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Ecosystem Service Value Assessment of the Yellow River Delta Based on Satellite Remote Sensing Data

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Abstract: The Yellow River Delta (YRD) stands as a globally significant wetland, playing a pivotal role in sustaining regional ecosystem stability and offering crucial ecosystem services to humanity. However, anthropogenic activities, particularly resource development, unavoidably disrupt the ecosystem, leading to the degradation of these vital services. Utilizing satellite remote sensing data, the InVEST model, and energy analysis, this study introduces the concept of 'emergy' as an 'intermediate variable' to investigate the spatiotemporal changes in the ecosystem service value of the YRD. Five distinct types of ecosystem services are selected for quantitative assessment and analysis of the YRD's spatiotemporal evolution from 1990 to 2020. Results indicate a 63.7% decline in the total value of ecosystem services from 1990 to 2010, followed by a 16.5% increase from 2010 to 2020. The study also unveils spatial shifts in high- and low-value areas of ecosystem services and attributes these changes to rapid urbanization and alterations in land use and cover. The assessment of ecosystem service values concretizes the intangible ecosystem service functions of natural resources. This lays the foundation for establishing a mechanism that combines positive incentives and reverse pressure to achieve the economic valuation of ecosystem service.

Keywords: ecosystem services; energy analysis; ecosystem service value; invest

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1. Introduction

Ecosystem services play a vital role in the socio-economic development of human society by providing environmental and material foundation. They serve as a crucial link between natural, social, and economic systems [1]. However, the current global scenario is characterized by rapid urbanization, which results in significant changes in regional land use, population growth, industrial concentration, and a disregard for ecological environmental protection during land development and utilization. These factors, combined with frequent human activities, contribute to the degradation of regional ecosystems [2]. Consequently, the quality of ecosystem services and products declines due to their severe impact.

In recent years, there has been an increasing global recognition of the need to evaluate ecosystem services [3]. China, in particular, has introduced the concept of "Lucid waters and lush mountains are invaluable assets" to achieve a harmonious balance between the economy and the environment [4]. The ecosystem services value (ESV) is used to assess and quantify ecosystem services, enabling the conversion of natural ecosystems' contributions into measurable economic values. This approach facilitates the measurement of the importance of ecosystems for economic development and the extent to which they contribute to human society. The valuation of ecosystem services provides a tangible representation of ESV at the national or regional level, either in monetary or non-monetary terms [5]. It encompasses the benefits that the ecological environment provides to humanity [6,7] and helps evaluate the level of synergy between ecological quality and the economy [8,9]. Therefore, conducting objective and scientific monetary assessments of ecosystem services can serve as a scientific basis for regional ecological civilization construction, ecological conservation policies, ecological compensation standards, and sustainable development planning. It also offers scientific support to ensure the security of regional ecosystem services in the context of rapid urbanization, thereby contributing to the harmonious and sustainable development of the regional society, economy, and natural environment.

The assessment of ESVs has become a prominent research focus and challenge in the field of ecosystem service theory due to the impact of human activities on ecosystems and the degradation of ecological environments. Existing studies have employed diverse research approaches and methods to explore different types of ecosystems, such as forests [10,11], wetlands [12], farmlands [13], and grasslands [14]. Value assessments of ecosystem services have been conducted at various spatial scales, including global [15,16], national [17,18], provincial, metropolitan area [19], urban [20,21], and watershed scales [22,23]. Ecosystem service function assessments primarily involve physical quantity assessment, value assessment, and emergy assessment [24]. Value assessment is commonly conducted using monetary values as a metric, with methods such as the functional value method [25] and the equivalence factor method [10,26]. The functional value method encompasses approaches such as market value, replacement cost, and opportunity cost methods, among others. In a study conducted by Shivaraj Thapa [12] on the Begnas Basin in Nepal, functional value methods were employed to determine the ecosystem service value. Liu [27] analyzed the spatiotemporal evolution of ESVs in the East China Sea Bay based on the modified equivalence factor method. Value assessment methods, on the other hand, have been widely used in ecosystem service evaluation due to their intuitive results and the possibility of aggregating values for different services [28,29]. However, the value assessment method relies on market prices, which can be volatile and may affect the accuracy and reliability of valuation results. Additionally, these methods have limitations, including one-sided evaluation criteria, lack of comprehensiveness, and difficulty in objectively reflecting the spatial differentiation of ecological values in natural resource systems [30]. In the current context of rapid urbanization and land use changes, aligning assessment results with the economic system poses challenges. Additionally, physical quantity assessment is a non-monetary quantitative evaluation method that focuses on measuring material mass. Physical quantity assessment methods include empirical knowledge or dynamic assessment models. With advancements in remote sensing technology and spatial analysis techniques, assessment models for ecosystem services can now dynamically quantify ESV at different spatial scales. Examples of such models include InVEST [31,32], Solves [33], and ARIES [34]. Among these models, the InVEST model is currently the most widely used and mature model [35]. The dynamic assessment model of ecosystem services provides a foundation for quantifying, visualizing, and refining the evaluation of ecosystem service values [36]. Physical quantity assessment results are relatively objective and stable, as they can reflect the mechanisms underlying the formation of ecosystem services and emphasize the integration of ecological processes and services [37]. However, this method has a limitation in dealing with the various dimensions of individual ecosystem services. This makes it challenging to aggregate the production and service quantities of different ecosystem products [38].

The emergy theory was developed by the American ecologist Odum and served as the basis of this study. The emergy theory utilizes the energy conversion rate to convert the physical quantity of different ecosystem services into solar energy and provides a comprehensive method to evaluate the contribution of different ecosystem services by quantifying the flow of energy and resources in the ecosystem. Based on this theory, some scholars used the energy-to-money ratio to convert solar energy values back into monetary value in order to achieve the value evaluation of ecosystem services [39–42]. Consequently, emergy is considered an "intermediate quantity" that bridges the gap between physical quantity and value in this study. It provides an analytical framework based on emergy theory, enabling the quantitative analysis of both ecological and economic systems. The primary goal is to establish a unified measurement standard [43]. This method effectively addresses the limitation of aggregating ecosystem services due to the lack of standardized measurement units. It also facilitates the comprehensive analysis and interconversion of material flows, emergy flows, and monetary flows within an ecosystem.

The Yellow River Delta wetland is internationally recognized as one of the most valuable and representative estuarine wetland ecosystems worldwide [44]. However, this ecosystem has faced various ecological environmental challenges, including wetland shrinkage, vegetation degradation, and loss of biodiversity, due to factors such as petroleum extraction, expansion of farmland, aquaculture development, and urbanization. To raise awareness of the importance of ecosystem services, it is crucial to gain a comprehensive understanding of the dynamic evolution of ecosystem service values in the coastal wetlands of the Yellow River Delta. This study focuses specifically on the Yellow River Delta and employs satellite remote sensing data and the InVEST model to quantitatively assess and visually analyze the material quantities of five ecosystem services: crop production, water conservation, carbon storage, habitat quality, and soil retention from 1990 to 2020. This analysis offers a scientific and practical reference for the protection of ecosystem services, natural asset accounting, and ecological compensation in the Yellow River Delta.

2. Materials and Methods

2.1. Study Area

The Yellow River Delta, located between Laizhou Bay and Bohai Bay, is one of the largest and youngest rivermouth deltas in China. It is renowned for its abundant biodiversity and is considered the most well-preserved wetland ecosystem in the warm-temperate zone of the country. This research conducted in this study focuses on the area surrounding Ninghai in Kenli County, extending from the northern mouth of the Tao'er River to the southern mouth of the Xiaoqing River. The study area spans from 118°1′1″ to 118°4′1″ E and 37°20′57″ to 38°12′18″ N, covering an approximate land area of 5400 square kilometers (Figure 1). The Yellow River Delta experiences a warm–temperate monsoon continental climate [45], characterized by a significant portion (about 70%) of its annual precipitation occurring during the summer season. The average annual temperature, precipitation, and evaporation are 12.1 °C, 551.6 mm, and 1928.2 mm, respectively.

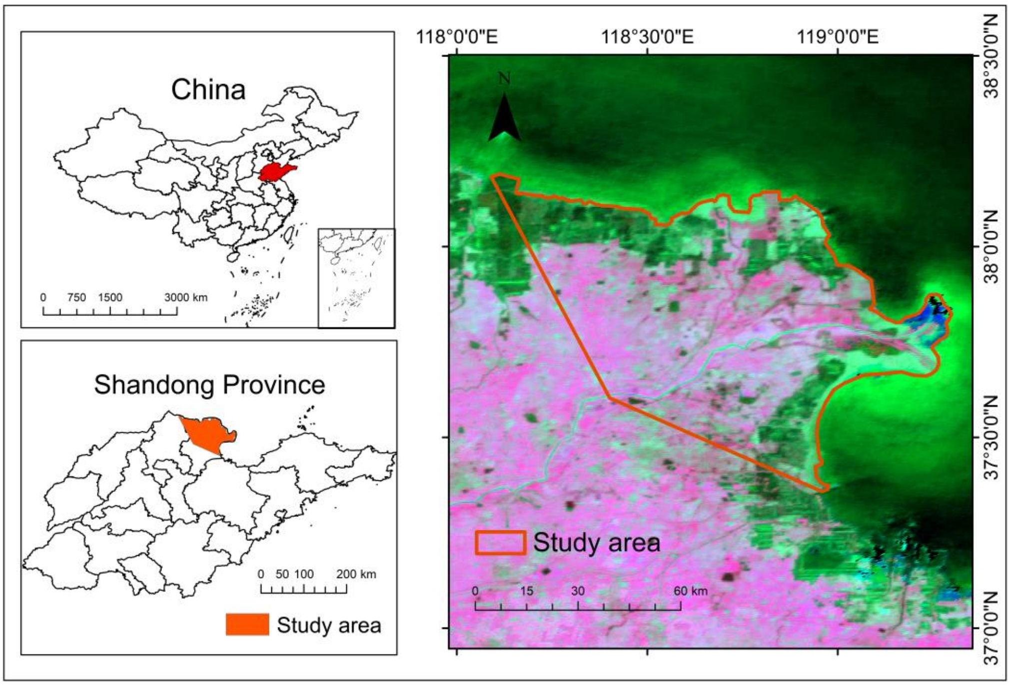

Figure 1. Geography of the Yellow River Delta. Pink represents areas covered with vegetation, while other colors indicate areas without vegetation.

A land area has been formed at the river mouth of the Yellow River over the past century due to the fluctuation of its estuary in the Yellow River Delta. The area is characterized by extensive alluvial plains and tidal wetlands enriched with abundant sediment brought by the Yellow River from its upstream areas. Due to its diverse biological communities, including a significant bird population, the Yellow River Delta is known as the "international airport for birds". It is also rich in mineral resources, with substantial reserves of petroleum, geothermal water, rock salt, and coal. The Shengli Oil Field, the second-largest oil field in China, is located in this area. Consequently, the Yellow River Delta faces a significant challenge in balancing ecological conservation and economic development.

2.2. Data Preparation and Processing

The study uses three main types of data: meteorological data, satellite remote sensing data, and socio-economic statistical data (Table 1). The meteorological data encompass rainfall and potential evapotranspiration data. The rainfall data were obtained from the official website of the National Aeronautics and Space Administration (NASA). The potential evapotranspiration data were calculated using the modified Hargreaves method [46]. The rainfall erosivity factor (R factor) and soil erodibility factor (K factor) were derived from the rainfall data. The satellite remote sensing data involve digital elevation model (DEM) data and satellite images. DEM data were sourced from the Geospatial Data Cloud. The slope factor for erosion was calculated based on the DEM. Landsat-5 and Landsat-8 satellite images, as well as the normalized difference vegetation index (NDVI), were obtained through geographic data analysis using the Google Earth Engine platform (GEE). Land use and land cover (LUCC) data based on Landsat imagery can be derived using a support vector machine algorithm. The root depth and available water data were derived from the LUCC data. The socio-economic data used in this study consisted mainly of regional GDP data for the Yellow River Delta. These data were obtained from the Statistical Yearbooks of Dongying and Binzhou and included GDP data for various counties and districts. The emergy–money ratio was calculated based on the regional GDP data and the total emergy. The periods for these data were the years 1990, 2000, 2010, and 2020.

Table 1. Data preparation and Data sources.

	Data	Data Source	Data Scale
Meteorol-gical data	Rainfall	NASA (https://www.nasa.gov/) (accessed on 27 June 2023)	30
	Potential evapotranspiration	Based on meteorological station data, calculate using a formula $ET_0 = 0.0013 - 0.48RA \times (T_{avg} + 17.0) \times (TD - 0.0123P)^{0.76}$	30
	Rainfall erosivity factors (R)	$R = 0.053 \times pre^{1.6548}$	30
	Soil erodibility factor (K)	Calculations based on rainfall data Du (2017) [47]	30
Satellite remote sensing data	DEM	Geospatial Data Cloud Website (https://www.gscloud.cn/) (accessed on 10 July 2023)	30
	Topographic erosivity factor (LS)	Computation based on DEM data	30
	Landsat 5	GEE (Google Earth Engine)	30
	Landsat 8	GEE (Google Earth Engine)	30
	LUCC	Perform supervised classification using the SVM algorithm	30
	NDVI	GEE (Google Earth Engine)	30
	Root Depth	Referencing the InVEST root depth table, creating raster data using LUCC	30
	PAWC	Referencing the InVEST pawc table, creating raster data using LUCC	30

Table 1. *Cont.*

	Data	Data Source	Data Scale
Socioeco-omic data	GDP	Dongying Statistical Yearbook, Binzhou Statistical Yearbook	
	EMR	Calculate based on total energy value and GDP	

This study utilized Landsat-5 and Landsat-8 satellite images as the primary data source. Specifically, the images with high vegetation coverage during the summer season were selected. They were screened to ensure that cloud cover was less than 5%. Feature extraction was performed to facilitate the extraction of vegetation information for visual interpretation. The Google Earth Engine (GEE) platform was used in conjunction with the support vector machine (SVM) algorithm for LUCC mapping. This approach allowed for the interpretation of LUCC maps for the years 1990, 2000, 2010, and 2020. The Yellow River Delta was classified into twelve land use types, including farmland, forestland, the Yellow River, open water, grassland, residential area, mudflat, salt ponds, aquaculture ponds, industrial land, ports, and saline–alkali land. The classification accuracy for the respective years was 89%, 91%, 93%, and 92%. Furthermore, multiple field surveys were conducted in the Yellow River Delta to validate the results of the remote sensing image classification, ensuring the accuracy and consistency of the classification outcomes.

2.3. Methods for Assessing Ecosystem Service Values

This study adopted the indicator classification system provided by the Millennium Ecosystem Assessment (MA, UNEP) and took into account the unique characteristics of the YRD ecosystem.The YRD has a large area of arable land, which is crucial for meeting the food needs and food security of the population. The region's food production services provide enormous ecological and economic value. Wetlands, swamps, and forests in the YRD are important carbon storage reservoirs in the ecosystem, with rich organic matter accumulation capabilities that can absorb and fix a large amount of carbon. At the same time, there are 1524 species of wild animals and 393 species of plants distributed in the study area. The high degree of biodiversity indicates the existence of rich species diversity in the ecosystem of the region, providing a high habitat quality function. Additionally, vegetation coverage in the region is high. Through root structure and multi-level vegetation coverage, forest and grassland can increase soil water permeability, improve soil water storage capacity, slow down the impact and erosion of raindrops on the soil, form a protective layer, prevent soil erosion and loss, and provide huge water conservation and soil conservation functions. As a result, the ecosystem services in the YRD were classified into distinct categories, including crop production, water conservation, carbon storage, habitat quality, and soil retention. In the assessment process, we used satellite remote sensing data and the InVEST model to quantify and visually analyze the material quantities of each ecosystem service. Next, we applied an emergy transformity to convert each ecosystem service into its corresponding emergy. Finally, we employed an emergy–money ratio specific to the study area to convert each ecosystem service into its corresponding economic value. This facilitated the estimation of the total value and spatial distribution of ecosystem services within the study area. Figure 2 illustrates the research procedure of this article.

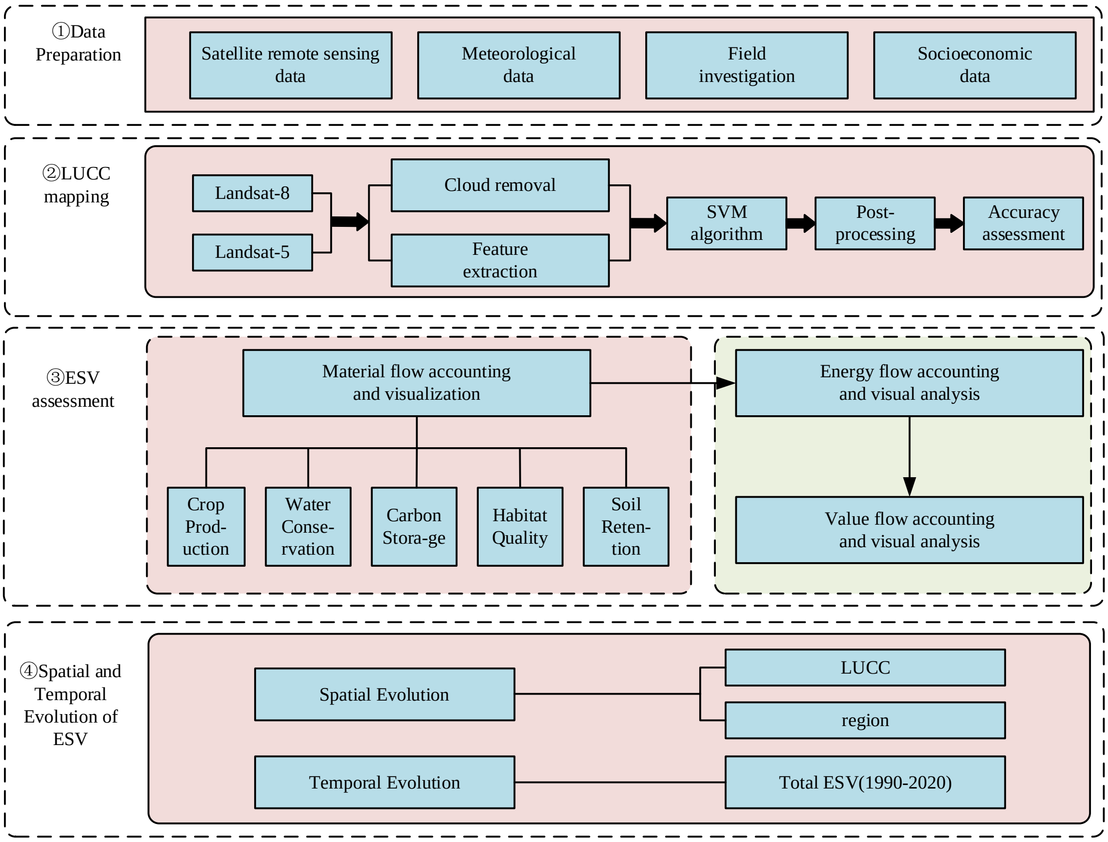

Figure 2. Framework of this study.

2.3.1. Crop Production

The crop production service refers to the service rendered by agricultural land in the production of food. The crop production of each county in the YRD is allocated to the agricultural lands in the corresponding county. Then, the agricultural yield is further allocated to grid cells using the normalized difference vegetation index (NDVI). The formula is as follows:

$$Q_{cp} = \frac{NDVI_i}{NDVI_{sum}(j,n)} \times G_{sum}(j,n), \quad (1)$$

where Q_{cp} represents the physical quantity of food production (t), $G_{sum}(j,n)$ is the total crop production of the j-th LULC type in the nth county, and $NDVI_{sum}(j,n)$ stands for the cumulative NDVI value of the j-th LULC type in the n-th county.

Based on the physical quantity of crop production, the emergy was calculated for the crop production service. The formula is as follows:

$$Em_{cp} = Q_{cp} \times T_{cp}, \quad (2)$$

where Em_{cp} represents the total emergy of crop production service (sej). Q_{cp} is the physical quantity of crop production (t); T_{cp} represents the emergy transformity rate of crop production, with a value of 1.58×10^{15} sej/t [48]. Parameters are shown as Supplementary Information.

The value of the crop production service was calculated based on the EMR. The formula is as follows:

$$Em\$_{cp} = \frac{Em_{cp}}{EMR}, \quad (3)$$

where $Em\$_{cp}$ represents the value of the crop production service ($). Em_{cp} is the emergy of the crop production service (sej). EMR is the emergy–money ratio (sej/$).

2.3.2. Water Conservation

The InVEST model calculates water yield based on the Budyko water balance principle [49]. It defines the water yield of each grid cell as the difference between precipitation and actual evapotranspiration. Water conservation represents the amount of water that flows into the ecosystem, which is derived by subtracting surface runoff from the water yield results. The formula is as follows:

$$Y_{xj} = (1 - \frac{AET_{xj}}{P_x}) \times P_x, \quad (4)$$

$$Q_{wc} = (Y_{xj} - Runoff_{xj}) \times S_j, \quad (5)$$

$$Runoff_{xj} = P_x \times C, \quad (6)$$

where Y_{xj} represents the annual water conservation of grid x in the j-th type of ecosystem (mm). Q_{wc} is the physical quantity of water conservation (m^3). P_x represents the annual precipitation of grid x. C represents the surface runoff coefficient. AET_{xj} and $Runoff_{xj}$ denote the annual actual evapotranspiration and surface runoff of grid x in the j-th type of ecosystem, respectively.

Based on the physical quantity of water conservation, the emergy value was calculated for the water conservation service. The formula is as follows:

$$Em_{wc} = Q_{wc} \times \rho \times G \times T_{wc}, \quad (7)$$

where Em_{wc} represents the total emergy of water conservation service (sej). Q_{wc} is the physical quantity of water conservation (m^3). ρ represents the density of water (1.0×10^6 g/m^3). G represents the Gibbs free energy (4.94 J/g). T_{wc} represents the emergy transformity rate of water conservation, with a value of 4.09×10^4 sej/J [50]. Parameters are shown as Supplementary Information.

The monetary values of water conservation services were calculated based on the EMR in the emergy analysis results. The formula is as follows:

$$Em\$_{wc} = \frac{Em_{wc}}{EMR}, \quad (8)$$

where $Em\$_{wc}$ represents the value of the water conservation service ($). Em_{wc} is the emergy of the water conservation service (sej). EMR is the emergy–money ratio (sej/$).

2.3.3. Carbon Storage

The InVEST carbon storage model is employed to simulate carbon storage services in the Yellow River Delta region. The model calculates carbon stocks based on LULC types as assessment units and estimates ecosystem carbon storage for different land use/cover types in the study area [40]. The carbon storage for each LULC type is divided into four basic carbon pools: aboveground carbon pool, belowground carbon pool, soil carbon pool, and detritus carbon pool (also known as dead organic carbon pool).

$$C_i = C_{i\_above} + C_{i\_below} + C_{i\_soil} + C_{i\_dead}, \quad (9)$$

$$Q_{cs} = \sum_{i=1}^{n} (C_i \times S_i), \quad (10)$$

where Q_{cs} represents carbon storage service physical quantity. Si represents the area of the i-th land use type. n represents the total number of LULC types in the study area. C_i, C_{i_above}, C_{i_below}, C_{i_soil}, and C_{i_dead} represent the carbon density of the i-th land use type, aboveground biochar, underground biochar, soil organic carbon, and dead organic carbon, respectively.

Based on the physical quantity of carbon storage, the emergy value was calculated for the carbon storage service. The formula is as follows:

$$Em_{cs} = Q_{cs} \times T_{cs}, \tag{11}$$

where Em_{cs} represents the emergy of carbon storage services (sej). Q_{cs} is the physical quantity of carbon storage (t). T_{cs} represents the emergy transformity rate of carbon storage, with the value of 3.78×10^{13} sej/t [50]. Parameters are shown as Supplementary Information.

The monetary values of carbon storage services were calculated based on the EMR in the emergy analysis results. The formula is as follows:

$$Em\$_{SC} = \frac{Em_{SC}}{EMR}, \tag{12}$$

where $Em\$_{cs}$ represents the value of the carbon storage service ($). Em_{cs} is the emergy of the carbon storage service (sej). EMR is the emergy–money ratio (sej/$).

2.3.4. Habitat Quality Service

The "Habitat Quality" module is a comprehensive indicator that assesses habitat suitability and degradation levels in the study area [51]. It utilizes land use data as a base and incorporates the maximum influence distance and relative weight of stress factors on habitats, along with the habitat suitability of different land classes and their sensitivity to stress factor disturbances. Regional habitat quality is assessed using the following formula:

$$Q_{xj} = H_j \left[1 - \left(\frac{{D_{xj}}^z}{{D_{xj}}^z + k^z} \right) \right], \tag{13}$$

where Q_{xj} represents the habitat quality index for grid x in land use type j. H_j is the habitat suitability score of land use type j. k represents the half-saturation constant, initially set to 0.5. D_{xj} represents the degradation degree of the habitat under the influence of stressors, which is referred to as the habitat degradation index.

The emergy of habitat quality services in the YRD was calculated based on the Habitat Quality Index. The formula is as follows [41].

$$m_{hq} = Q_{hq} \times T_{hq}, \tag{14}$$

where Em_{hq} represents the total emergy of habitat quality service (sej). Q_{hq} is the physical quantity of habitat quality (%). T_{hq} represents the emergy transformity rate of habitat quality, with the value of 2.92×10^{19} sej/y [50]. Parameters are shown as Supplementary Information.

The monetary values of habitat quality services were calculated based on the EMR in the emergy analysis results. The formula is as follows:

$$Em\$_{SC} = \frac{Em_{SC}}{EMR}, \tag{15}$$

where $Em\$_{SC}$ represents the value of the habitat quality service ($). Em_{SC} is the emergy of the habitat quality service (sej). EMR is the emergy–money ratio (sej/$).

2.3.5. Soil Retention Service

Soil retention is a critical issue with significant implications for human well-being and ecosystem functioning. Soil retention service refers to the ability of ecosystems to reduce soil erosion. This study uses the InVEST Sediment Delivery Ratio (SDR) model to estimate the soil retention service in the YRD region [52]. The formula is as follows:

$$Q_{SC} = A_p - A_r, \tag{16}$$

$$A_p = R \times K \times LS, \tag{17}$$

$$A_r = R \times K \times LS \times C \times P, \tag{18}$$

where Q_{sc} represents the potential soil retention quantity (t). A_p represents the potential soil erosion quantity (t). A_r represents the actual soil erosion quantity (t). LS denotes the slope length and steepness factor. C accounts for the vegetation cover and management factor. P signifies the soil retention practice factor. R is the rainfall erosivity factor. K is the soil erodibility factor.

The emergy of the soil retention services in the Yellow River Delta was calculated based on the physical quantity of soil retention. The formula is as follows:

$$Em_{SC} = Q_{SC} \times \mu \times T_{SC}, \tag{19}$$

where Em_{sr} represents the emergy of soil retention service (sej). Q_{sr} is the physical quantity of soil retention (t). μ is the energy conversion ratio for the topsoil layer (6.78 × 10^2 J). T_{cp} represents the emergy transformity rate of soil retention, with the value of 7.4 × 10^4 sej/J [50]. Parameters are shown as Supplementary Information.

The monetary values of soil retention services were calculated based on the *EMR* in the emergy analysis results. The formula is as follows:

$$Em\$_{SC} = \frac{Em_{SC}}{EMR}, \tag{20}$$

where $Em\$_{sr}$ represents the value of the soil retention service (\$). Em_{sr} is the emergy of the soil retention service (sej). *EMR* is the emergy–money ratio (sej/\$).

2.3.6. The Total Value of Ecosystem Services

The total value of ecosystem services is equal to the sum of individual ecosystem service values. The calculation formula is as follows:

$$Em_i = Q_i \times T_i, \tag{21}$$

$$EMR = \frac{Em_T}{GDP}, \tag{22}$$

$$Em\$_i = \frac{Em_i}{EMR}, \tag{23}$$

$$\mathrm{Em\$} = \sum_{i=1}^{5} \frac{Em_i}{EMR}, \tag{24}$$

where Em_i represents the emergy of the i-th ecosystem service. Q_i represents the physical quantity of the i-th ecosystem service. T_i represents the emergy transformity rate of the i-th ecosystem service. *EMR* is the emergy–money ratio of the study area. Em_T stands for the total emergy of the ecosystem in the study area. GDP represents the gross domestic product of the study area. $Em\$_i$ stands for the i-th ESV. Em\$ stands for the ESV.

3. Results

3.1. Emergy of Ecosystem Service

Over the period from 1990 to 2020, we evaluated the ecosystem service energy value of the YRD from a spatiotemporal perspective.

From the perspective of overall changes (Tables 2 and 3), the total emergy of ecosystem services in the YRD showed a declining trend from 1990 to 2010, with the emergy decreasing from 1.41 × 10^{21} sej in 1990 to 8.16 × 10^{20} sej in 2010, representing a decrease of 42.09%. However, from 2010 to 2020, the total emergy of ecosystem services exhibited an upward trend, increasing from 8.16 × 10^{20} sej in 2010 to 1.06 × 10^{21} sej in 2020, an increase of 29.78%. During the period from 1990 to 2010, except for the sharp increase in the emergy of food production, the emergy of habitat quality, carbon storage services, soil conservation services, and water retention services all showed a declining trend. However, during the period from 2010 to 2020, except for the declining trend of habitat quality, the emergy of the other services showed an upward trend. From 1990 to 2010, the emergy of habitat quality services exhibited an overall declining trend, decreasing from 1.41×10^{20} sej in 1990 to 1.17×10^{20} sej in 2010, representing a decrease of 17%. This decline is primarily attributed to the rapid expansion of human-intensive development areas, including urban construction, farmland, industrial land, and reclaimed aquaculture, which resulted in the gradual replacement of habitat land and a continuous decline in habitat quality. The carbon storage service experienced a decline of 16%, decreasing from 5.60×10^{20} sej in 1990 to 4.70×10^{20} sej in 2010. This reduction is due to a decrease in the area of forests and grasslands, areas with high vegetation cover that possess a greater capacity for carbon storage. The expansion of urban construction land has led to a decrease in the emergy of carbon storage services. The emergy of soil retention services decreased by 59% in 2010 compared to 1990. This decline can be attributed to the accelerated urbanization process and the expansion of aquaculture ponds, which disrupted the original vegetation and led to a reduction in soil conservation functionality. The emergy of water conservation services decreased by 84% in 2010 compared to 1990. This decline can be primarily attributed to the accelerated urbanization process and the expansion of aquaculture ponds along coastal marshes, which led to a reduction in the area of forests and marshes. The emergy of crop production significantly increased from 2.40×10^{20} sej in 1990 to 7.13×10^{20} sej in 2010, mainly due to the rapid expansion of cultivated land in the Yellow River Delta. This expansion led to a substantial increase in the energy value of crop production. However, there was some improvement between 2010 and 2020. The emergy of carbon storage services, soil retention services, and water conservation services have shown an upward trend, while habitat quality and food production have experienced a slight decline. This can be attributed to the impact of the policy on converting farmland to forest, which has resulted in a decrease in farmland area and an increase in forest land area. Consequently, the emergy of carbon storage services, soil retention services, and water conservation services increased by 6%, 62%, and 7%, respectively. However, the emergy of crop production decreased by 11%, from 7.13×10^{20} sej in 2010 to 6.32×10^{20} sej. During the period from 2010 to 2020, the emergy of habitat quality continued to exhibit a declining trend, with a reduction rate of 3%. This can be primarily attributed to the continued expansion of residential and industrial land, leading to the destruction of natural habitats.

Table 2. Emergy statistics for YRD's ecosystem services.

	Carbon Storage (sej)	Crop Production (sej)	Habitat Quality (sej)	Water Conservation (sej)	Soil Retention (sej)	Em_T
1990	5.60×10^{20}	2.40×10^{20}	1.41×10^{20}	5.58×10^{20}	8.49×10^{20}	1.41×10^{21}
2000	5.40×10^{20}	3.94×10^{20}	1.29×10^{20}	1.27×10^{20}	5.06×10^{20}	1.05×10^{21}
2010	4.70×10^{20}	7.13×10^{20}	1.17×10^{20}	8.94×10^{19}	3.46×10^{20}	8.16×10^{20}
2020	5.00×10^{20}	6.32×10^{20}	1.13×10^{20}	9.54×10^{19}	5.59×10^{20}	1.06×10^{21}

Table 3. Emergy changes of ecosystem services.

	Carbon Storage	Crop Production	Habitat Quality	Water Conservation	Soil Retention
1990–2010	−16%	197%	−17%	−84%	−59%
2010–2020	6%	−11%	−3%	7%	62%
1990–2020	−11%	163%	−20%	−83%	−34%

Based on the spatio-temporal analysis presented in Figure 3, the high value of crop production is primarily derived from the farmland areas in the central part of the study area, with the highest yields observed in the Kenli District and Lijin County. The high-value areas of crop production gradually expand along the southern, northern, and eastern regions along the banks of the Yellow River (Figure 3a). It is evident that the areas with high-value habitat quality are concentrated in the central–southern and central–northern regions of the study area, encompassing forested and grassland areas as well as coastal wetlands. In contrast, the areas with low-value habitat quality are predominantly found in regions characterized by intensive human activities, such as cultivated land, industrial land, residential areas, and aquaculture ponds. However, between 1990 and 2020, the forest and grassland areas in the central–southern region have gradually been encroached upon by cultivated land and residential areas. Meanwhile, the unregulated expansion of aquaculture ponds and salt fields in coastal wetland areas has resulted in a decrease in high-value areas and an outward expansion of low-value areas. Consequently, there has been a gradual decline in habitat quality (Figure 3b). The high-value areas of water conservation have gradually shifted from the central–southern and central–northern regions of the study area towards the eastern part. In contrast, the low-value areas, which were sporadically distributed within the study area in 1990, rapidly expanded towards the coastal wetlands (Figure 3c). High-value carbon storage is predominantly concentrated in the central region, which encompasses forested, grassland, and cultivated land areas. These areas exhibit high vegetation coverage, indicating relatively favorable conditions for ecosystem services and substantial levels of biotic carbon storage. Conversely, low-value carbon storage is sporadically distributed in the industrial land located in the eastern part of the study area (Figure 3d). The high-value areas of soil retention are primarily distributed along the inner ring of the coastal wetlands. Between 1990 and 2010, there was a gradual decrease in the extent of these high-value areas. However, they exhibited a gradual increase from 2010 to 2020 and shifted towards the central and eastern parts of the study area. The low-value areas, on the other hand, expanded from the eastern to the northeastern part of the study area. This particular region is characterized by the presence of industrial land, which increases the risk of soil exposure and erosion. Furthermore, it negatively affects the soil's water infiltration capacity and overall quality (Figure 3e).

3.2. Assessment of ESV

In terms of trends (Tables 4 and 5), the ESV experienced a decline of 64% from 1990 to 2010, with a total decrease of USD 5.96 billion. However, during the period from 2010 to 2020, the ESV indicated a growth rate of 17%, with a total increase of USD 560 million. Specifically, between 1990 and 2010, the values of carbon storage, water conservation, soil retention, and habitat quality showed a decreasing trend, with respective decreases of USD 1.23 billion, USD 2.14 billion, USD 2.84 billion, and USD 330 million. These reductions corresponded to decreasing rates of 59%, 92%, 81%, and 59%. In contrast, the value of crop production increased by USD 674 million, representing a growth rate of 94% during the same period. From 2010 to 2020, the values of carbon storage, water conservation, soil retention, habitat quality, and crop production all showed an increasing trend, with respective increases of USD 229 million, USD 42 million, USD 200 million, USD 28 million, and USD 60 million. The growth rates were 25%, 24%, 29%, 12%, and 29%, respectively.

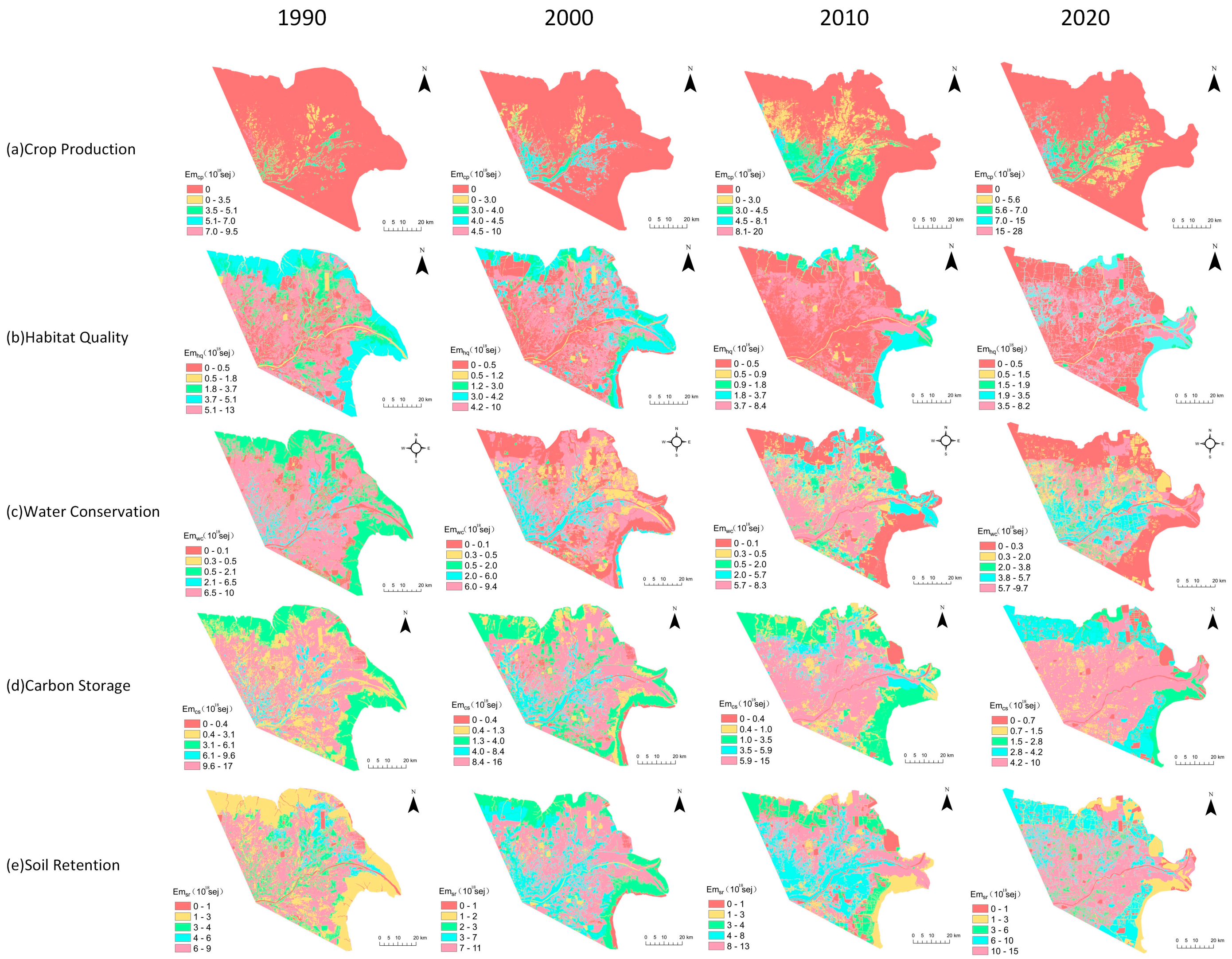

Figure 3. The spatial distribution of emergy of ecosystem services from 1990 to 2020. The investigated ecosystem services are (**a**) crop production, (**b**) habitat quality, (**c**) water conservation, (**d**) carbon storage, and (**e**) soil retention.

Table 4. Economic value statistics of ecosystem services.

	Carbon Storage ($)	Crop Production ($)	Habitat Quality ($)	Water Conservation ($)	Soil Retention ($)	Total ($)
1990	2.23×10^9	7.16×10^8	5.61×10^8	2.32×10^9	3.52×10^9	9.35×10^9
2000	1.02×10^9	8.37×10^8	2.74×10^8	4.56×10^8	1.07×10^9	3.66×10^9
2010	9.11×10^8	1.39×10^9	2.31×10^8	1.76×10^8	6.82×10^8	3.39×10^9
2020	1.14×10^9	1.45×10^9	2.59×10^8	2.18×10^8	8.82×10^8	3.95×10^9

Table 5. Value changes of ecosystem services.

	Carbon Storage ($)	Crop Production ($)	Habitat Quality ($)	Water Conservation ($)	Soil Retention ($)	Total ($)
1990–2010	−59%	94%	−59%	−92%	−81%	−64%
2010–2020	25%	4%	12%	24%	29%	17%
1990–2020	−49%	103%	−54%	−91%	−75%	−58%

Regarding spatial changes, the high-value area of the ESV showed a continuous reduction from 1990 to 2010. From 2010 to 2020, the high-value area slightly increased and expanded towards the inner ring of the coastal tidal flats and the eastern part of the study area. At the same time, the low-value area consistently expanded towards the coastal tidal flats. In 1990 and 2000, the high-value area of the ESV was mainly concentrated in the forest and grassland areas in the southern and northern regions of the study area, along with the coastal tidal flats area. By 2010, the high-value area shifted to the farmland in the central part of the study area and the surrounding grassland regions. However, due to the rapid expansion of aquaculture ponds in the coastal tidal flats region and the encroachment of farmland on grassland and forestland, the high-value area of ESV continued to shrink. As of 2020, the high-value area was predominantly located in the cultivated land in the central part of the study area, the surrounding grassland regions, and the forested areas in the eastern river mouth region. The low-value area, on the other hand, mainly encompassed the northern and southeastern coastal aquaculture pond regions, along with the northeastern industrial land. The low-value area expanded rapidly each year from 1990 to 2020 (Figure 4f).

From the perspective of various ecosystem services, high-value crop production is primarily distributed along the banks of the Yellow River, with the high-value area continuously expanding (Figure 4a). Between 1990 and 2020, the high value of habitat quality shifted from the southern and northern parts of the study area towards the north–central region, resulting in a continuous reduction in the high-value area. The low-value area gradually expanded towards the coastal tidal flats and the southern part of the study area (Figure 4b). The high value of water conservation gradually shifted from the southern and northern parts of the study area towards the eastern region, characterized by extensive vegetation. The root systems of these areas can penetrate and absorb water, contributing to groundwater replenishment. The low-value area rapidly expanded from sporadic distribution within the study area towards the coastal tidal flats, resulting in a significant increase in the low-value area (Figure 4c). The high value of carbon storage exhibited a relatively balanced spatial distribution, mainly concentrated in the central part of the study area, encompassing farmland, forestland, and grassland regions with higher vegetation coverage. The low value was sporadically distributed in the eastern industrial land (Figure 4d). The high-value soil retention moved from the inner ring of the coastal tidal flats towards the central and eastern parts of the study area, where forestland, grassland, and farmland are situated. The root systems of these areas effectively stabilized the soil, mitigating soil erosion and runoff. The low-value area was mainly found in the eastern Yellow River estuary and industrial land (Figure 4e).

The ESVs from 1990 to 2020 were USD 9.35 billion, USD 3.66 billion, USD 3.39 billion, and USD 3.95 billion, respectively (Table 4). Among them, the proportions of carbon storage value were 23.9%, 27.9%, 26.9%, and 28.9%. The proportions of water conservation value were 24.8%, 12.5%, 5.2%, and 5.5%. The proportions of soil retention values were 37.6%, 29.2%, 20.1%, and 22.3%. The proportions of habitat quality values were 6.0%, 7.5%, 6.8%, and 6.6%. The proportions of crop production values were 7.7%, 22.9%, 41.0%, and 36.7% (Figure 5). In summary, the value of carbon storage remained a significant and relatively stable part of the ESV from 2010 to 2020. The value of habitat quality showed minimal overall change but had a relatively smaller share. The proportion of soil retention values continued to decrease, but there was an increasing trend from 2010 to 2020. The value of water conservation experienced a relatively larger decrease, while the value of crop production showed a significant increase.

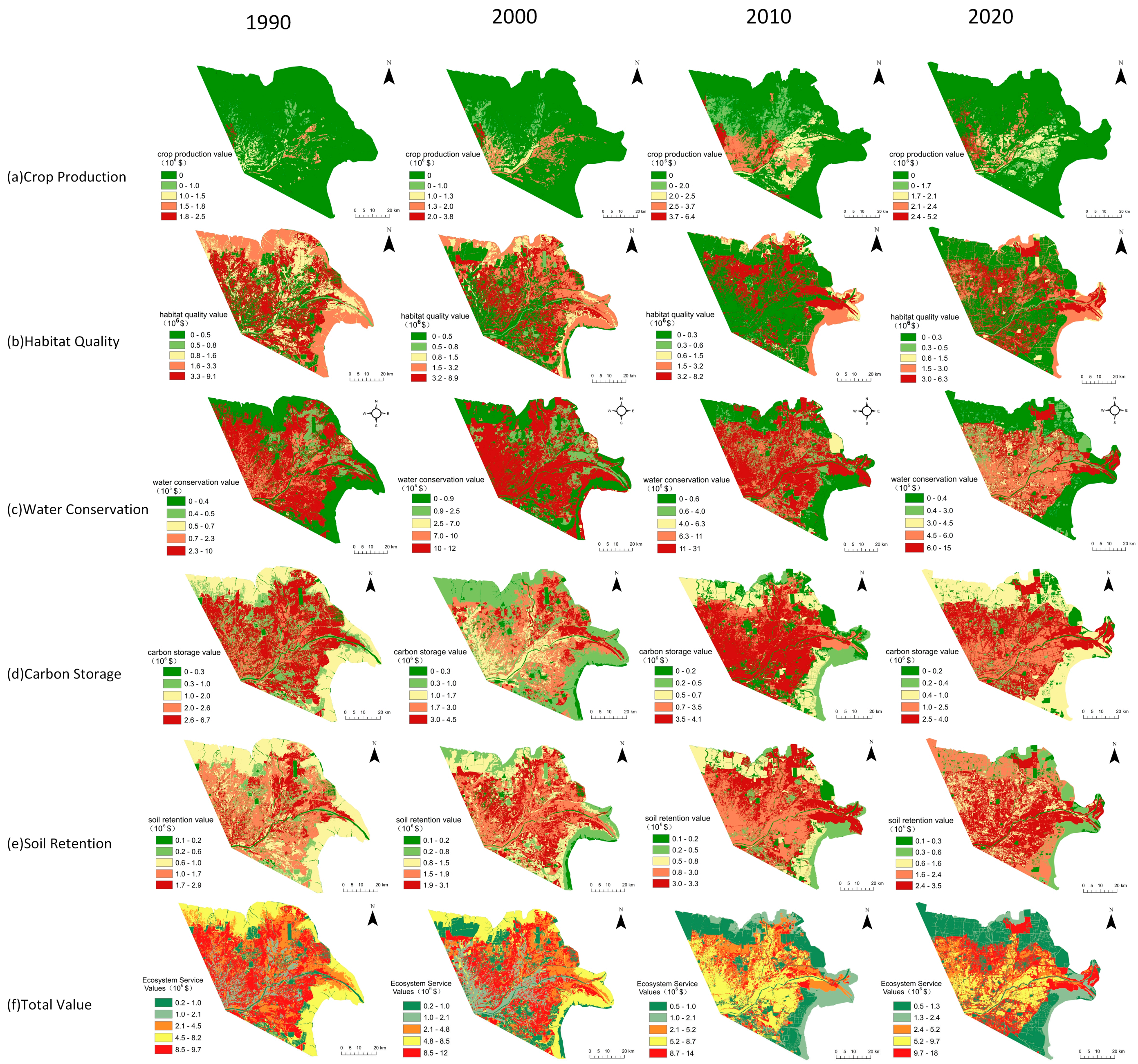

Figure 4. The spatial distribution of ecosystem service values from 1990 to 2020. The investigated ecosystem services are (**a**) the value of crop production, (**b**) the value of habitat quality, (**c**) the value of water conservation, (**d**) the value of carbon storage, (**e**) soil retention, and (**f**) ESV.

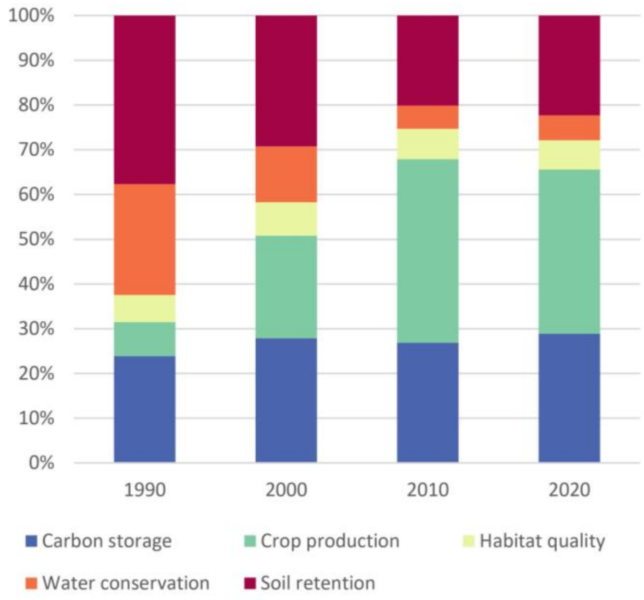

Figure 5. Proportion of ESV in YRD from 1990 to 2020.

4. Discussion

4.1. The Changes in YRD's ESV

Previous studies on ESV in the YRD mainly focused on ecological issues and prominent functional areas such as Dongying City, coastal wetlands, the Yellow River Estuary, and nature reserves. This study analyzed the changes and causes of ESV at the scale of the Yellow River Delta basin under the joint influence of economic development and ecological functions. The study results reveal a decrease in the ESV in the YRD from 1990 to 2010, with a total reduction of USD 5.96 billion. However, between 2010 and 2020, a noticeable increase in the ESV occurred, amounting to a total rise of USD 560 million. Based on the equivalent factor method, Liu et al. [53] revealed that the total value of ecosystem services in the coastal wetlands of the YRD showed a decreasing trend from 2000 to 2010. Using the energy analysis method, Wang et al. [2] suggested that the total value of ecosystem services in the high-efficiency ecological economic zone of the YRD showed an increasing trend from 2009 to 2025. These results are consistent with the findings of this study.

When assessed in terms of emergy, the ecosystem services in 2010 exhibited a declining trend compared to 1990 in the YRD. When considering the EMR for the respective years, the monetary value of ecosystem services also exhibited a declining trend compared to 1990. This is mainly attributed to changes in the EMR of the YRD during the period from 1990 to 2010. Odum [54] and Lan et al. [55] suggested that the energy-to-currency ratio is typically much lower in developed countries or regions compared to underdeveloped ones. This is because developing countries often require a higher energy input for each unit of GDP. The decrease in the emergy of ecosystem services in the YRD during 1990–2010 resulted from excessive land and resource exploitation, increased environmental pollution, and ecosystem degradation. This led to a weakened supply capacity of ecosystem services while the EMR showed an upward trend. The EMR in the Yellow River Delta was 2.51×10^{11} sej/$ in 1990, which increased to 4.71×10^{11} sej/$ in 2000 and further rose to 5.07×10^{11} sej/$ in 2010. This indicates an improvement in social productivity and significant socio-economic development in Dongying, as reflected in the substantial growth of GDP from USD 1.1 billion in 1990 to USD 6.6 billion in 2010. However, the excessive exploitation of resources resulted in severe disturbances and degradation of the ecosystem, leading to a weakened supply capacity of ecosystem services. The rapid economic development exerted tremendous pressure on the ecological environment, causing a continuous decline in the functionality of the natural ecosystems. Consequently, the ESV in 2010 experienced a decline rate of 64%. Furthermore, during the period from 2010 to 2020, the ESV in the YRD exhibited an increasing trend. This can be attributed to the modernization process that the YRD region underwent during this period. With economic growth and technological advancements, the energy and resource values provided by ecosystem services were used more efficiently, resulting in an increase in emergy. However, the EMR showed a declining trend, indicating a decrease in the monetary value corresponding to a unit of emergy. The EMR decreased from 5.01×10^{11} sej/$ in 2010 to 4.37×10^{11} sej/$ in 2020. Regional GDP increased from USD 6.6 billion in 2010 to USD 9.1 billion in 2020. This indicates a rising level of modernization in the YRD. However, with increased awareness of environmental protection and ecological values, measures such as environmental taxation and ecological compensation were implemented to reduce excessive exploitation of environmental resources. As a result, the ESV showed an upward trend from 2010 to 2020, with a growth rate of 17%.

4.2. The Impact of LUCC Change on ESV

Land use/land cover change (LUCC) inevitably impacts the ESV [56]. Values corresponding to different land use types were extracted based on land use maps of the YRD in 1990, 2000, 2010, and 2020 (Figure 6). The ESV of various land use types in the YRD from 1990 to 2020 ranked as follows: grassland > mudflat > farmland > forestland > Yellow River > open water > saline–alkali land (Figure 6). Zhang et al. [57] found that the grassland ESV was the highest in the ecological assessment, consistent with the trend of changes in this study. Among them, the value of grassland decreased from USD 4.81 billion in 1990 to USD 1.57 billion in 2010, with a decline rate of 67%. This decline was mainly due to the conversion of grassland into construction land and cropland. Cropland area rapidly increased from 376 km^2 in 1990 to 1477 km^2 in 2010, while construction land expanded from 75 km^2 to 235 km^2. In contrast, grassland area decreased from 1751 km^2 to 618 km^2, with a decline rate of 65%. This transformation might be driven by the need for crop production, urban expansion, or economic development, resulting in a reduction of ESV provided by grasslands. From 2010 to 2020, the value of grassland showed an overall increasing trend, rising from USD 1.57 billion to USD 2.10 billion. This increase was attributed to ecological protection strategies implemented in the YRD, such as grassland restoration programs. During this period, the cropland area decreased from 1477 km^2 to 835 km^2, while the grassland area increased from 618 km^2 to 1230 km^2, and the forestland area increased from 629 km^2 to 906 km^2. These policies of converting cropland to grassland and forestland enhanced the stability and ecosystem service functions of the region, resulting in the observed increase in grassland value. Additionally, the value of mudflats exhibited an overall decreasing trend from 1990 to 2020, decreasing from USD 3.80 billion to USD 484 million, with a decline rate of 87%. This decline was primarily attributed to the rapid expansion of salt ponds and aquaculture sites encroaching on mudflats. The salt pond area increased from 15 km^2 to 180 km^2, and the aquaculture pond area increased from 493 km^2 to 976 km^2, while the mudflat area decreased from 1256 km^2 in 1990 to 436 km^2 in 2020. This transformation negatively impacted the vegetation and habitat of the mudflat, resulting in degradation, wetland loss, and a decline in biodiversity. As a result, the ESV provided by the mudflat was reduced.

4.3. Limitations and Future Work of the Study

This study aims to make the intangible ecosystem service functions of natural resources explicit, which can lay the foundation for establishing a mechanism that combines positive incentives and negative pressure to achieve the realization of ecological product value. Within the scope of this study, it is important to note the following limitations, which should be further explored in future studies. Firstly, due to limited data availability, parameter data such as soil conservation and carbon density in carbon storage are obtained based on relevant literature and empirical formulas from previous studies. In the future, it is hoped that field measurements and other methods can be used to further study the corresponding data and parameters, and other models can be combined with the InVEST model to improve the accuracy of data results. Secondly, this paper evaluates five types of service functions within the study area, namely carbon storage, soil retention, habitat quality, crop production, and water conservation. In the future, a more comprehensive evaluation system will be constructed by selecting a greater variety of ecosystem service types. The changing value of ecosystem services in the YRD will be thoroughly examined by including aspects like recreational tourism. Moreover, the YRD region has a relatively vast wetland area, and further research is needed to account for wetland ecological service functions based on the energy theory. At the same time, research on ecosystem service flows (emergy flow and value flow) and the actual impact range of service values also need to be further deepened. Additionally, there are controversies regarding the concept, classification system, evaluation methods, and accuracy of ecosystem services. There are inherent uncertainties in the quantification or monetization of ecosystem services, and the socio-economic development levels vary among countries and regions. Consequently, ESV may fluctuate depending on the specific research area. More data and innovative methods are needed to reduce these uncertainties in future studies, promote the research results on ecosystem service value to be put into practice, and apply the quantitative evaluation results of ecosystem service value to the establishment of regional ecosystem management systems and the formulation of ecosystem compensation policies.

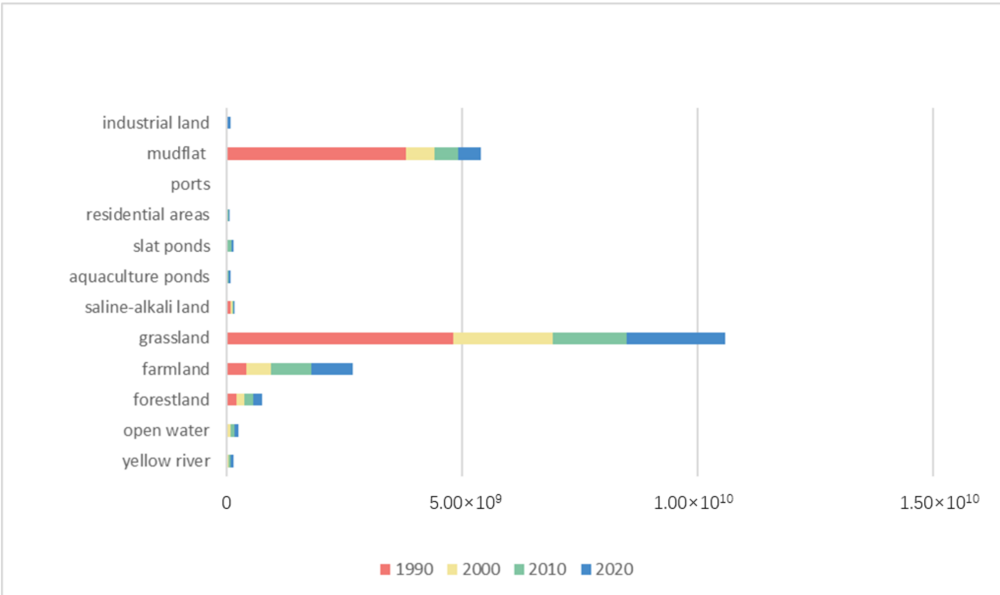

Figure 6. ESV of different land use types from 1990 to 2020.

5. Conclusions

This study utilized the concept of “emergy” as an “intermediate quantity” that bridges the gap between physical quantity and value, enabling a quantitative analysis that integrates ecological and economic systems. The research assessed the emergy value and total value of five ecosystem services in the YRD from 1990 to 2020 and subsequently analyzed their spatiotemporal changes. The findings are as follows:

(1) The total ecosystem service emergy of the YRD showed a decreasing increasing trend from 1990 to 2020, with the lowest energy values ranging from 1.41×10^{21} to 1.06×10^{21}, indicating a degradation of ecosystem service functions. During the period from 1990 to 2010, with the exception of crop production services, which saw a significant increase, the emergy of the other five ecosystem services displayed a decreasing trend. From 2010 to 2020, the emergy of ecosystem services in the YRD experienced an increase with the exception of crop production and habitat quality services.

(2) With the development of the social economy, construction land, salt fields, and aquaculture ponds continue to expand. The ESV of the YRD shows a decreasing increasing trend, ranging from USD 9.35 billion to USD 3.95 billion, with the lowest in 2010, causing a con-

tinuous decline in the functionality of the natural ecosystems. Grasslands and mudflats are the main land types contributing to ESV. The government departments should coordinate the contradiction between economic development and ecological protection, strengthen the protection of land use in areas with high ecosystem service value, scientifically and reasonably prepare regional construction and ecological protection plans, optimize the spatial layout of land use, and strictly protect the existing forest land, grassland, mudflats, and other ecological land.

(3) During the period from 1990 to 2010, there was a continuous reduction in the high-value area of ESV. From 2010 to 2020, the high-value area showed a slight increase, expanding towards the inner coastal mudflat and the eastern part of the study area. According to the spatial distribution of ESV in the YRD from 1990 to 2020, priority should be given to ecological compensation for low-value areas, which face greater threats and risks. Ecological compensation measures can restore and improve their ecological functions and enhance the resilience and adaptability of the ecosystem.

In the context of rapid urbanization, visualizing the ESV can provide decision-makers with a science-based reference for developing regional development plans, implementing ecological conservation measures and formulating ecological compensation policies.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land13030276/s1, Table S1:The carbon density of each land use/land cover (mg/ha); Table S2: Biophysical table of water yield; Table S3: Biophysical table of soil retention; Table S4: Threat source impact distance level weights; Table S5: Sensitivity of threat factors for different land uses; Table S6. Emergy transformity rate. References [58–61] are cited in the supplementary materials.

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