An Assessment of Ecosystem Services and Trade-offs in the Yellow River Area Using the InVest Model

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Abstract

This study investigates the evolutionary patterns of ecological system services in the Yellow River Area and assesses the trade-offs and synergies among these services to inform the precise formulation of ecological preservation and quality-oriented policies throughout the area. The Yellow River Area was selected as investigation zone to elucidate effect mechanisms of land use alteration on ecosystem services. We employed the InVest to quantify four critical ecological system services indicators: water yield, sediment retention, carbon storage, and habitat quality. The temporal and spatial dynamics of ecological system services were explored at the prefecture-level city scale, and the trade-offs and synergies between distinct service categories quantified. The findings demonstrate: (1) The integrated land use change intensity in the Yellow River Area from 0.03% to 0.19% between 1990 and 2020. Significant land use conversions occurred primarily between grassland-cultivated land interfaces, grassland-unused land boundaries, and cultivated land-construction land conversions. (2) Between 1990 and 2020, ecological system services in the Yellow River Area exhibited varying trends: water yield service showed a "V"-shaped curve with early reduction then rebound, totaling a 0.49×10^4 t increase; carbon sequestration slightly decreased; soil conservation fluctuated but generally increased by 0.30×10^8 t; and habitat quality continuously declined. Spatially, zones of high water yield in the southeast decreased, whereas zones of low water yield in the northwest shrank. The geographical distribution of soil conservation, carbon sequestration and habitat quality services remained relatively stable. (3) The importance zoning analysis revealed that the western part of the upper reaches of the study area is classified as extremely important and highly important areas; the middle reaches, lower reaches, and southeastern part of the upper reaches are classified as moderately important areas; and the northwestern part of the upper reaches is classified as generally important areas. (4) The interactions between ecological system services within the research region varied across different periods.

Keywords

Ecological system services; InVest; Spatiotemporal dynamics; Trade-offs and synergies; Yellow River Area.

1. INTRODUCTION

Recently, escalating global temperature rise and continuous human-induced actions have intensified pressures on ecosystems, rendering ecological issues a focal point of global concern [1]. Consequently, the Chinese government has actively promoted ecological civilization construction, recognizing it as a critical foundation for achieving sustainable development [2].

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The 19th National Congress of the Communist Party of China articulated that "harmony between humanity and nature" is a fundamental principle, and ecological civilization construction is an integral component of the national development strategy, emphasizing the provision of superior ecological products to meet the growing needs of the people for a better life [3]. However, China's ecological civilization construction currently faces multiple challenges. The accelerated development of socioeconomic activities, including population growth, urban expansion, and industrial and agricultural production, has exacerbated environmental pollution, global warming, land degradation, and biodiversity reduction, culminated in ecosystem degradation and a decline in ecosystem service functions, thereby threatening the sustainable socioeconomic development and national ecological security [4,5]. In this context, assessing regional ecosystem services, exploring their spatio-temporal dynamics, and understanding their interrelationships are crucial for guiding ecological conservation and policy formulation, which is vital for maintaining regional ecological security and ensuring long-term socioeconomic stability and sustainable development.

Ecosystem service value (ESV) serves as a critical metric for quantifying ecosystem services, representing the economic, social, and ecological worth derived from ecosystems based on human needs [6,7]. The concept of "ecosystem services" was initially introduced by Costanza et al. in the 1970s, who also applied the equivalent factor method to assess global ESV [8.9]. Following the 2005 publication of UN's Millennium Ecosystem Assessment (MEA) document, scholarly investigation into ecological system services has accelerated [10], with an increasing body of researchers utilizing ESV to investigate various aspects of ecosystem services [11]. Research scales have encompassed watersheds [12], provincial regions [13], as well as metropolitan areas and urban agglomerations [14,15]. The research content primarily focuses on the temporal-spatial variations of ecological system services [16], the identification of driving factors [17], and the analysis of trade-offs and synergies [18,19]. In summary, while numerous studies on ecosystem services have been conducted in China across different spatio-temporal scales in recent years, research specifically targeting key ecological protection areas remains insufficient.

The Yellow River Area functions as a crucial environmental barrier as well as corridor in China, harboring significant ecosystem service values [20]. However, economic development has led to escalating ecological crises, including soil erosion and biodiversity loss [21-23], consequently diminishing ecosystem service values. This decline constrains the high-standard economic growth within the region and poses a threat to national ecological security [24]. Recognizing this, the ecological conservation and high-quality development of the Yellow River Area was prioritized as a key national strategy on September 18, 2019 [25]. This study, therefore, aims to assess ecological system services in the Yellow River Area, analyze interdependencies between service categories among them, to enhance regional ecological benefits and promote ecological conservation and green, high-quality development. Utilizing land use datasets from 1990, 2000, 2010, and 2020, this research employs the InVest model to quantify four critical ecological system services: water yield, soil conservation, carbon storage, and habitat quality. The spatio-temporal patterns of these services are examined at the prefecture-level city scale, and interactions and interdependencies among different ecological system services are analyzed. The findings are intended to inform the precise formulation of policies for ecological protection and advanced regional development in the Yellow River Area.

2. DATA AND METHOD

2.1. Study area

The Yellow River, spanning approximately 5464 km, originates in Qinghai Province. It traverses nine provinces and autonomous regions, including Qinghai, Sichuan, Gansu, Ningxia,

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Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong (Figure 1), situated between 30°10′ and 43°13′ N latitude and 89°29′ and 119°19′ E longitude. The total drainage area encompasses roughly $203.3 \times 10^4 km^2$. The drainage basin exhibits a complex and diverse climate, transitioning from arid and semi-arid conditions in the west to semi-humid conditions in the east. The upper reaches, primarily positioned along the Qinghai-Tibet Plateau, are characterized by a high-altitude, cold, and arid climate, with a rugged topography dominated by mountainous terrain. Vegetation primarily consists of alpine meadows and shrub lands, rendering the ecosystem ecologically fragile. The middle reaches, situated on the Loess Plateau, experience cold, dry winters and hot, rainy summers, with significant diurnal temperature variations. The topography is marked by plateaus and hills featuring vegetation primarily comprising deciduous broadleaf forests and shrub lands. This region is marked by low vegetation cover, severe soil erosion, and critical ecological challenges. The lower reaches, located in the North China Plain, feature cold, dry winters and hot, rainy summers, with concentrated precipitation during the summer months. The terrain is flat, with fertile soil, constituting a significant agricultural region of China. Vegetation is predominantly composed of cultivated crops, with limited natural vegetation, primarily consisting of drought-resistant shrubs and herbaceous plants.

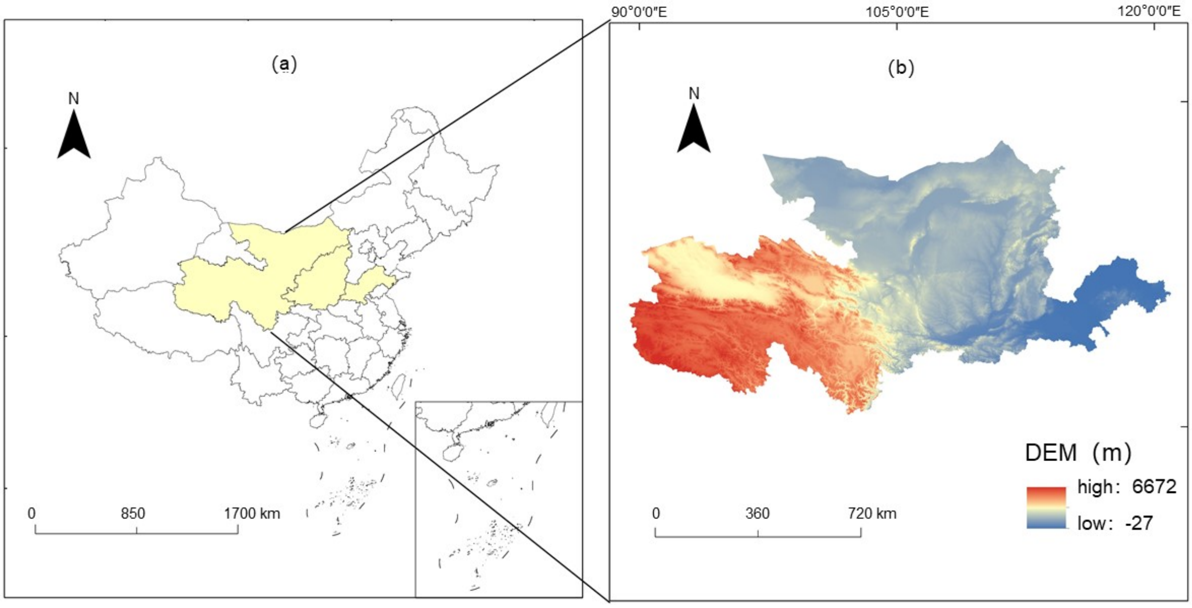

Figure 1. Study Area

2.2. Data Sources

The Yellow River Basin experiences low annual runoff and significant spatio-temporal variability, leading to pronounced water scarcity. Furthermore, severe soil erosion and biodiversity loss have critically impacted soil productivity and the ecological environment. Concurrently, the extensive grasslands within the basin constitute a vital part of carbon sequestration. Consequently, this study investigates the ecological system services of water yield, soil conservation, carbon sequestration and habitat quality. The datasets utilized include four periods of Land Use/Cover datasets for the Yellow River Area, Digital Elevation Model (DEM) datasets, and the pertinent Ecological System Service module data necessitated by the InVest model (Table 1).

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Table 1. Rerch Data and Sourcessea

Data types	Data nomenclature	Data sources
Underlying datasets	Land Use/Cover	Resource and Environment Science and Data Center (www.resdc.cn)
	Digital elevation model	Resource and Environment Science and Data Center (www.resdc.cn)
Water yield	Precipitation	National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn)
	Potential evapotranspiration	National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn)
	Root Restricting Layer Depth Plant Available Water Content	The Harmonized World Soil Database
	Watersheds	GeoNetwork spatial database
Soil conservation	The rainfall erosive factor (R)	Reference to relevant literature [26]
	Soil erosion factor K	Based on soil texture data calculation
	Vegetation coverage and soil conservation measures factors	Model guidelines and references [27]
Carbon storage	Carbon Pools	References [28]
Habitat quality	Threats Table	Based on land use data extraction
	Sensitivity Table	InVest Model User Manual and References [29]

2.3. Materials and methods

2.3.1 Land Use Dynamics and Transition Matrix

The Land Use change metrics characterize the alterations in land use types over a specific timeframe, encompassing both single-type dynamic degree indices and integrated land use change metrics. The single-type dynamic degree indices reflects the rate and extent of change for a particular land use type within the study area over a defined timeframe. Conversely, the Integrated Land Use Change Metrics represents the aggregate transformation of land use types across the entire research domain[30]. The Land Transfer Matrix, a tool derived from systems analysis, provides a quantitative description of the transitions among various land use types within the research domain [31]. The specific computational formulas are presented below:

$$V = \frac{U_j - U_i}{U_i} \times \frac{1}{t} \times 100\% \tag{1}$$

$$LC = \frac{\sum_{i=1}^{n} \Delta LU_{i-j}}{2\sum_{i=1}^{n} \Delta LU_i} \tag{2}$$

$$A_{ij} = \begin{bmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{bmatrix} \tag{3}$$

In this context, V represents the degree of single land use change (%), where U_i and U_j denote the area (km^2) of a specific land use type at the beginning and end of the study period, respectively, and t signifies the duration of the study. LC denotes the comprehensive land use dynamic degree (%), with LU_i representing the initial area (km^2) of the i-th land type during the study period. ΔLU_{i-j} signifies the absolute value of the area (km^2) converted from land type i to land type j during the study period, and T represents the study period. The variables i and j represent land use types. A_{ij} denotes the area (km^2) of land use conversion from type i to type j from the beginning to the end of the study, where i(i=1,2,3,…,n) and j(j=1,2,3,…,n) represent the land use types at the beginning and end of the study, respectively, and n represents the number of land use types.

2.3.2 Quantification of ecosystem services

This study employs four modules from the InVest model to assess the ecological system services in the Yellow River Area, namely water yield, carbon sequestration, soil conservation and habitat quality.

(1) Water yield (WY)

Water yield represents the capacity of a region to generate available water resources. This research utilizes the InVest framework's water yield component to quantify water yield in the Yellow River Area. This algorithm operates on hydrological cycle principles, determined by the residual of precipitation after accounting for evapotranspiration for each grid cell; a larger supply indicates a stronger water supply service [32,33]. The specific computational formulas are presented below:

$$Y_{xj} = \left[1 - \frac{AET_{xj}}{P_x}\right] P_x \tag{4}$$

Where: Y_{xj} is the annual water yield (mm) on grid cell x of land use type j; P_x is the average annual precipitation (mm) of grid cell x; AET_{xj} is the annual actual evapotranspiration (mm) of grid cell x of land use type j. According to the above content, the input data required to run the water supply module includes raster data such as land use, rainfall, and reference evapotranspiration, as well as vector data and biophysical tables of the watershed. Finally, the results of the model are calibrated by adjusting the seasonal parameter Z.

(2) Carbon sequestration (CS)

Carbon sequestration reflect the ecological function of absorbing carbon dioxide. This investigation employed the carbon storage component of the InVest framework to estimate carbon sequestration in the Yellow River Area. This module considers four carbon reservoirs: above ground biomass carbon, below ground biomass carbon, soil carbon, and dead organic matter carbon. The total amount of these four carbon pools across the research domain represents the carbon storage at that time point; a larger carbon storage indicates that the ecosystem can effectively absorb carbon dioxide and store carbon, which helps mitigate the greenhouse effect [34,35]. The specific computational formulas are presented below:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{5}$$

Where: C_{total} represents the total carbon storage of the study area ($t \cdot hm^{-2}$); C_{above} is the above ground carbon storage ($t \cdot hm^{-2}$); C_{below} is the below ground carbon storage ($t \cdot hm^{-2}$); C_{soil} is the soil carbon storage ($t \cdot hm^{-2}$); C_{dead} is the dead organic matter carbon storage

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(t·hm^{-2}). According to the photosynthesis equation, for every 1 t of dry matter produced, 1.63 t of CO_2 can be fixed, and 1.19 t of O_2 is released, which is used to estimate the oxygen release of vegetation in the study area. The main input data for this module includes land use and biophysical parameter tables.

(3) Soil conservation (SC)

Soil conservation indicates the effectiveness of an ecological system in preventing soil loss and maintaining soil quality. This study utilizes the sediment delivery ratio component within the InVest framework to quantify soil conservation services in the Yellow River Area. A higher soil conservation value indicates less soil erosion and favorable vegetation cover. The specific computational formulas are presented below:

$$RKLS_n = R_n \times K_n \times L_n \times S_n \quad (6)$$

$$USLE_n = R_n \times K_n \times L_n \times S_n \times C_n \times P_n \quad (7)$$

$$SK_n = RKLS_n - USLE_n \quad (8)$$

Where: $\mathrm{RKLS_n}$ represents potential soil erosion (t); $\mathrm{USLE_n}$ represents actual soil erosion (t); $\mathrm{SK_n}$ represents soil conservation (t); $\mathrm{R_n}$ is the rainfall erosivity factor; $\mathrm{K_n}$ is the soil erodibility factor; $\mathrm{L_n}$ is the slope length factor; $\mathrm{S_n}$ is the slope steepness factor; $\mathrm{C_n}$ is the cover management factor; and $\mathrm{P_n}$ is the support practice factor. Based on this, the soil conservation module requires raster data inputs including land use, DEM (Digital Elevation Model), rainfall erosivity factor, and soil erodibility factor, along with vector data representing the Yellow River Basin and biophysical tables. Model parameter settings are referenced from the model's help files and previous research [36,37].

(4) Habitat quality (HQ)

Habitat quality represents the ability of an ecological system to maintain viable habitats. This study calculates the habitat quality index by assessing the vulnerability of different land cover and the intensity of threat sources using the habitat quality component in the InVest model. A higher index value indicates greater ecosystem structural integrity, richer biodiversity, and better habitat quality [38]. The specific computational formulas are presented below:

$$Q_{xy} = H_j \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}\right) \quad (9)$$

Where: Q_{xy} is the habitat quality of grid cell x in land-use type j; D_{xj} is the threat level experienced by grid cell x in land-use type j; k is the half-saturation constant, typically half of the maximum value of D_{xj}; H_j is the habitat suitability of land-use type j; z is a normalization constant, generally taken as 2.5. The habitat quality module requires input of land use, threat factor, threat source data tables, and sensitivity data tables, and the model results are calibrated by adjusting the half-saturation parameter.

2.3.3 Ecosystem Service Trade-off Degree

Ecological system services trade-offs and synergies denote the degree and effects of relationships between diverse services throughout ecological systems. This study utilizes the Ecological system services Trade-off Degree to represent the coordination relationship of Ecological system services trade-offs. The formula is as follows:

$$ESTD_{mn} = \frac{ESC_{mb} - ESC_{ma}}{ESC_{nb} - ESC_{na}} \tag{10}$$

Where: $ESTD_{mn}$ represents the degree of synergy of two ecological system services, m and n, representing the degree and direction of interaction between two ecological system services; ESC_{mb} is the amount of substance of the m-th ecological system services at the moment of b; ESC_{ma} is the amount of material of the m-th ecological system services at moment a; ESC_{nb} is the amount of substance of the n-th ecological system services at moment b; ESC_{na} is the amount of substance of the n-th ecological system services at moment a. When $ESTD_{mn}$ is negative, it indicates that the m and n ecological system servicess exhibit a trade-off relationship; when $ESTD_{mn}$ is positive, it indicates a synergistic relationship. The absolute value of $ESTD_{mn}$ represents the degree of change in the m-th ecological system services compared to the change in the n-th ecological system services.

3. RESULTS AND ANALYSIS

3.1. Land Use Change Analysis

3.1.1 Land Use Dynamic Degree Change

Spatial distribution patterns of land cover categories in the Yellow River Area in 1990, 2000, 2010, 2020 are illustrated in Figure 2. The primary land use categories are grassland and undeveloped land, collectively accounting for an average coverage of 67.98% of the total basin area. Over time, the area of forestland, grassland, water, and construction land within the basin demonstrated an overall expansion trend, while cultivated land and unused land exhibited a declining trajectory. Construction land experienced rapid growth, increasing by $2.37 \times 10^4 km^2$, a growth rate of 62.62%. Conversely, undeveloped land and agricultural land experienced significant reductions, by $2.60 \times 10^4 km^2$ and $1.71 \times 10^4 km^2$, respectively, with reduction rates of 4.68% and 4.67%. Spatially, land use types in the basin exhibit distinct regional differences, with the upper reaches characterized by grassland and undeveloped land, the middle reaches by cultivated land, grassland, and the lower reaches primarily by cultivated land. Regarding spatial dynamics, urban expansion is most pronounced in the upper and mid-basin. Downstream regions show a more significant growth in water body and a marked decrease in unused land area.

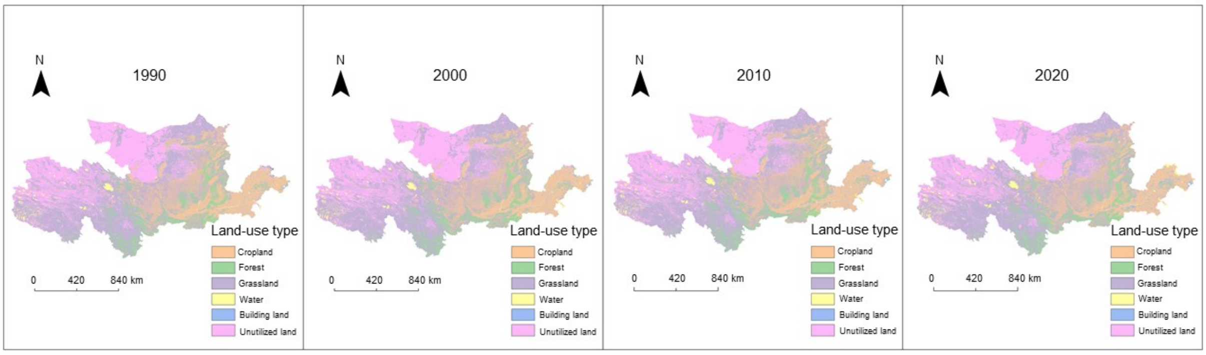

Figure 2. Distribution of Land Use Types in the Yellow River Area from 1990 to 2020

According to Figure 3, the integrated land use change metrics of the Yellow River Area between 1990 and 2020 demonstrate a pronounced upward trajectory, rising from 0.03% to 0.19%, indicating an intensification of human activities' impact on land resources and frequent land use conversions. The single-type dynamic degree shows different trends. Cultivated land and undeveloped land show a sustained decreasing trend, while construction land, water,

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grassland, and forestland generally show an increasing trend. Specifically, the upper reaches expansion in construction land area; mid-basin reduction in cultivated land and undeveloped land area, and an increase in construction land area; the lower reaches shrinkage in unused land area and an increase in water body.

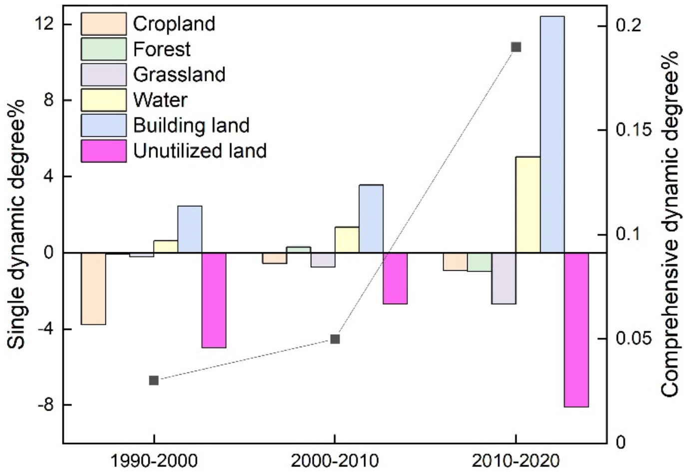

Figure 3. Dynamics of land use change in the Yellow River Area from 1990 to 2020

3.1.2 Land Use Conversion Dynamics

The land use conversion patterns across the Yellow River Watershed between 1990 and 2020 are illustrated in Figure 4. During the period of 1990-2000, significant land use transitions occurred, particularly among dominant land types including grassland, cropland, and undeveloped land. Specifically, grassland primarily converted to undeveloped land, agricultural land, and woodland, with conversion areas of 806452 km^2, 74163 km^2, 56851 km^2, correspondingly. Agricultural land mainly transitioned to grassland and construction land, with conversion areas of 78760 km^2 and 23490 km^2, respectively. Unused land primarily transitioned to grassland, with a conversion area of 81512 km^2. Forestland and water mainly transitioned to grassland, with conversion areas of 56145 km^2 and 9510 km^2, correspondingly. Construction land primarily transitioned to agricultural land, with a conversion area of 25681 km^2. Furthermore, the area of grassland decreased due to greater grassland outflow than inflow, while the area of construction land increased due to greater inflow than outflow.

Between 2000 and 2010, land use/cover change exhibited relatively minor alterations, primarily involving the transformation of agricultural land to construction land and grassland, with respective transformation areas of 3432 km^2 and 3415 km^2. Secondary changes included reciprocal transformations between grassland and undeveloped land, where grassland transitioned to undeveloped land (2584 km^2), and unused land converted to grassland (1804 km^2). Furthermore, minor conversion extents forestland and construction land were transitioned to grassland, with conversion areas of 641 km^2 and 35 km^2, respectively. Consequently, the extent of agricultural land diminished due to greater outgoing than incoming transfers, while the area of construction land increased due to greater incoming than outgoing transfers.

From 2010 to 2020, the trends in Land Use/Cover were similar to those observed between 1990 and 2000. Grassland primarily converted to undeveloped land and agricultural land, with transfer areas of 93504 km^2 and 72872 km^2, respectively. Agricultural land primarily shifted to grassland, construction land, and forestland, with transfer areas of 71138 km^2, 22756 km^2, and 17244 km^2, respectively. Unused land principally transformed into grassland,

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with a transfer area of 73502 km². Forestland and water mainly converted to grassland, with transfer areas of 52667 km² and 10925 km², correspondingly. Construction land primarily converted to cultivated land, with a transfer area of 33640 km². As a result, the areas of unused land and cultivated land decreased due to greater outgoing than incoming transfers, while the coverage of grassland and construction land zones expanded due to greater incoming than outgoing transfers.

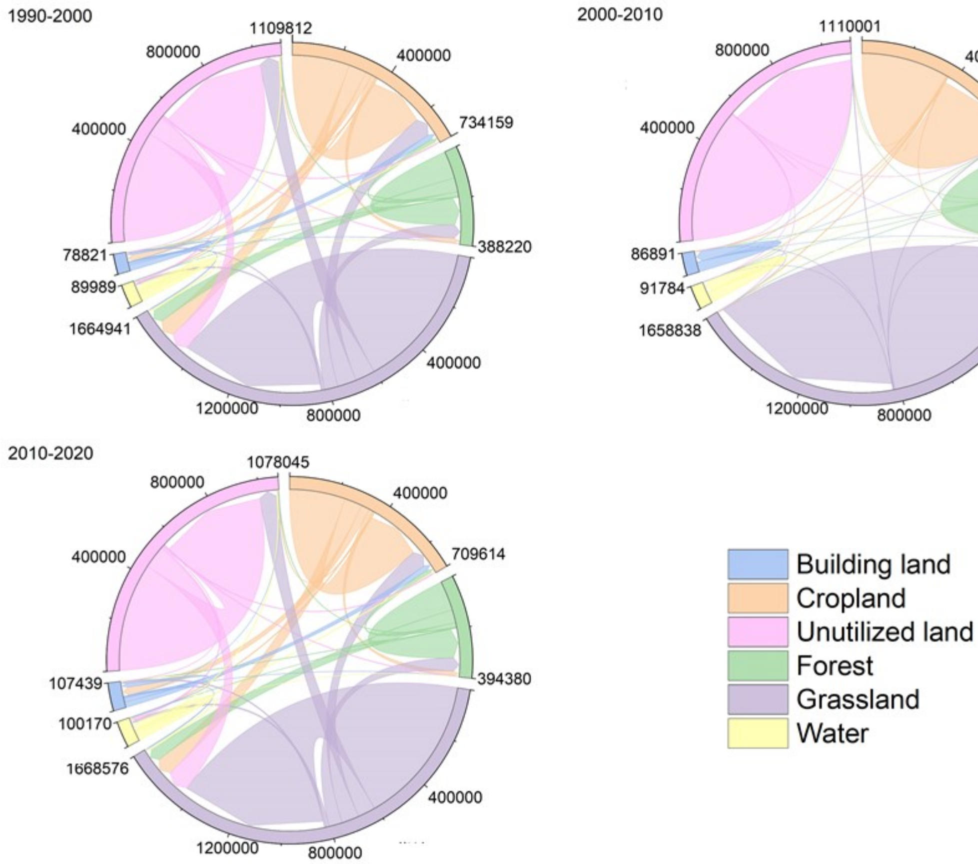

Figure 4. Illustrates the land use transition map of the Yellow River Area from 1990 to 2020

Overall, the land use transitions in the Yellow River Area were relatively significant during the periods of 1990-2000 and 2010-2020, while the changes were relatively minor between 2000 and 2010. This phenomenon can be explained by fast-paced economic growth and accelerated urbanization between 1990 and 2000, which boosted land requirements, leading to the transformation of extensive regions of grassland into cultivated land. During 2000-2010, the economic growth was relatively stable, leading to minor alterations in land cover. Between 2010 and 2020, the adjustment and upgrading of the economic structure created new demands for land utilization, leading to substantial modifications to land cover [39-41]. The most significant land utilization transitions were observed between grassland and unused land, and between grassland and cultivated land. This may be related to the melting of permafrost caused by global warming-driven elevation in thermal conditions and moisture levels, which in turn exacerbated soil erosion and grassland degradation. It is also associated with climate change, particularly increased precipitation, as well as activities such as returning farmland to forest and grassland, and human economic development [42,43].

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3.2. Spatio-temporal characteristics of ecosystem service values

3.2.1 Water yield

Between 1990 and 2020, the material quantity of water yield in the Yellow River Area displayed a "V"-shaped trajectory, first declining then rising (Figure 5). It decreased from 18.3× 10^4t t in 1990 to 13.7× 10^4t in 2000, then rose to 18.82× 10^4t in 2020, showing a net upward trajectory. Specifically, the water yield in the headwater regions of the Yellow River Area increased by 2.16 × 10^4t, with a growth rate of 26.74%; the water yield in the middle reaches decreased by 0.06× 10^4t, with a decline of 1.21%; and the water yield in the lower reaches decreased by 1.62× 10^4t, with a decline of 29.00%.

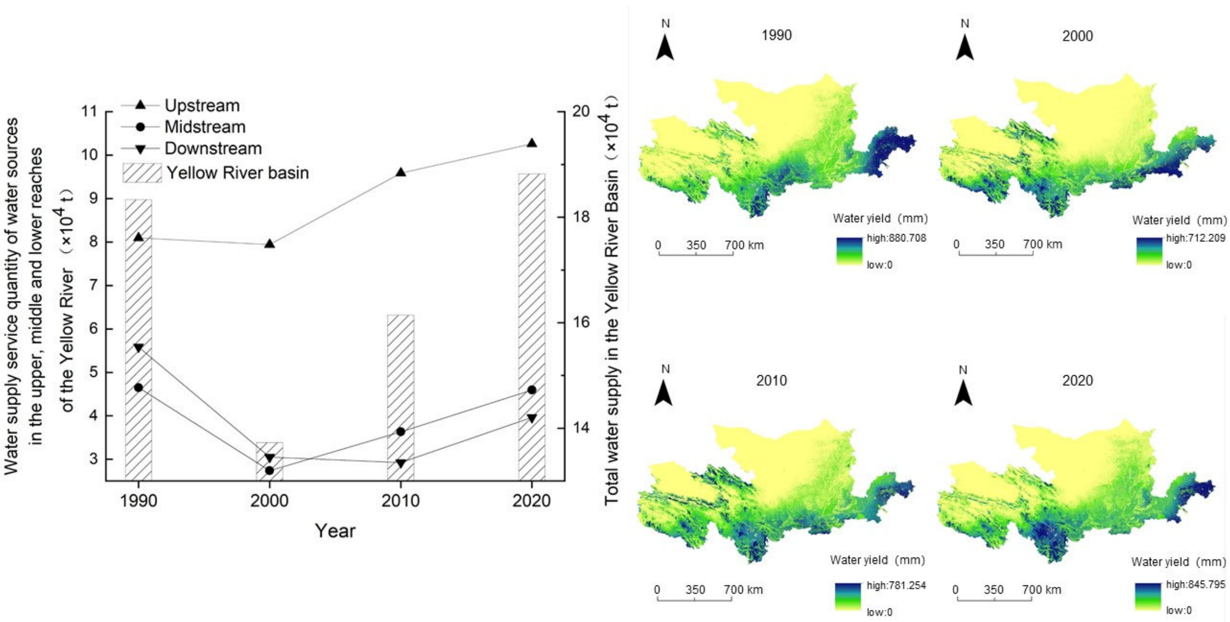

Figure 5. Spatio-temporal Distribution of Water Yield in the Yellow River Area from 1990 to 2020

The distribution of water yield in the Yellow River Area varies significantly (Figure 5), typically demonstrating a declining gradient from southeast to northwest. The upper southern and lower reaches have higher water yields, while the upper northern region has lower water yields. In 1990, the distribution pattern showed high values in the southeastern lower reaches and minimum measurements in the northwestern headwater regions. By 2000, the high-value area in the southeastern lower reaches decreased, and the southwestern upper reaches became a high-value area. By 2010, the low-value area in the northwestern upper reaches decreased, with a trend of reduction from the southern to the central zones. By 2020, the overall water yield in the Yellow River Area augmented, with high-value zones predominantly situated within the southern upper reaches and the eastern lower reaches, while the northern upper reaches had lower water yields. This geographical arrangement is primarily influenced by the precipitation regime and land utilization types [44]. Regions with elevated precipitation levels and high canopy cover have stronger water yield potential. Conversely, zones with low average precipitation and sparse vegetation density have weaker water yield potential.

3.2.2 Carbon sequestration

Based on temporal analysis (Figure 6), the carbon sequestration service in the Yellow River Area demonstrated a downward trajectory in material quantity, with a minor overall change, decreasing from 101.76 × 10^8 t to 101.70 × 10^8 t. Specifically, the carbon sequestration service in the upper reaches of the Yellow River Area increased by 0.82× 10^8 mm, representing

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a 1.25% increase; the service in the middle reaches decreased by 0.29×10^8 mm, a 1.05% decrease; and the service in the lower reaches decreased by 0.59×10^8 mm, a 6.93% decrease.

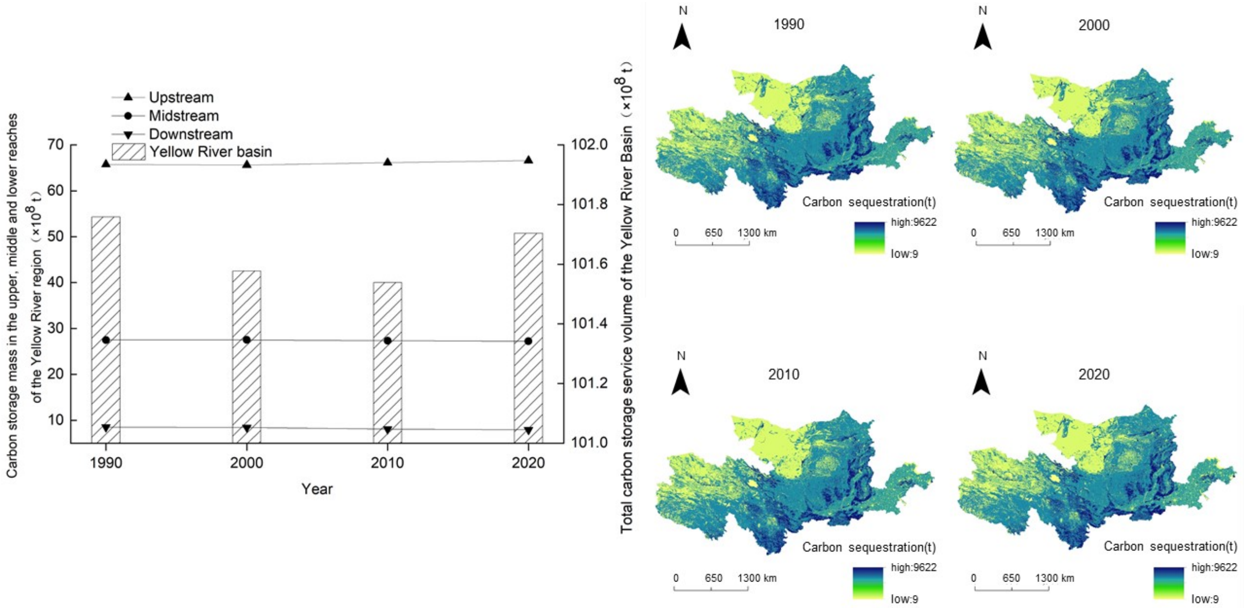

Figure 6. Spatio-temporal Distribution of Carbon Sequestration and Oxygen Release in the Yellow River Area from 1990 to 2020

Spatially (Figure 6), the carbon storage in the Yellow River Area ranged from 0 to 9622 t, with a multi-year average carbon storage of 101.645×10^8 t. High-value areas of carbon sequestration were distributed throughout the headwater zones, midstream regions, and downstream areas of the Yellow River Area, covering a wide area; low-value areas were concentrated in the northwestern part of the upper reaches, with a gradually decreasing area. Vegetation is one of the primary factors in carbon sequestration and oxygen release; therefore, the land utilization types in high-value zones are mainly forestland and grassland, while the land utilization types in low-value areas are primarily unused land.

3.2.3 Soil conservation

The quantity of soil conservation services throughout the Yellow River Area exhibits significant interannual variability, yet demonstrates a net upward trajectory (Figure 7). Throughout the 1990-2020 timeframe, there was an increase from 99.47×10^8 tons to 99.77×10^8 tons. Specifically, soil conservation functions in the headwater regions of the basin increased by 1.10×10^8 tons, representing a 1.98% increase; in the midstream sectors, soil conservation services decreased by 0.86×10^8 tons, a 2.27% decrease; and in the lower reaches, soil conservation services decreased by 0.06×10^8 tons, a 0.90% increase.

Spatially (Figure 7), areas with higher soil conservation quantities predominantly occur in the forested regions in southerly upper reaches and the Taihang Mountains in the middle reaches. These areas, rich in forest resources and high vegetation cover, exhibit strong soil conservation capacity within their ecosystems. Areas with lower soil conservation quantities are distributed in unused land and construction land, where sparse vegetation, rapid urbanization, and frequent human activities result in lower soil conservation capacity within the regional ecosystems.

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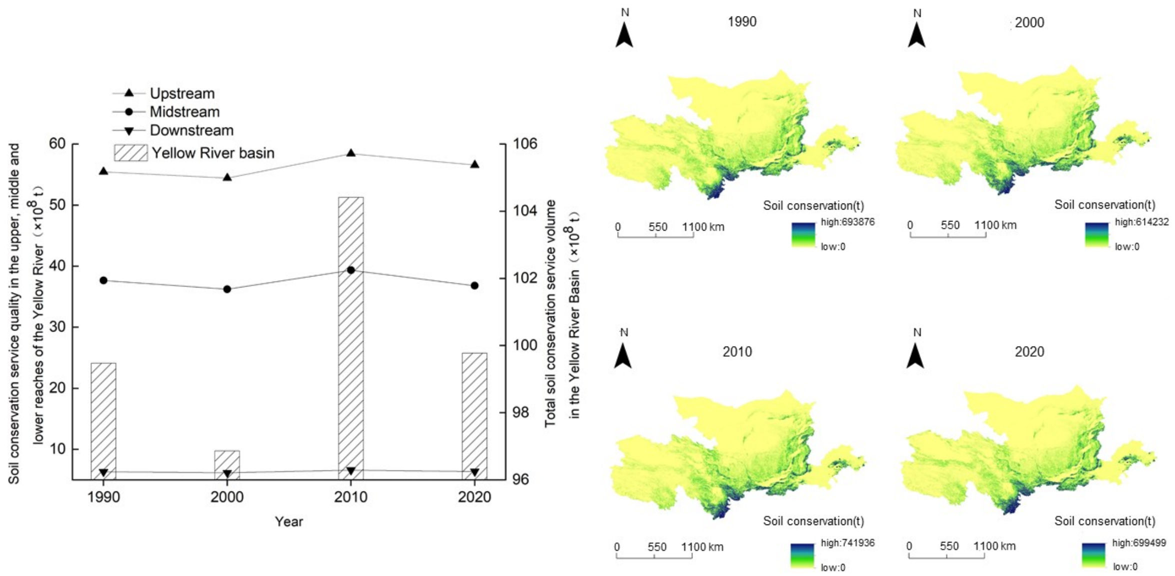

Figure 7. Spatio-temporal Distribution of Soil Conservation in the Yellow River Area from 1990 to 2020

3.2.4 Habitat quality

Temporally (Figure 8), the habitat quality services in the Yellow River Area generally showed a continuous downward trend, with the average habitat quality indices from 1990 to 2020 being 0.361, 0.357, 0.348, and 0.347, respectively. The habitat quality index throughout headwater zones of the basin fell from 0.624 to 0.617, that in the middle reaches from 0.522 to 0.531, and that in the downstream from 0.331 to 0.309. The downstream region experienced the greatest reduction in habitat quality index, followed by the midstream zones. Index fell from 0.331 to 0.309. The downstream region displayed the most pronounced degradation in the habitat quality index, followed by the midstream.

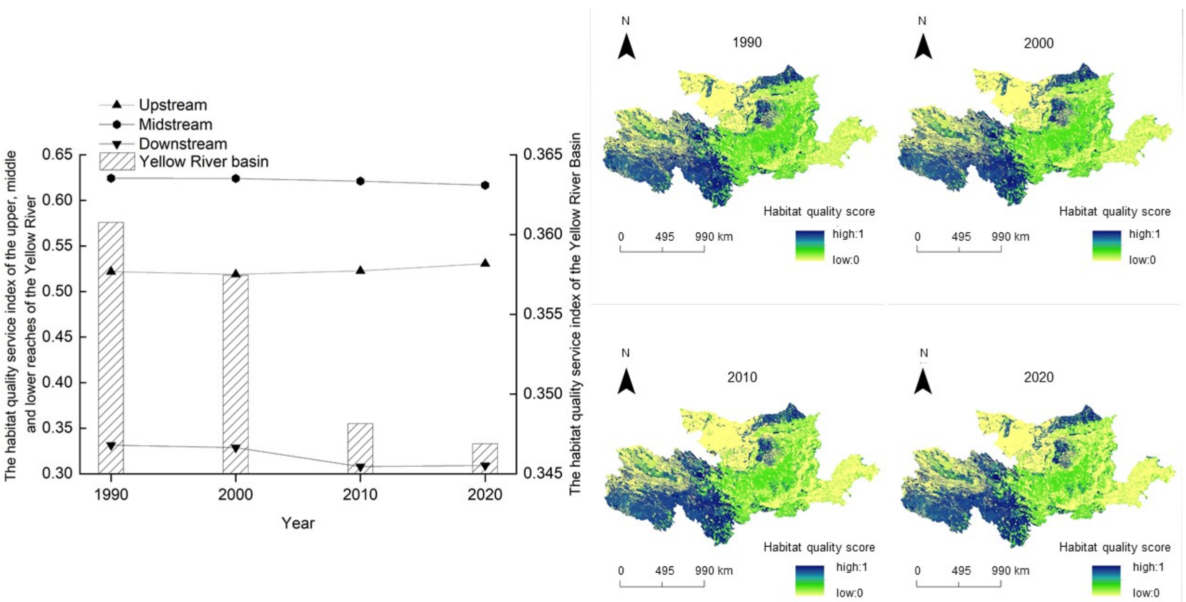

Figure 8. Spatio-temporal distribution map of habitat quality in the Yellow River Area from 1990 to 2020

Spatially (Figure 8), the spatial distribution pattern of habitat quality in the Yellow River Area over the three-decade timeframe was generally consistent, and the overall distribution did not

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change substantially, with higher scores for forested land and grassland in the southwestern part of the upstream and grassland areas in the north, and lower scores for unutilized land and construction land in the northwestern part of the upstream and eastern part of the downstream region, which was predominantly connected to land use across the watershed. The forested and grassland zones have good environmental quality, rich biodiversity, and strong ecosystem resilience, resulting in high habitat quality scores. Conversely, the unused land and construction land areas have fragile ecological environments, weak ecosystem resilience, and significant human activity impacts, leading to low habitat quality scores.

3.3. Ecosystem service importance zoning

Given the varying units of the four ecosystem services—water yield, carbon sequestration, soil conservation, and habitat quality—a normalization process is required to eliminate unit discrepancies for a clearer and more intuitive assessment of ecological system services value in the Yellow River Area. The normalized results of the four ecosystem services are then overlaid. Using the raster calculator in ArcGIS 10.2, a weighted sum is performed with a weight value of 0.25. The results are classified into four importance levels using the natural breaks method: extremely important, highly important, moderately important, and generally important. This identifies the zones within the Yellow River Area that contribute the most to human well-being through ecosystem services, providing a scientific foundation for resource development, environmental protection, and land-use planning, thereby promoting sustainable and coordinated ecological and economic development.

As illustrated in Figure 9, the critically and considerably significant ecological system services zones throughout the Yellow River Area are primarily distributed within the western part of the upper reaches. This region's land utilization types are predominantly forestland and grassland, indicates high water production, carbon sequestration, soil conservation service capabilities, along with good habitat quality and high ecological system services value. Moderately important regions are predominantly situated within midstream sectors, downstream areas, and southeastern headwater zones, representing the largest proportion of the four ecosystem services. These areas are predominantly cultivated land, influenced by human activities and high land-use intensity, with all four ecosystem services at a moderate level. Generally important areas are predominantly situated in the northwestern sectors of the upper reaches. These areas are primarily unused land, with weak water yield, carbon sequestration, soil conservation service capabilities, resulting in ecological fragility and low habitat quality.

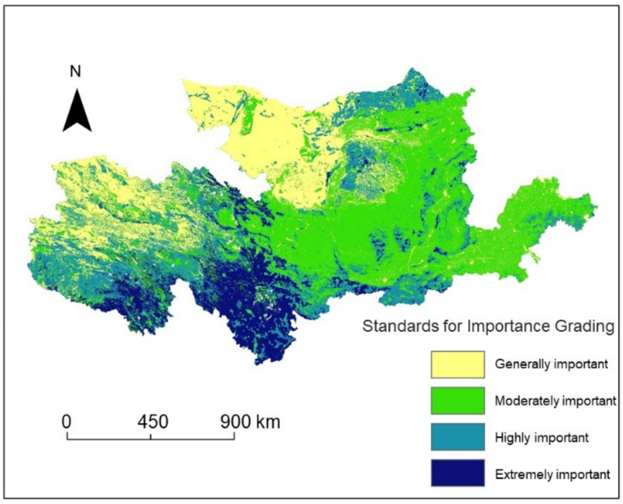

Figure 9. Spatial Distribution Map of Ecosystem Service Importance in the Yellow River Area

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3.4. Analysis of the Trade-offs and Synergies of Ecosystem Services

As illustrated in Figure 10 the trade-offs and synergies among ecological system services in the Yellow River Area exhibit varying trends across different stages. The highest synergy demonstrates the strongest correlation with water yield and soil conservation, while the highest trade-off occurs between habitat quality and soil conservation. Specifically, the trade-off and synergy associations among the four ecological system services throughout the 1990-2000 timeframe constitute 16 types, with 10 types showing positive values and 6 types showing negative values, suggesting that the associations among ecological system services in the research area are primarily synergistic. The types with strong synergy are habitat quality and carbon sequestration; the types with high synergy are water yield and carbon sequestration, and habitat quality and water yield; the types showing weak synergy are water yield and habitat quality, carbon sequestration, water yield, and carbon sequestration and habitat quality. The type with a strong trade-off is habitat quality and soil conservation; the types with a high trade-off are water yield and soil conservation, and carbon sequestration and oxygen release and soil conservation; soil conservation demonstrates a weak trade-off relationship with the remaining three services.

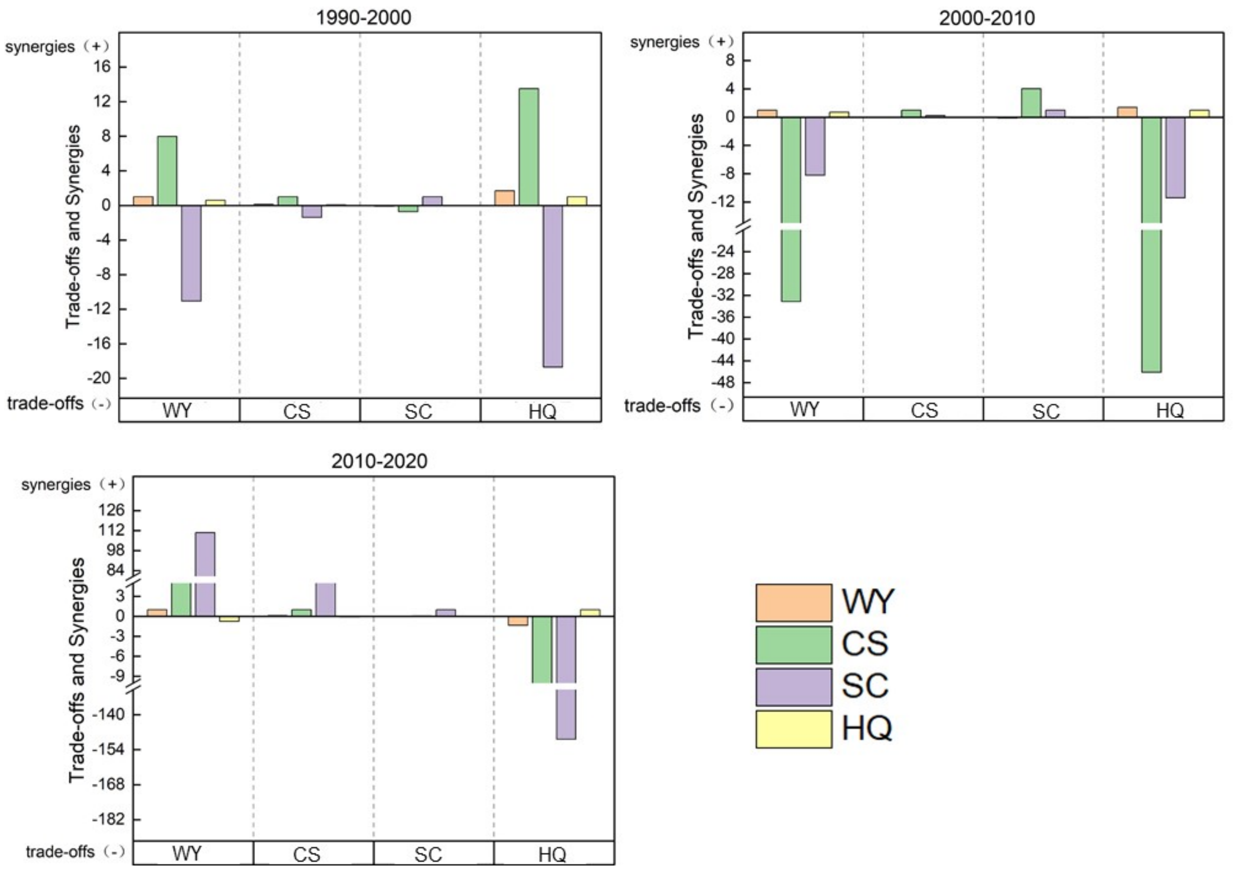

Figure 10. Ecosystem service trade-offs and synergies in the Yellow River Area from 1990 to 2020

Throughout the 2000-2010 interval, the interactions among ecosystem services exhibited alterations in both magnitude and direction. Examination of the 16 trade-off/synergy types, derived from the four ecosystem services, revealed an equilibrium, with eight types demonstrating positive relationships and eight exhibiting negative relationships. The dominant synergy types included soil conservation with carbon sequestration, and habitat quality with water yield. Weak synergy was observed between water yield and habitat quality, and between carbon sequestration with soil conservation. Strong trade-offs were identified between habitat quality and carbon sequestration, water yield and carbon sequestration, and habitat quality and soil conservation. The trade-off was more pronounced between water yield and soil conservation, while weak trade-offs were observed between soil conservation and water yield, and habitat quality, carbon sequestration, and water yield.

Throughout the 2010-2020 interval, within the Yellow River Area, the 16 trade-off/synergy types among the four ecosystem services showed a shift towards synergy, with ten types exhibiting positive relationships and six showing negative relationships. Strong synergy was observed between water yield and soil conservation, and between carbon sequestration and soil conservation. The synergy was more pronounced between water yield and carbon sequestration, while weak synergy was observed between carbon sequestration and water yield, and between soil conservation and carbon sequestration, and between soil conservation and water yield. Strong trade-offs were identified between habitat quality and soil conservation, and carbon sequestration. The trade-off was more pronounced between habitat quality and water yield, while weak trade-offs were observed between water yield and habitat quality, carbon sequestration and oxygen release and habitat quality, and soil conservation and habitat quality. Compared to the interval spanning 1990 to 2010, the synergy between water yield and soil conservation in the Yellow River Area has increased.

The synergistic associations between water yield service and soil conservation, and between carbon sequestration and soil conservation, exhibited continuous enhancement across the three periods. The trade-off relationships between carbon sequestration and habitat quality, and between habitat quality and water yield service, demonstrated a consistent increase. The trade-off and synergistic relationships between water yield service and carbon sequestration, and between habitat quality and soil conservation, initially decreased and then increased, with water yield service and carbon sequestration predominantly exhibiting a synergistic association, and habitat quality and soil conservation primarily displaying a trade-off relationship. The trade-off and synergistic associations between habitat quality and soil conservation, and between soil conservation and carbon sequestration and oxygen release, initially increased and then decreased, with habitat quality and soil conservation generally showing a trade-off association, and soil conservation and carbon sequestration generally exhibiting a synergistic association.

4. DISCUSSION AND CONCLUSIONS

4.1. Discussion

Over the three decades from 1990 to 2020, the region of undeveloped land and cultivated land in the Yellow River Area diminished, while the area of construction land, water bodies, grassland, and forest land grew. Water yield and soil conservation services exhibited an upward trajectory, whereas carbon sequestration and habitat quality services, generally showed a diminishing trend. The paramount and markedly essential domains for ecosystem services are chiefly positioned in the western portion of the upstream region. Moderately important areas are mainly distributed in the midstream sections and the Shandong Peninsula in the downstream. Generally important areas predominantly occur in the unused land in the northwestern portion of the headwater areas, which is largely aligns with the determination of prior investigations [45].

The shifts in grassland, undeveloped land, cultivated land, forestland, and construction land are primarily influenced by anthropogenic activities such as ecological projects and urbanization, while the increase in water area is mainly affected by increased precipitation [46-48] The extremely and highly important ecosystem service regions are mainly distributed across the source region of the Yellow River Area, a key national ecological function region, and a vital

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water conservation area and biodiversity priority conservation area in China. Strict protection measures should be implemented to ensure the integrity of the ecosystem is maintained. Moderately important areas are primarily distributed across the cultivated land and construction land of the middle and lower reaches, where land use intensity is high. A combination of sustainable utilization and ecological protection should be adopted to prevent further degradation of ecosystem services. Generally important areas are primarily located in the Alxa League of Inner Mongolia, an area characterized by harsh natural conditions, extensive deserts and Gobi, low vegetation coverage, and poor soil. Ecological governance and restoration should be prioritized to restore and strengthen ecological system services.

Between 1990 and 2000, all four ecological system services in the Yellow River Area exhibited a decreasing trend. This reduction was chiefly linked to the rapid advancement of industrialization and urbanization, coupled with an incomplete ecological protection policy framework. Industrial pollution and land overuse exacerbated ecosystem degradation, while ecological restoration and environmental protection measures did not keep pace with economic development [49]. From 2000 to 2010, water yield and soil conservation services showed an upward trend, largely attributed to the enactment of ecological initiatives such as the "South-to-North Water Diversion" and "Grain for Green" programs. Conversely, carbon sequestration and oxygen release, along with habitat quality services, decreased. This was mainly attributed to the accelerated industrialization and urbanization during this period, compounded by the increased frequency of extreme climate events due to global warming, which undermined ecosystem stability and resilience. During this decade, the carbon emissions in the Yellow River Area grew at a rate of 12.1% [50]. From 2010 to 2020, water yield and carbon sequestration services increased, primarily due to major ecological projects in the upper reaches, such as the "Three-River-Source National Park," and policies like "carbon emission trading." However, soil retention and habitat quality services declined, mainly due to the intensive application of pesticides and fertilizers in the Yellow River Area during this period, leading to soil and water pollution [51].

Throughout the period spanning 1990-2020, the Yellow River Area exhibited a dominant synergistic relationship among ecosystem services. The highest synergy was observed between water yield and soil conservation, with a synergy degree of 25.85. This may be attributed to the enactment of ecological initiatives including the Grain for Green Program in China, which increased vegetation cover, effectively controlling soil erosion and enhancing soil conservation. Simultaneously, the increase in vegetation also contributed to water resource conservation and supply. The highest trade-off was found between habitat quality and carbon sequestration, with a trade-off degree of 38.10. This could be due to the limited resources within the ecosystem. Boosting carbon sequestration often necessitates increased vegetation cover, potentially consuming land resources originally allocated for biodiversity conservation and habitat maintenance, thereby impacting habitat quality.

4.2. Conclusion

This study employed InVest to quantify four representative ecological system services within the Yellow River Area, subsequently analyzing the trade-offs and synergies among these services. The objective was to establish a theoretical basis for the precise formulation of ecological preservation and high-quality development policies in the region. Key outcomes are presented below::

(1)Significant land use changes and intensified human activities were observed in the Yellow River Area, distinguished by prevalent land use transitions. From 1990 to 2000, grassland primarily converted to undeveloped land, cultivated land, and forest; cultivated land shifted into grassland and construction land; and unused land converted to grassland. This resulted in a decrease in grassland area and an increase in construction land. Between 2000 and 2010, cultivated land converted to construction land and grassland; grassland and unused land exhibited mutual conversions, resulting in a diminishment in cultivated land area and an augmentation of construction land. From 2010 to 2020, grassland converted to unused land and cultivated land; cultivated land shifted into grassland, construction land, and forest. The zones of undeveloped land and cultivated land declined, while grassland and construction land areas increased. Overall, the zone of grassland and construction land expanded, whereas cultivated land and undeveloped land areas contracted.

(2) Throughout the three-decade period from 1990 to 2020, marked transformations occurred in the ecological system service quantity across the Yellow River Area. The water yield displayed a V-pattern trajectory, first declining and then rising, with an overall increase. Carbon sequestration demonstrated a minor reduction with minimal fluctuation. Soil retention services displayed notable volatility, yet demonstrated an overall increase. Habitat quality experienced a continuous decline. Spatially, the water yield service was higher in the southeast and lower in the northwest. High-value zones for carbon sequestration were widely distributed, while low-value regions were predominantly located in the upstream section of the northwest. High-value regions for soil retention services were predominantly located in the forested areas of the upstream section' southern area and the Taihang Mountains in the middle reaches, with low-value areas in unused land and construction land. High-value areas for habitat quality were found in the forested and grassland areas of the upper reaches' southwest and the grasslands in the north, while low-value areas were in the unused land and construction land of the upper reaches' northwest and the lower reaches' east.

(3) The zoning of the significance of ecological system services in the Yellow River Area displays that: the western portion of the upper reaches is an area of extreme and high importance, dominated by woodlands and grasslands, with high habitat quality and high ecosystem service capacity; the midstream section and the downstream section of the Shandong Peninsula is an area of medium importance, dominated by cultivated land, highly influenced by human activities and with medium service capacity; and the northwestern part of the upper reaches is an area of average importance, dominated by unutilized land and with low service capacity and habitat quality.

(4) The relationships between ecological system services in the research area varied from one stage to another, with synergistic relationships between all services except soil conservation, which was a trade-off with the other three services in 1990-2000, and equilibrium between synergistic relationships and trade-offs in 2000-2010, and synergistic relationships between all services except habitat quality, which was a trade-off with the other three services in 2010-2020. The synergistic and trade-off relationships are in equilibrium from 2000 to 2010.

REFERENCES

[1] Wu, S., Ma, C., 2024. Global forest ecosystems face multiple challenges. Ecological Economy 40 (11), 1–4.

[2] Si, W., 2024. China's advantages, modes of thinking, and pathways for ecological civilization construction. Southeast Academic Research (6), 128–139.

[3] Chang, Q., 2024. Chinese modernization with harmonious coexistence between humanity and nature. China Renmin University Press, Beijing.

[4] Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosystem Services 28, 1–16.

[5] Zhang, Y., Liu, B., Bi, X., Wang, B., Sui, R., 2023. Research progress in ecosystem services from the perspective of stakeholder perceptions. Journal of Natural Resources 38 (5), 1300–1317.

[6] Zhang, B., Xie, G., Xiao, Y., Lun, F., 2010. Classification of ecosystem services based on human needs. China Population, Resources and Environment 20 (6), 64–67.

[7] Schägnera, J.P., Branderb, L., Maesa, J., et al., 2013. Mapping ecosystem services' values: current practice and future prospects. Ecosystem Services 4, 33–44.

[8] Costanza, R., Arge, R., de Groot, R., et al., 1997. The value of the world's ecosystem services and natural capital. Nature 387 (6630), 253–260.

[9] Li, K., Shi, Y., Tang, Y., et al., 2024. Spatiotemporal evolution and correlation analysis of ESV and LER in the middle reaches of the Yellow River. Journal of Safety and Environment, 1–11.

[10] Huang, G., Jiang, Y., Liu, Z., et al., 2016. Research progress on human well-being: a sustainable science perspective. Acta Ecologica Sinica 36 (23), 7519–7527.

[11] Sannigrahi, S., Chakraborti, S., Joshi, P.K., et al., 2019. Ecosystem service value assessment of a natural reserve region for strengthening protection and conservation. Journal of Environmental Management 244, 208–227.

[12] Mei, Z., Zhang, Y., Huang, X., Liu, Z., 2024. Ecosystem service-based ecological risk assessment in the Qinghai Lake Basin and analysis of spatial heterogeneity influencing factors. Acta Ecologica Sinica 44 (12), 4973–4986.

[13] Sun, Y., Lin, X., Li, S., Wang, J., Luo, C., 2024. Evaluation of the spatiotemporal dynamics and driving factors of ecosystem service trade-offs in Guizhou Province. Acta Scientiae Circumstantiae 44 (9), 401–413.

[14] He, G., Zhang, L., Lei, X., Sun, Y., Wan, Y., Xiong, H., 2024. Ecological risk assessment and influencing factors based on ecosystem service supply-demand clusters in Wuhan Metropolitan Area. Chinese Journal of Applied Ecology 35 (5), 1347–1358.

[15] Sun, Z., Wang, S., Chen, B., 2024. Construction of ecological security patterns and evaluation of ecological resilience based on ecosystem services: A case study of Changsha-Zhuzhou-Xiangtan urban agglomeration. Acta Ecologica Sinica 44 (11), 4650–4661.

[16] Zhang, B., Li, Z., Feng, Q., Lu, Z., Zhang, B., Cheng, W., 2024. Evolution analysis of ecosystem service value in the Qilian Mountains based on land use change. Acta Ecologica Sinica 44 (10), 4187–4202.

[17] Yang, J., Gao, F., Xu, H., Liu, K., Han, F., In press. Spatiotemporal evolution and driving factors of ecosystem service value in the Aksu River Basin. Environmental Science, 1–19.

[18] Wang, S., Xu, X., Huang, L., Shi, H., Gu, Q., Liu, H., 2024. Trade-offs and synergies among ecosystem services in the black soil region of Northeast China. Acta Ecologica Sinica (21), 1–16.

[19] Liu, Y., 2023. Characteristics of ecosystem services and their trade-off and synergy relationships in the Yellow River Basin [Dissertation]. Northwest A&F University, Yangling.

[20] Li, H., 2024. Systematic identification and outlook of ecological and environmental issues in the Yellow River Basin. Research of Environmental Sciences 37 (1), 1–10.

[21] Robinson, A., Lehmann, J., Barriopedro, D., et al., 2021. Increasing heat and rainfall extremes now far outside the historical climate. npj Climate and Atmospheric Science 4 (1), 45.

[22] Zhou, X., Chen, Y., Zhou, Y., et al., 2022. Management countermeasures for ecological protection and restoration under the "Global Standard for Nature-Based Solutions" by IUCN. Landscape Architecture, 29 (6), 20–25. https://doi.org/10.14085/j.fjyl.2022.06.0020.06

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202507_11(7).0003

[23] Liu, Y., Zhang, S., Li, H., et al., 2024. Progress and research prospects of comprehensive management of ecological clean small watersheds in China. Acta Ecologica Sinica. https://doi.org/10.20103/j.stxb.202404190874. Accessed on December 2, 2024.

[24] Luo, J., Xia, J., Hao, F., et al., 2024. Theoretical thinking and practical development of spatial synergy and high-level governance of human activities in Chinese river basins. Journal of Natural Resources 39 (11), 2505–2524.

[25] Wang, D., 2024. Practices and development paths of ecological collaborative governance in the Yellow River Basin. People's Tribune (20), 55–59.

[26] Zhang, W., Fu, J., 2003. Estimation of rainfall erosivity using different types of rainfall data. Resources Science (1), 35–41.

[27] Gesangzhuoma, Wang, F., Zhu, X., Soil conservation and influencing factors in the Yarlung Tsangpo River Basin based on the InVEST model. Environmental Protection Science, 1–10.

[28] Xie, X., Sun, B., Zhou, H., et al., 2004. Estimation and spatial distribution analysis of soil organic carbon density and stocks in China. Soil Bulletin 41 (1), 35–43.

[29] [29]Chen, Y., Qiao, F., Jiang, L., 2016. Impact of land use pattern changes on regional scale habitat quality - A case study in Beijing using the InVEST model. Acta Scientiarum Naturalium Universitatis Pekinensis 52 (3), 553–562.

[30] Qiu, H.H., Hu, B.Q., Zhang, Z., 2021. Impacts of land use change on ecosystem service value based on SDGs report - Taking Guangxi as an example. Ecological Indicators 133, 108366.

[31] Wu, C.Y., Chen, B.W., Huang, X.J., Dennis Wei, Y.H., 2020. Effect of land-use change and optimization on the ecosystem service values of Jiangsu Province, China. Ecological Indicators 117, 106507.

[32] Zhang, L., Hickel, K., Dawes, W.R., et al., 2004. A rational function approach for estimating mean annual evapotranspiration. Water Resources Research 40 (2), 89–97. https://doi.org/10.1029/2003WR002710

[33] Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research 37 (3), 701–708. https://doi.org/10.1029/2000WR900325

[34] Zhang, Y., Shi, X., Tang, Q., 2021. Carbon storage assessment under different land use scenarios in the upper reaches of Fenhe River. Acta Ecologica Sinica 41 (1), 360–373.

[35] Li, K., Wang, S., Cao, M., 2003. Carbon storage in vegetation and soils in China. Science China (Series D: Earth Sciences) (1), 72–80.

[36] He, S., Zhu, W., Cui, Y., et al., 2019. Soil erosion characteristics in the Qi River Basin of Taihang Mountains based on the InVEST model. Resources and Environment in the Yangtze Basin 28 (2), 426–439.

[37] Liu, Y., Liu, X., Zhang, B., et al., 2020. Assessment of soil and water conservation functions in artificial shrub-grass ecosystems in the loess hilly region. Journal of Soil and Water Conservation 34 (3), 84–90.

[38] Forman, R.T., Sperling, D., Bissonette, J.A., et al., 2003. Road Ecology: Science and Solutions. Island Press, Washington, DC.

[39] Xiao, D., Niu, H., Yan, H., Fan, L., Zhao, S., 2020. Spatiotemporal evolution of land use patterns in the Yellow River Basin (Henan section) from 1990 to 2018. Transactions of the Chinese Society of Agricultural Engineering 36 (15), 271–281+326.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202507_11(7).0003

[40] Fu, L., Chi, Y., Yu, Y., Zhang, L., Liu, S., Wang, X., Xu, K., Wang, J., Zhang, X., 2022. Characteristics and influencing factors of land use change in the Yellow River Basin from 2000 to 2020. Journal of Ecology and Environmental Sciences 31 (10), 1927–1938.

[41] Huang, Y., Li, X., Yu, Q., Huang, H., 2022. Analysis of land use changes and driving forces in the Yellow River Basin from 1995 to 2018. Journal of Northwest Forestry University 37 (6), 113–121.

[42] Liao, M., Fang, X., Jiang, X., Zhu, Q., Jin, J., Ren, L., Yan, Y., 2024. Spatiotemporal characteristics of land use/cover changes in the Yellow River Basin over the past 40 years. Journal of Soil and Water Conservation 38 (2), 165–177+189.

[43] Cheng, Y., Liu, L., Cheng, Q., Xu, Z., An, Q., Wang, X., 2025. Vegetation dynamics and their response to wet-dry transitions in the upper and middle reaches of the Yellow River. Acta Ecologica Sinica (4), 1–11.

[44] Yang, J., Xie, B., Zhang, D., 2020. Spatial-temporal variation of water yield in the Yellow River Basin and its response to precipitation and land use change based on the InVEST model. Chinese Journal of Applied Ecology 31 (8), 2731–2739.

[45] Wang, Y., Sun, X., 2024. Spatiotemporal evolution and influencing factors of ecosystem service value in the Yellow River Basin. Environmental Science 45 (5), 2767–2779.

[46] Lou, J., Dang, X., Meng, Z., Zhang, H., Song, H., 2024. Analysis of land use changes and driving forces in the top ten gullies of the Yellow River Basin from 1986 to 2020. Journal of Soil and Water Conservation 38 (1), 319–327+336.

[47] Chen, W., Li, J., Zhu, L., 2019. Spatial differentiation and sensitivity analysis of ecosystem service values in the middle reaches of the Yangtze River. Journal of Natural Resources 34 (2), 325–337.

[48] Huang, J., Zhang, G., Yu, H., et al., 2020. Spatiotemporal characteristics of climate change in the Yellow River Basin over the past 40 years. Journal of Hydraulic Engineering 51 (9), 1048–1058.

[49] Hou, P., Gao, J., Chen, Y., 2021. Development process and evolutionary characteristics of China's ecological protection policies. Acta Ecologica Sinica 41 (4), 1656–1667.

[50] Du, H., Wei, W., Zhang, X., Ji, X., 2021. Spatiotemporal patterns and influencing factors of carbon emissions from energy consumption in the Yellow River Basin based on DMSP/OLS and NPP/VIIRS nighttime light data. Geographical Research 40 (7), 2051–2065.

[51] Zhang, Z., Yang, J., Chen, H., Liu, J., Shu, X., Shi, Y., Guo, C., 2024. Spatiotemporal characteristics of fertilizer usage and grain production in the Yellow River Basin from 2000 to 2021. Bulletin of Soil and Water Conservation 44 (2), 312–321+332.