# COMPREHENSIVE EVALUATION OF ECOSYSTEM BENEFITS AND RESTORATION STRATEGIES—A CASE STUDY IN HUOZHOU, CHINA

He, J. Y.[1] – Ding, G. M.[2] – Wang, S.[1*] – Wang, J. F.[1] – Jin, R. X.[1]

[1]*School of Geographical Science, Shanxi Normal University, Taiyuan 030031, PR China*

[2]*The Management Center of Qilian Mountain National Nature Reserve in Gansu Province, Zhangye 734000, PR China*

[*]*Corresponding author*
*e-mail: wangsheng@sxnu.edu.cn*

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**Abstract.** In recent years, global ecosystems have generally degraded, which not only directly threatens the stability of the support system for earth life, but also profoundly affects the sustainable development and well-being of human society. As a highly ecologically sensitive area with a high intensity of human disturbance and a fragile natural environment in China, Huozhou City urgently needs to carry out a comprehensive evaluation of ecosystem benefits to provide scientific guidance for the coordinated development of natural ecology and the social economy. In this study, numerical simulations were used as the core means, and a comprehensive evaluation system covering natural background indicators (land use structure, vegetation coverage, landscape fragmentation) and ecosystem service indicators (water yield, soil retention, carbon sequestration, habitat quality) was constructed to quantitatively assess the spatio-temporal evolution of comprehensive ecosystem benefits in Huozhou City from 2003 to 2023, and targeted ecological restoration strategies were proposed. The results showed that: (1) Farmland, construction land, and forests in Huozhou City increased from 2003 to 2023, mainly converted from grassland. The landscape fragmentation index increased by 0.002, while vegetation coverage decreased by 0.179. (2) Ecosystem services declined over the past 20 years, with water yield, soil conservation and the habitat quality index decreasing by 91.89 mm, 46.51 t $hm^{-2}$ and 0.081, respectively, while the range of variation in carbon sequestration was relatively small. (3) The comprehensive ecosystem benefit index (CEBI) declined significantly, from 0.354 in 2003 to 0.284 in 2023. The areas with high CEBI were located in the northeastern forest belts, while the low-value areas were distributed along the southwestern industrial and mining belts, which was in line with the direction of grid-based expansion of construction land. In the future, an ecological restoration strategy of "zonal restoration, industrial and mining constraints, and natural recovery" should be adopted in Huozhou City. This study will provide a quantitative scale and scientific reference for the restoration of high-pressure ecosystems caused by human activities.
**Keywords:** *ecosystem services, ecological restoration, effectiveness evaluation, InVEST model, Huozhou City*

## Introduction

At present, the global ecosystem is undergoing an unprecedented degradation, mainly manifested as intensified land desertification, sharp decline in biodiversity, pollution and shortage of water resources, continuous decline of forest coverage, and significant weakening of key ecosystem services. The severe trend not only directly threatened the support system stability of earth lives, but also profoundly affects the sustainable development and well-being of human society (Metzger et al., 2006). As a developing country with large population, huge economic volume and complex natural environment, the ecosystem in China faces particularly prominent challenges (Zhu and Cai, 2023), especially the Loess Plateau in northern China. Due to the rapid industrialization and urbanization process, various ecological problems, such as soil erosion, air pollution, water resources shortage and biological habitat loss are emerging in a concentrated manner (Fu et al., 2017), which make the Loess Plateau a typical region for studying the pressure, driving factors, and response strategies of ecosystem degradation.

In view of the ecological problems on the Loess Plateau, scholars have focused on ecosystem assessment and ecological restoration. In the hilly and gully areas of the Loess Plateau, Yang et al. (2022) found that multiple ecosystem services had been significantly enhanced as the vegetation restorations, and the main reasons were the implementations of the Grain for Green Project. As a typical ecologically fragile area on the Loess Plateau, the areas with high ecological risks were distributed in the central and southwestern of the Fen River Basin; while the areas with low ecological risks were located in the northern, eastern and western parts (Wang et al., 2025b). Both high-risk and low-risk areas exhibited significant spatial agglomeration effects. Using the InVEST model and the CA-Markov model, Wang et al. (2023) analyzed the spatio-temporal evolution of habitat quality on the Loess Plateau, and explored the impacts of natural factors, human activities and multi-factor landscape patterns on habitat quality. Tu et al. (2024) quantitatively evaluated the relationship between supply and demand of ecosystem services on the Loess Plateau from 2000 to 2020, and proposed ecological restoration zoning and corresponding optimization strategies.

As the core area of the Loess Plateau and the energy-intensive chemical industry base, Shanxi Province has long been confronted with “dual ecological shackles”: On the one hand, the natural vulnerability (e.g. soil erosion and vegetation degradation) is deeply imprinted on the loess gully landscape. On the other hand, the high-intensity coal mining has triggered surface subsidence, groundwater depletion, and sharp decline in biodiversity, making this region a typical sample of the dual accumulation of “ecological resource” contradictions (Omer et al., 2021). By constructing the targeted assessment system for ecosystem services in Shanxi Province. Wang et al. (2024) found that the water conservation, sand fixation, environmental purification, and habitat quality in the loess hilly area of western Shanxi have improved, while the comprehensive ecosystem services in the eastern and central Shanxi tended to deteriorate. Chen et al. (2025) quantified four key ecosystem services and their driving factors in Shanxi Province, and clarified the trade-off/synergy relationships among ecosystem services. However, whether in the Loess Plateau or Shanxi Province, existing studies have paid more attention to regions dominated by natural environments due to the difficulty in quantifying the human activities disturbance on ecosystems, the studies on quantitative assessment and restoration strategies of ecosystem benefits in the ecologically fragile areas subject to dual disturbances from natural environment and human activities are relatively weak.

As a major heavy industrial zone and coal base in Shanxi Province and even in China, Huozhou City has an annual coal output of approximately 15 million tons. The high-intensity industrial activities have caused numerous ecological issues. Huozhou City has become a typical ecologically fragile area with dual disturbances from natural environments and human activities. An assessment of the ecological restoration effectiveness was urgently needed. In view of this, an assessment system covering natural background elements and ecosystem services for the comprehensive ecosystem benefits was constructed in Huozhou City. The natural background elements included land use structure, vegetation and soil parameters, and landscape patterns, and the multi-dimensional ecosystem services indicators included water yield, soil conservation, carbon sequestration, and habitat quality. Then the spatio-temporal evolution of comprehensive ecosystem benefits from 2003 to 2023 was analyzed, and the targeted strategies for ecological restoration were proposed, with the aim of providing references and


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suggestions for the rational utilization of land and the ecological civilization construction in China, thereby promoting the transformation and upgrading of industries and the sustainable development of the social economy, and providing a quantitative benchmark for the restoration of high-pressure ecosystems by human activities.

## Materials and methods

### *Study area*

Huozhou City (36°26′-36°47′ N, 111°37′-112°02′ E) is located in the southern Shanxi Province, China, and serves as a transitional zone connecting the Jinzhong Basin and the Linfen Basin (*Fig. 1*). The land surface is covered with a thick loess layer, and the terrain exhibits significant gradational, transitional and complex features: the eastern part is a steep medium and low mountainous area with Taiyue Mountain (Huo Mountain) as the main body, the loess hills and residual plateaus are widely spread in the central area with severe soil erosion, an open and flat alluvial plain along the axis of the Fen River is distributed in the western (Tang et al., 2020). It is the warm temperate semi-arid climate in Huozhou City, with concentrated precipitation in summer and large inter-annual variations. The tributaries of the Fen River in the area are mostly seasonal rivers. The soil is mainly poor brown soil, with organic matter decreasing from the northeast to the southwest, the organic matter content ranges from 0.29 to 3.94 grams. The vegetation has degraded into sparse shrub and grassland, presenting typical ecologically fragile characteristics. The permanent population of Huozhou City is approximately 270000, with medium urbanization rate and profound cultural heritage. Huozhou is a typical resource-based city. The economy is highly dependent on coal resources, with coal mining and coal chemical industry as pillar industries. Long-term high-intensity coal mining has led to large-scale ecological degradation, such as surface subsidence destroying a large number of farmlands, significant drop in groundwater level, water resource shortage and pollution, and intense landscape fragmentation, etc. Recently, Huozhou City is facing the challenges of transformation and development from the single industrial structure.

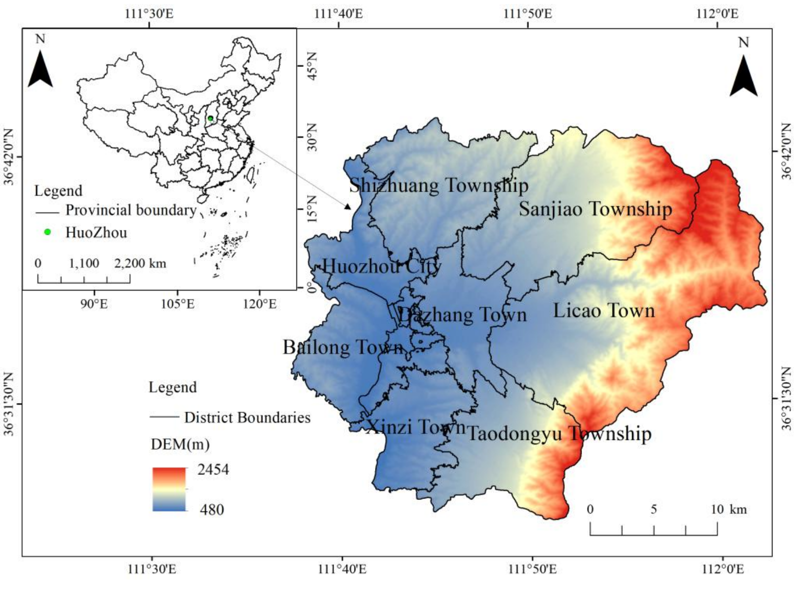


***Figure 1.*** *Geographical location and altitude of Huozhou City*


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## *Data sources*

The meteorological data used in this study were obtained from the National Tibetan Plateau Data Center, including monthly precipitation (Peng, 2020), potential evapotranspiration (Peng, 2022). The datasets were interpolated into the grid maps with a spatial resolution 100 m × 100 m (Ding and Peng, 2020). Remote sensing data included land use, vegetation coverage, digital elevation model (DEM), and soil data. The land use in 2003, 2013, and 2023 was from the "China 30-meter Annual Land Cover Dataset and Its Dynamic Changes (CLCD)", which was generated by the Google Earth Engine (GEE) platform. The original land use types were divided into 9 categories: farmland, forest, shrub, grassland, water, ice and snow, bare land, impermeable surface, and wetland (Yang and Huang, 2021). Vegetation coverage data was obtained through pre-processing of Landsat images. The DEM was from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution 30 m×30 m, which was used for the terrain factors analysis such as elevation and slope. Landsat images and DEM were both sourced from the Geospatial Data Cloud (http://www.gscloud.cn). Soil dataset was collected from the Second National Land Survey of China and downloaded from the National Tibetan Plateau Data Center. The original data was the 1:1000000 soil maps provided by the Institute of Soil Science, Chinese Academy of Sciences (Zhang and Zhang, 2012), which was used to calculate soil depth, soil erodibility factors, and plant available water content. All the raster maps were clipped using the standard map boundaries of China, and the unified spatial resolution was 100 m×100 m, with the coordinate system reprojection as CGCS2000_3_Degree_GK_Zone_37.

## *Methods*

### *Construction of the comprehensive ecosystem benefits index system*

In response to the ecological issues such as vegetation reduction, soil erosion, and biological habitats loss in Huozhou City, a comprehensive index system including three natural background elements (land use, vegetation coverage, and landscape fragmentation) and four key ecosystem services (water yield, soil conservation, carbon sequestration, and habitat quality) were constructed. The target layer was the comprehensive ecosystem benefits, and the criterion layer included natural background elements and key ecosystem services (*Table 1*). To quantify the impacts of various natural background elements and ecosystem services, the Analytic Hierarchy Process (AHP) method was used to determine the weights of target layer, criterion layer, and index layer. A judgment matrix was used to calculate the maximum eigenvalue ($\lambda_{max}$) and the corresponding eigenvector ($\omega$). The weights of each factor were obtained through normalization of the eigenvectors (*Table 1*). The results were subjected to consistency testing, which met the test standards (Gao et al., 2016).

### *Assessment methods for comprehensive ecosystem benefits*

The land use change is evaluated using a single land use dynamic index. The index can represent the quantitative variations in different land use types within the study area over a certain time period. Vegetation coverage is usually defined as the percentage of the vertical projection area of vegetation (including leaves, stems, and branches) on the ground to the total area, which could be calculated from the band calculation of remote sensing images. Firstly, the images covering Huozhou City in 2003, 2013, and 2023 were


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radiometrically calibrated and atmospherically corrected, then the target area was masked and cropped, at last, the three-phase vegetation coverage data were obtained through band calculation (Wang et al., 2022). Landscape fragmentation (patch density) is an indicator reflecting the degree of patch fragmentation in the landscape, which can be calculated by the ratio of land use type patches numbers to the total patch area (Fischer and Lindenmayer, 2007).

***Table 1.*** *Comprehensive ecosystem benefits index system and weights*

| Target layer | Criterion layer | Index layer | Weight (%) |
|---|---|---|---|
| Comprehensive ecosystem benefits index | Natural background elements | Land use | 6.26 |
| | | Vegetation coverage | 5.54 |
| | | Landscape fragmentation | 5.17 |
| | Ecosystem services | Water yield | 27.60 |
| | | Soil conservation | 29.81 |
| | | Carbon sequestration | 12.90 |
| | | Habitat quality | 12.72 |

Using relevant modules in the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), four key ecosystem services (water yield, soil conservation, carbon sequestration, and habitat quality) in Huozhou City were assessed. The detailed methods and principles (Sharp et al., 2015) are shown in *Table 2*.

The software used in this study for calculating and preparing charts and maps is Arcgis.

***Table 2.*** *Assessment methods and principles of ecosystem services*

| Index layer | Evaluation indicators | Methods | Principles | References |
|---|---|---|---|---|
| Water yield | Water yield volume | Water yield module | Water balance equation | Budyko, 1974 |
| Soil conservation | Soil conservation volume | Sediment delivery ratio module | Revised universal soil loss equation (RUSLE) | Wischmeier and Smith, 1965 |
| Carbon sequestration | Carbon sequestration volume | Carbon module | Ecosystem carbon storage is divided into aboveground, underground, soil and dead organic carbon reservoir, the average carbon density of above four carbon reservoirs are calculated based on different land use types. By multiplying the area of each land use type by its carbon density, total carbon storage is obtained by summing them up | Wang et al., 2025a |
| Habitat quality | Habitat quality index | Habitat quality module | Based on land use classification, combined with the habitat suitability, influence distance and weight of stress factors, and sensitivity assessment of each habitat type to stress factors | Zhao et al., 2025 |

## Results

### *Natural background elements*

The current status and variation of land use in Huozhou City in 2003, 2013 and 2023 were shown in *Figure 2* and *Table 3*. The main land use types in Huozhou City were


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farmland, forest land, grassland and impervious water surfaces (construction land), while the areas of shrubs and water bodies were small and scattered (*Fig. 2*). From 2003 to 2023, farmland, forest land, construction land, shrubs and water bodies in Huozhou City all showed an increasing trend, while the grassland showed a decreasing trend. The farmland presented the largest increase, which was from 263.3 km$^2$ in 2003 to 353.52 km$^2$ in 2023, with an increase of 90.23 km$^2$. As the rapid advancement of urbanization, construction land continued to expand, with an increase of 12.29 km$^2$ over 20 years. Forest land showed a slow growth, increasing from 236.02 km$^2$ in 2003 to 244 km$^2$ in 2023. All the increase of above land use types was mostly from the conversion of grassland, resulting in a continuous decrease of grassland. The decreasing rate of grassland was faster from 2003 to 2013, with a total reduction of 75.79 km$^2$, while the rate slowed down from 2013 to 2023, with a reduction of 34.73 km$^2$.

***Table 3.*** *Land use change in Huozhou City from 2003 to 2023*

| Period | Item | Farmland | Forest land | Grassland | Construction land | Shrubland | Wetland |
|---|---|---|---|---|---|---|---|
| 2003 | Area/km$^2$ | 263.30 | 236.02 | 176.75 | 88.46 | 0.89 | 0.04 |
| | Ratio/% | 34.40 | 30.83 | 23.09 | 11.56 | 0.12 | 0.01 |
| 2013 | Area/km$^2$ | 322.85 | 243.78 | 100.96 | 97.56 | 0.22 | 0.06 |
| | Ratio/% | 42.18 | 31.85 | 13.19 | 12.75 | 0.03 | 0.01 |
| 2023 | Area/km$^2$ | 353.52 | 244.00 | 66.23 | 100.75 | 0.89 | 0.06 |
| | Ratio/% | 46.19 | 31.88 | 8.65 | 13.16 | 0.12 | 0.01 |
| 2003-2013 | Area change/km$^2$ | 59.55 | 7.77 | -75.79 | 9.11 | -0.66 | 0.02 |
| | Single dynamic/% | 0.23 | 0.03 | -0.43 | 0.10 | -0.75 | 0.69 |
| 2013-2023 | Area change/km$^2$ | 30.68 | 0.21 | -34.73 | 3.18 | 0.67 | 0.00 |
| | Single dynamic/% | 0.10 | 0.00 | -0.34 | 0.03 | 2.97 | -0.06 |
| 2003-2023 | Area change/km$^2$ | 90.23 | 7.98 | -110.53 | 12.29 | 0.00 | 0.02 |
| | Single dynamic/% | 0.34 | 0.03 | -0.63 | 0.14 | 0.00 | 0.59 |

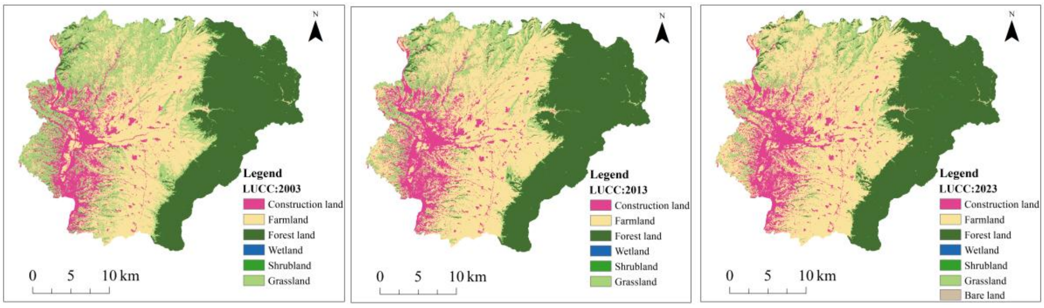


***Figure 2.*** *Spatial-temporal evolution of land use types from 2003 to 2023*

*Figure 3* presented the spatio-temporal evolution of vegetation coverage in Huozhou City from 2003 to 2023. The spatial pattern of vegetation coverage generally showed “high - medium - low” gradient distributions from east to west. Over the past 20-years, the vegetation coverage in Huozhou City showed a continuous decreasing trend, with the average vegetation coverage dropping from 0.465 in 2003 to 0.286 in 2023. Especially in the Taiyue Mountain, the reducing trend of vegetation coverage was more obvious. The deforestation and destruction of forests in the Taiyue Mountain has gradually intensified, resulting in a decline in forest vegetation coverage. In the southwest of Huozhou City, the


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expansion of construction land encroaching on grasslands had continued, and the intensity of mining activities was high, causing a sharp reduction in the grassland in the southwest and central region, and a decrease in vegetation coverage.

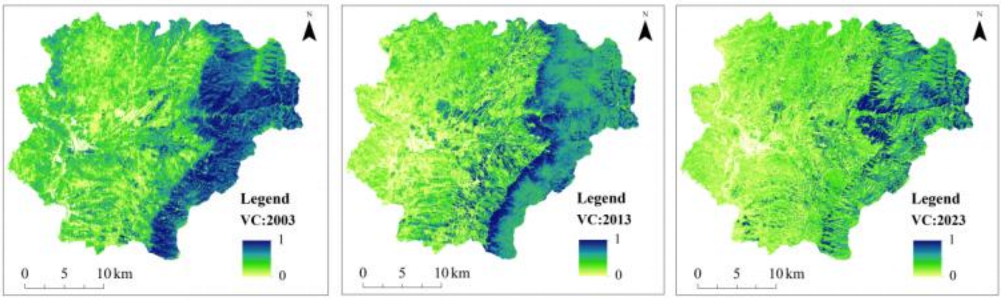


***Figure 3.*** *Spatial-temporal evolution of vegetation coverage (VC) from 2003 to 2023*

The landscape fragmentation in Huozhou City tended to intensify with the patch densities increasing. The landscape fragmentation index had risen from 0.111 to 0.113, indicating an increase in landscape security risks, which was closely related to the expansion of farmland and construction land. The areas with fragmentation index exceeding 0.12 expanded significantly (*Fig. 4*), and the ecological connectivity has obviously weakened. Due to the grid-based division of construction land in the central and southwestern plains, the fragmentation degree has increased significantly, which was related to the high human concentration, frequent industrial and agricultural activities, and high mining intensity. Construction land encroached on grassland and shrubland, leading to the reduction the landscape connectivity and high fragmentation. The forests in Huozhou City were mainly distributed in the Taiyue Mountain, where the fragmentation degree was relatively low. However, due to ecological damage, the eastern forests were facing ecological crises, and the fragmentation degree has increased.

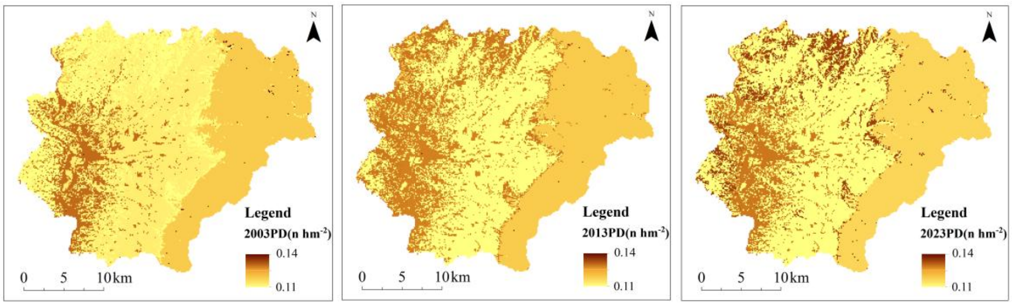


***Figure 4.*** *Spatial-temporal evolution of landscape fragmentation from 2003 to 2023*

### *Ecosystem services*

The spatio-temporal patterns of ecosystem services in Huozhou City in 2003, 2013 and 2023 were shown in *Figure 5*. In the recent two decades, the water yield (WY) in Huozhou City showed the trend of “first decreasing and then increasing” (*Fig. 5a*). Water yield volume in 2003, 2013 and 2023 was 435.99 mm, 318.87 mm and 344.10 mm, respectively. Since 2013, the water yield has rebounded, which was related to ecological restoration measures such as the Grain for Green Project and the reclamation of mining


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zones. Over the past 20 years, soil conservation (SC) and habitat quality (HQ) in Huozhou City have continued to decline (*Fig. 5b, d*), which was consistent with the precipitation reduction and vegetation degradation. The average soil conservation decreased from 164.73 t hm$^{-2}$ in 2003 to 118.22 t hm$^{-2}$ in 2023, with a reduction rate of 28.23%. The habitat quality index decreased from 0.454 in 2003 to 0.373 in 2023, breaking through the ecological crisis threshold of 0.4, and showing a positive correlation with the intensity of mining activities. The variation in carbon sequestration (CS) is relatively small (*Fig. 5c*), with the average annual carbon sequestration of 142 t hm$^{-2}$. The stability of carbon sequestration was related to both the grassland reduction and the increase in forests and farmland.

Spatially, the ecosystem services in Huozhou City exhibited a pattern of "high in the northeast and low in the southwest", and the spatial distribution was sheet-like or band-like. The eastern (especially the northeastern) region provided the best ecosystem services within the Huozhou City. Forest land was the main land use type in the eastern region, which was located in the mountains with high vegetation coverage, and also had low building density and human interference. Farmland is widely distributed in the central region. The agricultural activities play a certain positive effect on ecosystem services, which can be specifically manifested that farmland was often flooded throughout the year, with a stable structure and less soil erosion. The western and southern regions had extensive construction land and residential areas, with highly intensive human activity, frequent mining activities and poor ecosystem services, where exhibited the spatial distribution of "fragmentation" and "marginalization". The ranking of ecosystem services from high to low for different land use types was: Forest land > Grassland > Wetland > Farmland > Construction land > Unused land.

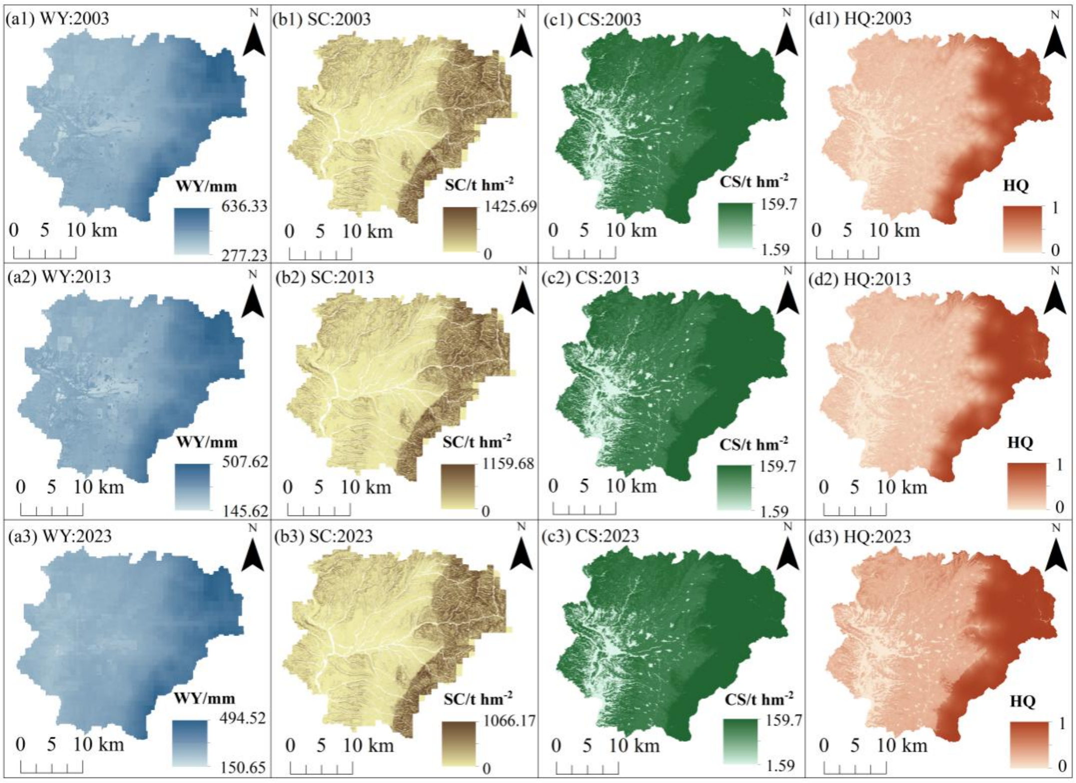


***Figure 5.*** *Spatial-temporal variations of (a) water yield (WY), (b) soil conservation (SC), (c) carbon sequestration (CS) and (d) habitat quality (HQ) in 2003, 2013 and 2023*


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### *Assessment of comprehensive ecosystem benefits*

The spatio-temporal variation of the comprehensive ecosystem benefit index (CEBI) for the Huozhou City was obtained (*Fig. 6*) by the weighted calculation of natural background elements and ecosystem service indicators. The comprehensive ecosystem benefit index in 2003, 2013, and 2023 was 0.354, 0.353, and 0.283, respectively, which showed a trend of “slight decrease - accelerated decline”. From 2003 to 2013, the industrial and mining activities were intense in Huozhou City. Meanwhile, the Grain for Green Project and reclamation of mining zones were also widely carried out, then water and soil conservation and carbon sequestration capabilities were enhanced, which slowed down the decline of comprehensive ecosystem benefits. “Industrialization” and “urbanization” continued to advance with the rapid economic development in 2013-2023. The more frequent mining activities and the construction land expansion led to the ecological landscape fragmentation, vegetation coverage decrease, water yield reduction, and even triggered soil erosion. Spatial differentiation of the comprehensive ecosystem benefit index was obvious, with a general distribution feature of “high in the northeast and low in the southwest”, which was basically consistent with the spatial pattern of ecosystem services. The areas with high CEBI were concentrated in the northeastern forest belts, and the areas with low CEBI spread along the southwestern industrial and mining belts, highly overlapping with the grid-based expansion of construction land. For the different land use types, the forest land in Huozhou City provided the highest comprehensive ecosystem benefit, while the construction land provided the lowest.

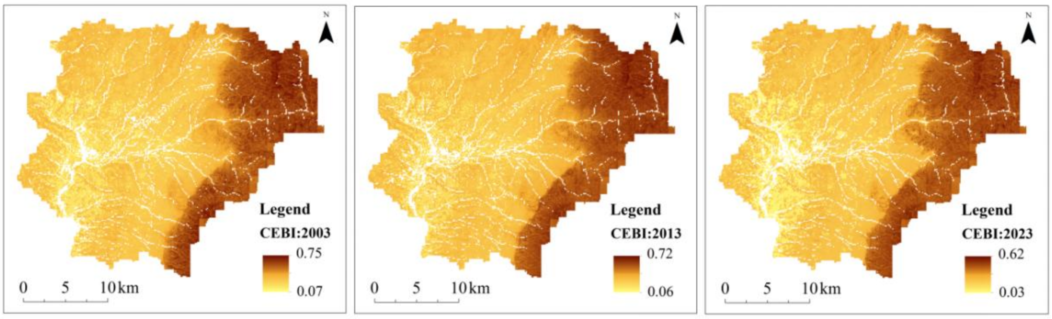


***Figure 6.*** *Spatial-temporal variation of the comprehensive ecosystem benefit index (CEBI) in 2003, 2013 and 2023*

## Discussion

For the natural background elements, the land use types in Huozhou City were mainly farmland, forest land, grassland and construction land. Farmland, forest land and construction land have increased since 2003, which was derived from grassland. It was consistent with the land use changes in Linfen City, which was also located in the middle reaches of the Fen River Basin and was adjacent to Huozhou City (Yang et al., 2024). The land use types in Linfen City were mainly farmland, followed by grassland and forest land. Recently, construction land, forest land and water bodies have increased, which were transferred from grassland. Over the past 20 years, the vegetation coverage in Huozhou City showed a decreasing trend, which was different from the fluctuating upward trend in Shanxi Province (Jia et al., 2024). 44.4% of Shanxi Province presented an improvement in vegetation coverage, with only 7.4% of the area showing significant degradation. The


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vegetation coverage decrease in Huozhou City might be closely related to the construction land expansion, high mining intensity, etc. Huozhou City was a representative ecologically fragile area under the dual disturbances of climate change and human activities.

For the ecosystem services, the construction land expanded, grassland shrunk, the soil conservation capacity decreased and the quality of habitats deteriorated over the past 20 years, which was consistent with the variation of hilly areas of the Loess Plateau (Huang et al., 2016): the intensification of cultivated land directly led to the ecosystem services attenuation. With the increase of human activities intensity index, the habitat quality index decreased significantly. It was worth noting that the case of Huozhou City further highlighted the amplifying effect of industrial and mining disturbances. Compared with the "Grain for Green Project to enhance ecosystem services" in Yulin District of Northern Shaanxi Province (Wang et al., 2021), the ecosystem services declined (e.g., the soil conservation capacity decreased by 28.23%) in Huozhou City although the forests has slightly increased by 7.98 km$^2$. In Shanxi Province, the negative correlation between the carbon emissions and ecosystem service intensity was most significant in energy-based cities. The greater the intensity of coal and steel industries, the stronger the land use carbon emission intensity, and the weaker the ecosystem services (Gao and Cui, 2025).

Huozhou City has vigorously promoted the Grain for Green Project and reclamations in mining zones since 2003, and the negative effect originated from "urbanization" and "industrialization" has gradually diminished (Deng et al., 2014). The implementation of water ecological restoration projects (e.g., the repair of embankments in the Fen River Basin and the prevention and protection projects for severely eroded sections) enhanced the water ecosystem services in the southwestern Huozhou (Liu et al., 2023). Ecological measures such as reforestation and resource protection also improved the environmental quality of Huozhou City. However, soil erosion, vegetation degradation, and water shortage remained the main ecological problems in this region in the past decade. As ecological governance often falls into the scale paradox of "local restoration and overall degradation", it was suggested that the ecological restoration strategy of Huozhou City should shift from improvement of single ecosystem service to optimization of the landscape pattern. For the ecological barrier in the northeast forest belts, mining activities should be strictly prohibited to strengthen the forest connectivity. For the ecological degradation in the southwest industrial and mining zones, a "mining + restoration" pattern should be implemented, and artificial wetlands could be constructed in the subsidence areas to enhance water yield capacity. For the urban-rural transitional zone in the central region, the ecological green space should be embedded into the grid-based construction land to break the positive feedback loop of landscape fragmentation.

## Conclusion

Huozhou City, a major industrial district and coal base in Shanxi Province even China, was a typical ecologically fragile area subjected to dual disturbances from natural environment and human activities. In this study, an assessment system of comprehensive ecosystem benefits was constructed based on natural background elements and key ecosystem services. The temporal and spatial evolution of natural background, ecosystem services, and comprehensive ecosystem benefits in Huozhou City from 2003 to 2023 was quantitative analyzed by using InVEST model, and the targeted strategies for ecological restoration were proposed. Main conclusions were as follows: (1) Land use structure has undergone significant changes. Over the past 20 years, farmland, construction land, and


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forests increased by 90.23, 12.29, and 7.98 $km^2$, respectively, while grassland decreased by 110.53 $km^2$. The landscape fragmentation index increased from 0.111 to 0.113, but the vegetation coverage decreased from 0.465 to 0.286. (2) Water yield showed a trend of "first decrease then increase", with the water yield volume of 435.99, 318.87, and 344.10 mm in 2003, 2013, and 2023, respectively. Soil conservation and habitat quality services declined, with the soil conservation volume and habitat quality index decreasing by 46.51 t $hm^{-2}$ and 0.081 from 2003 to 2023. Carbon sequestration changed little, and the average annual value was 142 t $hm^{-2}$. (3) Comprehensive ecosystem benefit index (CEBI) decreased from 0.354 in 2003 to 0.283 in 2023. The areas with high CEBI were concentrated in the northeastern forest belts, while the areas with low CEBI spread along the southwestern industrial and mining belts, overlapping with the expansion of construction land. (4) Optimizing the landscape pattern is a key ecological restoration strategy in Huozhou City. The northeastern ecological barrier district should strictly prohibit mining activities and strengthen forest connectivity; the southwestern ecological degraded district should implement the "mining + restoration" pattern to enhance water yield capacity; green space should be embedded into construction land in the central urban-rural transitional district. This study will provide scientific reference and practical experience for the rational utilization of land resources and ecological sustainability in other ecological fragile regions worldwide that are strongly disturbed by humans.

**Author contributions.** He Jiayu: Conceptualization, Investigation, Project administration, Supervision, Validation, Writing—review & editing. Ding Guomin: Data curation, Formal analysis, Methodology, Software, Writing—original draft preparation. Wang Sheng: Conceptualization, Formal analysis, Methodology, Resources, Supervision, Visualization. Wang Jinfeng: Writing—original draft preparation, Formal analysis, Methodology. Jin Ruoxuan: Data curation, Writing—review & editing.

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