north, with the maximum value in Jingyuan County and the minimum in Jinfeng District. Over the years, the dynamic changes in priority compensation areas for soil and water conservation have been relatively minor. Priority compensation areas are primarily located in the southern region, characterized by high ecological value and lagging economic development, while secondary priority areas are situated in the central and northern regions with lower ecological value and higher economic levels. Compensating these priority areas can effectively improve the efficiency of ecological compensation and promote sustainable regional ecological, economic, and social development.

Keywords: ecological service value; ecological compensation priority zone; soil and water conservation; InVEST model

1. Introduction

With the rapid development of the global economy, ecosystems face threats including habitat loss, resource shortages, and degradation of ecosystem services. The contradiction between natural resources, ecological environment, and sustainable development has become increasingly prominent. Integrating economic development with ecological protection has emerged as a focal issue of global concern. The *National 14th Five-Year Plan and Long-Range Objectives Through 2035* explicitly proposes improving the ecological protection compensation mechanism and increasing compensation efforts in key ecological function zones. Currently, research on ecological compensation mechanisms has become a critical priority.

Numerous studies have explored ecological compensation standards and mechanisms from multiple perspectives, providing theoretical foundations for coordinating regional economic development levels and soil and water conservation ecosystem services. For instance, Xiong et al. [?] analyzed ecological compensation standards for wetland restoration in Dongting Lake using estimated ecosystem service values, employing ecosystem service value equivalents as regional average representations. Guo et al. [?] applied an ecological compensation priority model to calculate unit-area ecosystem service values and ecological compensation priorities for 73 counties (cities) in the Beijing-Tianjin region, thereby identifying priority areas for ecological compensation. Yan et al. [?] selected farmers' per capita net income to modify ecological compensation priorities and introduced an ecological compensation threshold model to explore reasonable compensation ranges, though their study lacked sensitivity analysis of model parameters and research on compensation threshold spans.

Soil and water conservation ecological compensation serves as an important measure to maintain and consolidate ecological benefits, helping protect and improve ecosystem functions such as water retention, soil fertility, and carbon sequestration. Quantifying soil and water conservation service values is both a prerequisite for implementing ecological compensation and the foundation for determining compensation quotas, holding significant reference value for delineating compensation zones and exploring compensation models and operational mechanisms. However, existing domestic research has primarily focused on watershed scales and hotspot areas of ecosystem services, with limited studies on ecological compensation mechanisms in arid and semi-arid regions of Northwest China. Therefore, identifying priority areas for soil and water conservation ecological compensation in these regions is crucial for scientifically determining compensation zones and maximizing compensation benefits.

This study focuses on the Ningxia Yellow River Basin Ecological Protection and High-Quality Development Pilot Zone. We selected three key indicators from Ningxia' s soil and water conservation service functions—water retention, soil conservation, and carbon storage—for functional quantification and valuation. Building upon this, we combined the concept of ecological compensation priority and ecological vulnerability index calculations to identify priority areas for soil and water conservation ecological compensation in Ningxia, providing scientific guidance for regional compensation practices.

1.1 Study Area Overview

Ningxia is located in northwestern China, geographically positioned between 104°17 -107°39 E and 35°14 -39°23 N. It borders Shaanxi Province to the east, Inner Mongolia to the west and north, and Gansu Province to the south, covering a total area of 6.64$\times10^{4}$ km^2. The region comprises five prefecture-level cities and 22 districts and counties. The terrain elevation ranges from 950 to 3,546 m, sloping gradually from southwest to northeast. Climate transitions from semi-arid to semi-humid from north to south, with average annual precipitation increasing from 180 mm to 650 mm. The Yellow River enters through Zhongwei City, flows northeast across the plain, and exits through Shizuishan City.

Based on geographical factors, Ningxia can be divided into two major functional zones: the high-quality development zone of the Yellow River Basin in northern Ningxia and the soil and water conservation functional zone in southern Ningxia (Figure 1). The northern Yellow River Basin high-quality development zone features abundant agricultural resources, irrigation-based oases, and an arid climate. The southern soil and water conservation zone has relatively abundant rainfall resources, with vegetation dominated by forests and grasslands.

[Figure 1: see original paper]

1.2 Methods

1.2.1 Soil and Water Conservation Service Value Accounting Considering the national carbon neutrality strategic goals and the substantial carbon sequestration potential of soil and water conservation measures, this study incorporates carbon storage calculations into soil and water conservation service value estimation:

$$V_{\text{total}} = V_{\text{water}} + V_{\text{soil}} + V_{\text{carbon}}$$

where V_{total}, V_{water}, V_{soil}, and V_{carbon} represent the total soil and water conservation value, water retention value, soil conservation value, and carbon storage value, respectively, all in yuan.

The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model, developed by Stanford University and partner institutions, effectively quantifies and assesses regional ecosystem service functions. Following the *Technical Guidelines for Gross Terrestrial Ecosystem Product (GEP) Accounting* compiled by the Ministry of Ecology and Environment, we employed this model to evaluate soil and water conservation service quantities in Ningxia and converted them to monetary values.

1.2.1.1 Water Retention

Water Retention Quantity Calculation: Based on the water balance principle for calculating regional water yield, water retention was computed as follows:

$$\text{Retention} = \min(1, 249 \times K_{\text{sat}}/\text{Velocity}) \times \min(1, 0.9 \times \text{TI}) \times \text{Yield}$$

where Retention is water retention quantity (mm); Velocity is the flow velocity coefficient based on land use type empirical values; TI is the topographic index; K_{sat} is soil saturated hydraulic conductivity ($\text{mm} \cdot \text{day}^{-1}$), calculated using soil texture data; and Yield is annual water yield.

Water Retention Value Calculation: Due to the spillover nature of water retention benefits, which cannot spontaneously generate exclusive returns, its value was calculated using water prices from hydraulic engineering projects. Following the *Technical Regulations for Evaluation of Ecological Benefits of Forestry Ecological Engineering* (DB11/T 1099—2014):

$$V_{\text{water}} = \text{Retention} \times C$$

where V_{water} is water retention value ($\text{yuan} \cdot \text{ha}^{-1}$), Retention is water retention quantity ($\text{m}^3 \cdot \text{ha}^{-1}$), and C is the unit reservoir construction cost. Based on Ningxia' s consumer price index data, the 2020 engineering cost was calculated as 5 $\text{yuan} \cdot \text{m}^{-3}$, with 2020 as the baseline year.

1.2.1.2 Soil Conservation

Soil Conservation Quantity Calculation: This module calculates each plot' s capacity to maintain soil fertility, reduce sedimentation, and prevent land abandonment. Based on the Universal Soil Loss Equation, it quantifies regional erosion and soil conservation amounts:

$$Q = R \times K \times \text{LS} \times (1 - C \times P)$$

where Q is soil conservation quantity; R is rainfall erosivity factor ($\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{yr}^{-1}$), calculated using the rainfall erosivity model proposed by Zhang et al. [?]; K is soil erodibility factor ($\text{t} \cdot \text{ha} \cdot \text{h} \cdot \text{ha}^{-1} \cdot \text{MJ}^{-1} \cdot \text{mm}^{-1}$), sourced from the Pan-Third Pole Environmental Big Data Platform; LS factor is derived from topographic calculations; C is crop management factor; and P is soil and water conservation practice factor.

Soil Conservation Value Calculation: Using market value, opportunity cost, and shadow engineering methods, soil conservation service value was quantitatively assessed per hydrological response unit (HRU):

$$V_{\mathrm{soil}} = E_1 + E_2 + E_3 = 0.24 \times \sum_{i=1}^{3} B_i \times C_i \times D_i + p \times h \times \sum_{i=1}^{3} B_i \times C_i \times D_i + D \times \rho$$

where V_{soil} is total soil conservation value (yuan); E_1, E_2, and E_3 represent values for maintaining soil fertility, reducing land abandonment, and reducing sedimentation, respectively; B_i is average content of nitrogen, phosphorus, and potassium in soil (0.17%, 0.06%, 1.40%); C_i is conversion coefficient to corresponding fertilizers (urea, calcium superphosphate, potassium chloride) (1.40, 1.63, 1.36); D_i is market price of fertilizers from national market data (2,350 yuan $\cdot$ ton^{-1}); p is opportunity cost per unit land area (5 yuan); h is soil bulk density (1.25 g $\cdot$ cm^{-3}); ρ is sedimentation coefficient; and D is reservoir construction cost.

1.2.1.3 Carbon Storage

Carbon Storage Quantity Calculation: Total carbon storage comprises aboveground biomass, belowground biomass, dead organic carbon, and soil carbon. Based on carbon storage in different land use types:

$$\mathrm{CS} = (C_{\mathrm{above}} + C_{\mathrm{below}} + C_{\mathrm{dead}} + C_{\mathrm{soil}}) \times P$$

where CS is total regional carbon storage (t $\cdot$ ha^{-1}); C_{above}, C_{below}, C_{dead}, and C_{soil} represent aboveground, belowground, dead organic, and soil carbon storage (t $\cdot$ ha^{-2}), respectively; and P is the 2020 regional soil and water conservation rate.

Carbon Storage Value Calculation:

$$V_{\mathrm{carbon}} = \mathrm{CS} \times S$$

where V_{carbon} is total carbon storage value (yuan) and S is carbon trading price, using the 2020 price from the Carbon Emissions Trading Center (28 yuan $\cdot$ ton^{-1}).

1.2.2 Soil and Water Conservation Ecological Compensation Priority Area Identification Method To refine the identification of regional compensation zones, this study evaluates at the county scale from two dimensions: ecological compensation priority (ECPS) and ecological vulnerability index. First, compensation priority levels are divided into 0–30%, 30–60%, and 60–100% ranges based on ECPS scores. Second, ecological vulnerability degrees are classified using the natural breaks method. Finally, a scoring matrix combines ECPS and vulnerability to determine each county's compensation urgency (Table 1), with higher scores indicating greater priority for compensation.

1.2.2.1 Ecological Compensation Priority Calculation

This study introduces the ECPS concept, adapting soil and water conservation value to regional GDP to measure local compensation capacity and evaluate compensation urgency:

$$E_i = \frac{V_i}{q_i}$$

where E_i is the ECPS for region i; V_i is unit-area soil and water conservation service value (yuan $\cdot$ ha^{-2}); and q_i is unit-area GDP (yuan $\cdot$ ha^{-2}). Higher E_i indicates greater urgency for compensation due to insufficient local capacity to realize conservation value; lower values indicate less urgency.

1.2.2.2 Ecological Vulnerability Index Calculation

The ecological vulnerability degree—sensitivity—resilience framework evaluates regional ecological vulnerability [?, ?]. Nine indicators were selected across three target levels: population and economic activity pressures reflect human impacts; elevation, slope, and relief amplitude reflect terrain conditions; vegetation coverage and soil erosion intensity represent surface and soil factors; landscape diversity, soil organic matter, and biological abundance reflect ecological recovery status.

$$\text{EVI} = \sum_{i=1}^{n} P_i \times W_i$$

where EVI is ecological vulnerability index; P_i is score for each indicator; W_i is indicator weight; and n is total number of indicators.

1.3 Data Sources

Land use data (2020) were obtained from the Resources and Environmental Data Center of the Chinese Academy of Sciences. Meteorological data were sourced from the China Meteorological Data Sharing Service Network. Soil data came from the Harmonized World Soil Database (HWSDv1.2) of the Food and Agriculture Organization. Vegetation coverage data were obtained from the National Earth System Science Data Center. Social and economic data were derived from the Ningxia Statistical Yearbook.

2. Results and Analysis

2.1 Soil and Water Conservation Service Value Assessment

From 2000 to 2020, total water retention, soil conservation, and carbon storage in Ningxia were 18.63$×10^{8}$ m^3, 23.6$×10^{8}$ t, and 20.9$×10^{8}$ t, respectively. Spatial distributions of water retention and soil conservation were similar, showing a "high in south, low in north" pattern (Figure 2). Carbon storage hotspots were located in the Yellow River corridor and southern Ningxia hilly areas. In 2020, the southern soil and water conservation functional zone contributed 24×10^{8} m^3 water retention, 21.1×10^{8} t soil conservation, and 6.5×10^{8} t carbon storage, while the northern high-quality development zone contributed only 1.3×10^{8} m^3, 5.0×10^{8} t, and 2.5×10^{8} t, respectively—demonstrating substantial north-south disparities.

Total soil and water conservation service values were 247.89 billion yuan, 266.17 billion yuan, and 295.85 billion yuan for 2000, 2010, and 2020, respectively, showing an overall increasing trend. Water retention values were 153.9 billion, 140.12 billion, and 193.14 billion yuan; soil conservation values were 90.84 billion, 91.41 billion, and 78.46 billion yuan; and carbon storage values were 3.15 billion, 34.64 billion, and 24.25 billion yuan. Spatial distribution gradually increased from north to south, with high-value areas concentrated south of Tongxin County, medium-value areas in northern Ningxia and central Hongsipu and Yanchi counties, and low-value areas elsewhere.

[Figure 2: see original paper]

2.2 Soil and Water Conservation Ecological Compensation Priority

From 2000 to 2020, dynamic ECPS values showed minimal fluctuation across districts and counties (Figure 3). Jingyuan County consistently exhibited the highest compensation urgency (Table 3), with 2020 unit-area value of $1{,}636\times10^{4}$ yuan $\cdot$ km^{-2} but GDP of only 248.06×10^{4} yuan $\cdot$ km^{-2} —indicating a strong negative correlation between ecosystem service value and economic development. Jinfeng District showed the lowest priority, with GDP of 104.893 billion yuan $\cdot$ km^{-2} but service value of only 20.93×10^{4} yuan $\cdot$ km^{-2}.

[Figure 3: see original paper]

2.3 Ecological Vulnerability Assessment

Ecological vulnerability in Ningxia showed significant spatial heterogeneity, decreasing from south to north (Figure 4). Southern mountainous areas exhibited high vulnerability, while northern plains showed low vulnerability. The nine evaluation indicators revealed that terrain factors and vegetation coverage were primary drivers of vulnerability differences.

[Figure 4: see original paper]

2.4 Characteristics of Soil and Water Conservation Ecological Compensation Priority Areas

Integrating ECPS and ecological vulnerability, Ningxia' s compensation zones were classified into four types (Figure 5; Table 4). Priority compensation areas cover 63.95% of the region' s land area, with total soil and water conservation value of 189.22 billion yuan but only 20.6% of GDP. These areas are mainly distributed in southern Ningxia with rugged terrain, where soil erosion affects 25,800 km^2. Without intervention, this could cause persistent, irreversible impacts. These counties should receive priority funding to maintain high conservation values and enhance regional functions.

[Figure 5: see original paper]

Secondary compensation areas are located in Shapotou and Yuanzhou districts, covering 8,132 km^2 (12.24% of area) with 45.55 billion yuan in conservation value (15.39%). These areas also suffer serious soil erosion, accounting for 18.7% of the region' s total. With medium development potential, they should receive secondary funding after priority areas are compensated.

General and potential compensation areas are mainly in central and northern Ningxia, covering 23.81% of the area. Due to high industrialization and urbanization, these areas have low conservation value (61.08 billion yuan, 20.6%) but high economic contribution. They are inefficient compensation zones to be considered only when funds are abundant.

3. Discussion

Quantitative assessment of soil and water conservation service values is fundamental for measuring environmental quality and ecological compensation. Value levels largely depend on regional natural conditions and intrinsic ecosystem functions. In Ningxia, the southern mountainous and hilly terrain with extensive forest and grassland cover yields high conservation values, while the northern and central plains along the Yellow River, dominated by construction and cropland with low vegetation cover, yield low values. Thus, conservation value calculation is essential for identifying compensation zones.

This study analyzed dynamic ECPS indices from 2000–2020 based on conservation values and economic development. Priority indices remained relatively stable, with the highest value county (Jingyuan) being approximately 100 times that of the lowest (Xingqing District). These differences are constrained by natural ecosystem attributes, geography, and climate. Priority zones face limited development opportunities due to ecological protection responsibilities, while low-priority zones focus more on economic development with fewer ecological constraints. According to the beneficiary-pays principle, appropriately redistributing funds from economically advanced areas to lagging ecological zones facilitates high-quality transformation from ecological to economic value.

The rationale for identifying priority compensation areas is to allocate limited funds rationally to regions with high conservation value but backward economies. Since natural geography significantly influences ecosystem services and social development, we incorporated ecological vulnerability to improve compensation accuracy and maximize benefits. Priority compensation areas are predominantly forested, providing stronger conservation functions and greater values, yet sacrificing development opportunities. With sparse populations and poor conditions, these areas face prominent contradictions between ecological value and economic development, urgently requiring compensation support. Our ECPS method effectively identifies the most critical compensation areas, suggesting that funds from economically surplus districts should support those in urgent need, ensuring dynamic balance between ecological and economic resources.

4. Conclusions

1) From 2000 to 2020, Ningxia' s total soil and water conservation service values were 247.89 billion yuan, 266.17 billion yuan, and 295.85 billion yuan, respectively, showing an overall increasing trend. Spatial distribution gradually increases from north to south, with the highest unit value in Jingyuan County reaching 2,480$×10^{4}$ yuan·km^{-2}—approximately 100 times that of the lowest-value Xingqing District. These differences are primarily constrained by natural ecosystem attributes, geography, and climate.

2) Based on the ECPS classification method, Ningxia' s counties were divided into four compensation priority levels. Priority areas (Level I) are distributed in southern Ningxia with high conservation value and lagging economic development, urgently needing compensation. Low-priority areas (Level IV) are in central and northern Ningxia with low conservation value and high economic development, showing low compensation urgency. Levels II and III have medium conservation values and economic development, with moderate compensation urgency.

3) Priority and secondary compensation areas are mainly distributed in southern and central Ningxia, covering 76.19% of the region' s area. These areas contribute high conservation values but face high ecological vulnerability risks; however, lagging economic development limits their potential ecological value realization. They should receive priority funding. General and potential compensation areas are inefficient compensation zones where over-compensation may occur; their ecological issues warrant attention.

References

[1] Lu Y, Zhang L, Feng X, et al. Recent ecological transitions in China: greening, browning and influential factors[J]. Scientific Reports, 2015, 5: 8732.

[2] De Groot R, Brande L, Ploeg S, et al. Global estimates of the value of ecosystem and their services in monetary units[J]. Ecosystem Services, 2012, 1(1): 50-61.

[3] Farley J, Costanza R. Payments for ecosystem services: From local to global[J]. Ecological Economics, 2010, 69(11): 2060-2068.

[4] Costanza R, De Groot R, Farber S, et al. The value of the world ecosystem services and natural capital[J]. Nature, 1997, 387(6630): 253-260.

[5] Zhao Jianlin, Dong Zhiyang, Chang Zhaofeng. Ecological compensation of a desert water lifting irrigation project based on opportunity cost of ecosystem service value: A case study on Jingtaichuan Water Lifting Irrigation Project[J]. Arid Zone Research, 2019, 36(3): 743-751.

[6] Wang C D, Li W Q, Sun M X, et al. Exploring the formulation of ecological management policies by quantifying interregional primary ecosystem service flows in Yangtze River Delta region, China[J]. Journal of Environmental Management, 2021, 284: 112042.

[7] Sun L N, Lu W X, Yang Q C, et al. Ecological compensation estimation of soil and water conservation based on cost benefit analysis[J]. Water Resources Management, 2013, 27(8): 2709-2727.

[8] Xiong Y, Wang K L. Eco compensation effects of the wetland recovery in Dongting Lake area[J]. Journal of Geographical Sciences, 2010, 20(3): 389-405.

[9] Guo Niandong, Li Hengzhe, Li Chao, et al. Regional ecological compensation based on ecosystem service value in the area surrounding Beijing and Tianjin[J]. Chinese Journal of Eco Agriculture, 2015, 23(11): 1473-1480.

[10] Yan Youlong, Wang Jun, Wang Jinman. Study on eco-compensation thresholds of Min River basin based on ecosystem services[J]. China Land Science, 2021, 35(3): 97-106.

[11] Gao Zhenbin, Wang Xiaoli, Su Jing, et al. Ecological compensation of Dongjiang River basin based on evaluation of ecosystem service value[J]. Journal of Ecology and Rural Environment, 2018, 34(6): 563-570.

[12] Hu Ying, Feng Xiaoming, Gong Jie. Coordination analysis of the nature and social economic system of Ningxia Hui Autonomous Region based on ecosystem services[J]. Acta Ecologica Sinica, 2022, 42(16): 6523-6533.

[13] Wei Dong, Yang Yang, Ni Xilu, et al. Regional forest ecosystem services assessment: A case study of Ningxia Hui Autonomous[J]. Journal of Northwest Forestry University, 2018, 35(3): 278-284.

[14] Huang Yueyue, Yang Dong, Feng Lei. Spatiotemporal distributions of vegetation index and climatic productivity in Ningxia in recent years[J]. Journal of Hydroelectric Engineering, 2019, 38(11): 70-81.

[15] Sharp R, Chaplin Kramer R, Wood S, et al. InVEST 3.9.0 User Guide[EB/OL]. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund, 2020.

[16] Chinese Academy of Environmental Planning, Research Center for Eco-Environmental Sciences, CAS. Gross Terrestrial Ecosystem Product Accounting Technical Guidelines (20201654-T-469)[S]. Beijing: China Standards Press, 2020.

[17] Richard G Allen, Luis S Pereira, Dirk Raes. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements—FAO Irrigation and Drainage Paper 56[M]. Rome: FAO Food and Agriculture Organization of the United Nations, 1998.

[18] Jia Yufan, Wang Guoqing. Assessment of water conservation capacity of Yiluo River basin based on the InVEST model[J]. Journal of Soil and Water Conservation, 2023, 37(3): 101-108.

[19] Tian Yichao, Bai Xiaoyong, Huang Yuanlin, et al. Ecological compensation standard accounting of Chishui River Basin based on ecosystem service value[J]. Transactions of the Chinese Society for Agricultural Machinery, 2019, 50(11): 312-322.

[20] Zhang Wenbo, Fu Jinsheng. Rainfall erosivity estimation under different rainfall amount[J]. Resources Science, 2003, 27(1): 35-41.

[21] Yang Miaomiao, Yang Qingke, Zhang Keli, et al. Effects of content of soil rock fragments on calculating of soil erodibility[J]. Acta Pedologica Sinica, 2021, 58(5): 1157-1168.

[22] Yang Qinke. Soil Erodibility Dataset of Pan Third Pole (20 Countries) (2020, with a resolution of 7.5 arc second)[DB/OL]. National Tibetan Plateau Scientific Data Center, 2021.

[23] Desment P J, Govers G. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units[J]. Journal of Soil and Water Conservation, 1996, 51(5): 427-433.

[24] Wang Bei, Zhao Jun, Hu Xiufang. Analysis on trade-offs and synergistic relationships among multiple ecosystem services in the Shiyang River Basin[J]. Acta Ecologica Sinica, 2018, 38(21): 7582-7595.

[25] Zhu Qing, Zhou Zixiang, Liu Ting, et al. Vegetation restoration and ecosystem soil conservation service value increment in Yanhe Watershed, Loess Plateau[J]. Acta Ecologica Sinica, 2021, 41(7): 2557-2570.

[26] Wu Na, Song Xiaoyu, Kang Wenhui. Standard of payment for ecosystem services in a watershed based on InVEST model under different standpoints: A case study of the Weihe River in Gansu Province[J]. Acta Ecologica Sinica, 2018, 38(7): 2512-2522.

[27] Liu Yang, Zhang Jun, Zhou Dongmei, et al. Temporal and spatial variation of carbon storage in the Shule River Basin based on InVEST model[J]. Acta Ecologica Sinice, 2021, 41(10): 4052-4065.

[28] Xue Zhuobin. The Assessment of Ecosystem Services Functions in Yanhe River Based on the InVEST Model[D]. Xi' an: Northwest University, 2017.

[29] Ningxia Water Conservancy. Ningxia Hui Autonomous Region 2020 Soil and Water Conservation Bulletin[R]. 2020.

[30] Jin Lijuan, Xu Quanli. Ecological vulnerability assessment of Sichuan Province based on SRP model[J]. Ecological Science, 2022, 41(2): 156-165.

[31] Li Yonghua, Fan Qiang, Wang Xue, et al. Spatial and temporal differentiation of ecological vulnerability under the frequency of natural hazard based on srp model: A case study in Chaoyang County[J]. Scientia Geographica Sinica, 2015, 35(11): 1452-1459.

[32] Li Jiao, Li Lang, Wang Jie, et al. Priority areas recognition of ecological compensation for soil and water conservation: Taking Dongting Lake eco-economic zone as an example[J]. Journal of Ecology and Rural Environment, 2021, 37(4): 474-483.

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