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Spatiotemporal Heterogeneity of Coastal Wetland Ecosystem Services in the Yellow River Delta and Their Response to Multiple Drivers

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Abstract: Understanding on the spatiotemporal interactions between ecosystem services (ESs) and social–ecological drivers is crucial for the design of sustainable development strategies for coastal wetlands. In this paper, we took the Yellow River Delta (YRD) as a case study, based on multiple evaluation methods to study the spatiotemporal dynamics of ESs in the YRD from 1980 to 2020. With the help of principal component analysis (PCA) for identification of multiple drivers, we researched the spatiotemporal differentiation and influence mechanism of drivers on ESs, using the coupling coordination degree (CCD) model and geographically and temporally weighted regression (GTWR) model, and subsequently provided the development strategy for each district in Dongying City. The results showed that (1) the patterns of ESs were spatially heterogeneous, with a fluctuating upward trend from 1980 to 2020, which was mainly affected by regulating service. (2) Our spatiotemporal analysis of ES interactions identified that cultural service was mainly disorder with other ESs. Nevertheless, in wetlands, various ESs can basically develop in a coordinated manner. (3) We integrated multiple drivers into five principal components by PCA, to which the response of ESs had spatial heterogeneity. (4) Consequently, we integrated spatiotemporal knowledge on ES interactions and their drivers into spatial planning.

Keywords: Yellow River Delta; ecosystem service; coupled coordination degree; multiple driver; spatiotemporal heterogeneity

1. Introduction

Coastal wetland ecosystems provide a wealth of ecosystem goods and services to human societies [1], and directly or indirectly may facilitate sustainable human well-being [2,3], but coastal wetland ecosystems are also under serious threat from natural and human disturbances [4,5], such as sea level rise, reclamation [6], overuse [5], pollution, coastal erosion [7], and biological invasion [8]. Parallel with that, coastal wetland ecosystem services (ESs) are at risk of developmental dissonance between them [9], which not only results in the loss of coastal wetland ecosystem diversity [7], but also seriously weakens coastal wetland ESs [10]. In order to ensure the ability to provide human well-being continuously and examine the coordinated development level of urbanization and ESs, it is of great significance to assess the value of coastal wetland ESs scientifically [11], and explore the impact of social–ecological drivers on ESs, whose spatial heterogeneity can be conducive to a more efficient coastal resources development strategy, to ensure the better sustainable use of coastal resources [12].

Dongying City, located in the north of Shandong Province, is in the junction region of rivers, land, and sea, as a typical ecological transition zone. Over the past decades of reform and opening up, the land use/land cover (LULC) of Dongying City has undergone tremendous changes, and is currently the petrochemical base of Shandong Province, with

a large number of industrial construction lands [11]. In particular, with strong human interference, as an important part of the Yellow River Delta (YRD), Dongying City has the social–economic conditions directly relating to the Yellow River estuary and also has a great impact on the whole Shandong Province, which faces major ecological problems, such as salinization and vegetation destruction [11,13]. Therefore, this paper selected Dongying City, a typical municipal area where the YRD is located, as the study area.

The previous studies on the trade-offs/synergies between ESs poorly understood the spatial dynamics of coupled coordination among complex systems, so the coordination degree between ESs has not yet been fully investigated [14]. In view of this research gap, this study evaluated the interactions and coupled coordination of ESs in the YRD from 1980 to 2020 using the coupled coordination degree (CCD) model. Moreover, the correlation between drivers has largely been ignored by previous studies [15,16], which may lead to information redundancy, resulting in the complexity and uncertainty of subsequent analysis. Principal component analysis (PCA) can transform a group of related variables into a group of unrelated principal components (PCs), reducing information redundancy while maintaining the original information as much as possible, which reduces the calculation workload and increases the accuracy of subsequent analysis [17]. Consequently, multiple drivers summarized by this paper were transformed into several unrelated PCs by PCA, eliminating the impact of correlation between them. In addition, the analysis of coastal wetland ESs should consider not only the spatial heterogeneity of regionalization process variables, but also their temporal unsteadiness, which was what previous studies [18–20] lacked for comprehensive consideration. This study incorporated the geographically and temporally weighted regression (GTWR) model, which could reveal the spatiotemporal response characteristics of the regional ESs to the drivers more comprehensively [21], so as to provide theoretical support for the development of regionally ecological conservation measures.

The objectives of this study were to (1) reveal the spatiotemporal dynamics of ESs in the YRD from 1980 to 2020; (2) determine the spatial heterogeneity of trade-offs/synergies and CCD between ESs; (3) identify the dominant social–ecological drivers of ESs, as well as their spatial heterogeneity; (4) provide insights into the spatial planning and management strategies of Dongying City. The research framework diagram of this study is shown in Figure 1.
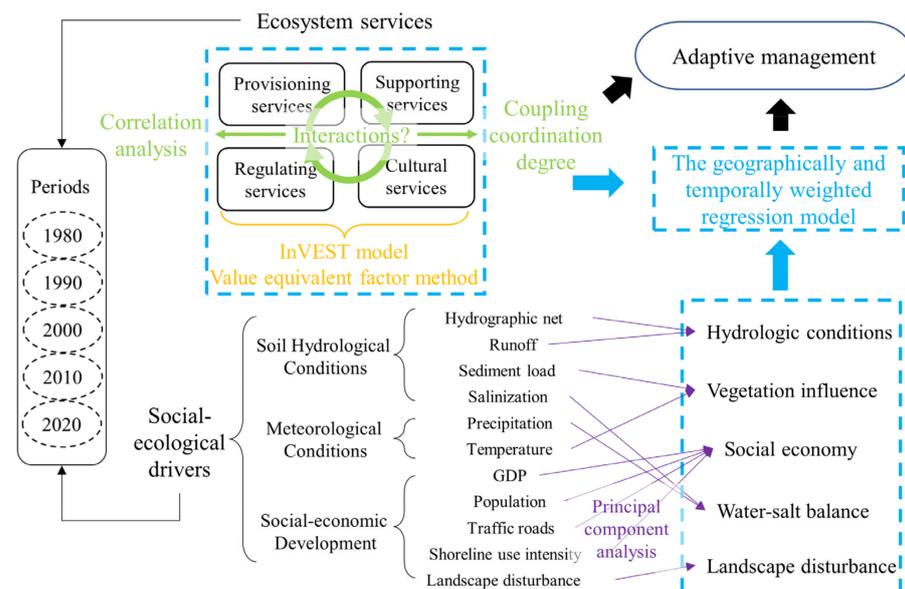

Figure 1. Research framework diagram. Green symbols represent the estimation method of the interaction of ecosystem services; yellow symbols represent the estimation method of ecosystem services; purple symbols represent principal component analysis; blue symbols represent geographically and temporally weighted regression model.

2. Materials and Methods

2.1. Study Area

Considering the integrity of the administrative region and the availability of research data, the entire Dongying city was taken as the study area in this study (Figure 2).
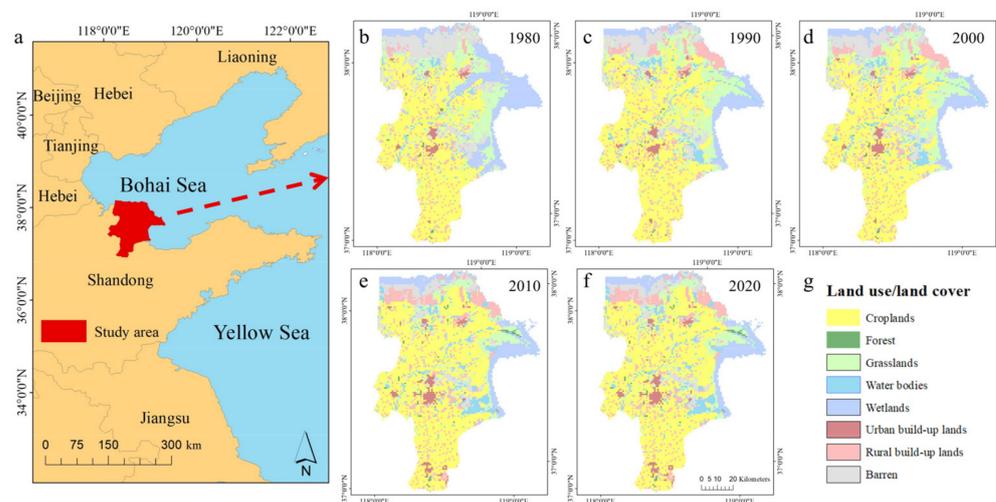
Figure 2. The location of Dongying city and its land use/land cover (LULC). (**a**) The location of Dongying city. (**b**–**f**) The LULC of Dongying city in 1980, 1990, 2000, 2010, and 2020, which was adopted from remote sensing monitoring data of LULC in China (http://www.dsac.cn/DataProduct/Detail/200804) (accessed on 1 February 2023). (**g**) The legends of LULC.

In terms of administrative division, 93% of the YRD belongs to Dongying City and 7% to Binzhou City [11]. Consequently, previous research on the YRD mostly focused on the whole Dongying City (118°7′~119°10′E, 36°55′~38°10′N), including Dongying District, Hekou District, Kenli County, Lijin County, and Guangrao County.

The YRD is a new land formed by the deposition of the Yellow River in the past hundred years, and has a continental monsoon climate. The terrain of the YRD inclines from southwest to northeast along the Yellow River trend, and the natural gradient is 1/8000~1/12,000, due to which a large amount of sediment is deposited in the Yellow River, forming the "suspended river on the ground". This area has large groundwater mineralization, high soil salinity, few woody plants, and a meadow landscape as the main body. The distribution of vegetation is mainly restricted by water, soil salinity, phreatic water level, landform type, and human activities [11].

2.2. Data Sources

The data sources for the assessment of ESs and social–ecological drivers are shown in Table 1. According to the research purpose and regional characteristics, LULC is divided into eight categories: croplands, forest, grasslands, water bodies, wetlands, urban built-up lands, rural built-up lands, and barren. After obtaining data for 1980, 1990, 2000, 2010, and 2020 in Table 1, all raster data with different spatial resolutions were resampled to 30 m × 30 m resolution to ensure the accuracy of the regional research by referring to relevant research [13,22].

2.3. ES Assessment

We identified 10 ESs based on the following criteria: (1) consistency with the classification of ESs by Millennium Ecological Assessment (MEA) [26] and previous studies [27]; (2) representativeness of ESs for social–economic conditions in the study area; (3) availability and feasibility of data. According to the characteristics of the YRD and the classification of ESs in the MEA [26], the YRD wetland ESs were classified as supporting service (SS), regulating service (RS), provisioning service (PS), and cultural service (CS) (Table 2). The

final evaluation system included 10 indicators, namely food production (FP), raw material (RM), soil conservation (SC), carbon storage (Ca.), habitat quality (HQ), gas regulation (GR), climate regulation (CR), water yield (WY), waste treatment (WT), and relaxation (Re.). Firstly, the ESs in 1980, 1990, 2000, 2010, and 2020 were quantified in monetary form. For the subsequent analysis, we superimposed all ESs classifications into four categories, namely SS, RS, SS, and CS.

Table 1. Summary of the primary data.

Data Type	Data Source/Processing
LULC	Remote sensing monitoring data of LULCs in China (http://www.dsac.cn/DataProduct/Detail/200804) (accessed on 1 February 2023)
Precipitation	WorldClim Historical monthly weather data [23,24] (https://www.worldclim.org/data/monthlywth.html) (accessed on 1 February 2023)
Temperature	WorldClim Historical monthly weather data [23,24] (https://www.worldclim.org/data/monthlywth.html) (accessed on 1 February 2023)
Digital elevation model (DEM)	SRTMDEMUTM 90M Resolution DEM Products (https://www.gscloud.cn/sources/accessdata/306?pid=302) (accessed on 3 February 2023)
Net primary productivity (NPP)	1 km raster dataset of monthly NPP of terrestrial ecosystems in China (http://www.geodoi.ac.cn/WebCn/doi.aspx?Id=1212) (accessed on 3 February 2023)
Rainfall erosivity	Rainfall erosivity mapping over mainland China based on high-density hourly rainfall records [25] (https://gda.bnu.edu.cn/sypt/sjgx/tdlytdfgsjj/111228.html) (accessed on 3 February 2023)
Hydrographic net	Euclidean distance from Yellow River
Gross domestic product (GDP)	Resource and Environment Science and Data Center (https://www.resdc.cn/DOI/DOI.aspx?DOIID=33) (accessed on 3 February 2023)
Population	WorldPop Open Population Repository (WOPR) (https://hub.worldpop.org/) (accessed on 7 February 2023)
Landscape disturbance	Remote sensing monitoring data of LULCs in China (http://www.dsac.cn/DataProduct/Detail/200804) (accessed on 1 February 2023)
Traffic roads	Euclidean distance from roads, whose data were obtained from OpenStreetMap (http://www.openstreetmap.org/) (accessed on 7 February 2023).
Shoreline use intensity	Geospatial Data Cloud (https://www.gscloud.cn/sources/index?pid=1&rootid=1) (accessed on 7 February 2023)
Salinization	Geospatial Data Cloud (https://www.gscloud.cn/sources/index?pid=1&rootid=1) (accessed on 7 February 2023
Runoff	Yellow River Sediment Bulletin
Sediment load	Index of Connectivity

Table 2. Overview of ecosystem services assessed in this study.

Category	Ecosystem Service	Formula	Paraphrase
Provisioning service	Food production	$V_1 = \sum_{i=1}^{n} S_i \times P_F$	S_i is the area of the cell i; n is the total number of cells; and P_F is the value equivalent factor of food production.
	Raw material	$V_2 = \sum_{i=1}^{n} S_i \times P_R$	S_i is the area of the cell i; n is the total number of cells; and P_R is the value equivalent factor of raw material.
Supporting service	Soil conservation	$SCA_i = PSASA_i - USLE_i$ $V_3 = SCA_i \times nut \times P_s$	$USLE_i$, PSA_i and SCA_i are the soil erosion amount every year, the potential soil erosion amount, and the soil conservation amount, respectively; nut is total nitrogen, phosphorus, and potassium nutrients in unit mass of soil [28,29]; and P_s is average price of nitrogen, phosphorus and potassium fertilizers [30].
	Carbon storage	$C = C_a + C_b + C_s + C_d$ $V_4 = C \times P_c$	C_a is the carbon density of aboveground carbon storage (kg/km^2); C_b is the carbon density of underground carbon storage (kg/km^2); C_s is the carbon density in soil (kg/km^2); C_d is the carbon density of litter (kg/km^2); and P_c is the carbon fixation price [31].
	Habitat quality	$V_5 = \sum_{i=1}^{n} S_i \times P_H$	S_i is the area of the cell i; n is the total number of cells; and P_H is the value equivalent factor of habitat quality.
Regulating service	Gas regulation	$V_6 = NPP \times 1.16 \times P_o$	NPP is the annual net primary productivity; and P_o is the price of oxygen [32].
	Climate regulation	$V_7 = \sum_{i=1}^{n} S_i \times P_{cr}$	S_i is the area of the cell i; n is the total number of cells; and P_{cr} is the value equivalent factor of climate regulation.
	Water yield	$WY_i = \left(1 - \frac{ARE_i}{P_i}\right) \times P_i$ $V_8 = WY_i \times P_y$	WY_i is the water yield in cell i, ARE_i is the mean reference evapotranspiration every year in cell I; P_i is the precipitation every year in cell I; and P_y is cost of unit reservoir capacity [33].
	Waste treatment	$V_9 = \sum_{i=1}^{n} S_i \times P_w$	S_i is the area of the cell i; n is the total number of cells; and P_r is the value equivalent factor of waste treatment.
Cultural service	Relaxation	$V_{10} = \sum_{i=1}^{n} S_i \times P_{re}$	S_i is the area of the cell i; n is the total number of cells; and P_{re} is the value equivalent factor of relaxation.

2.3.1. Equivalent Value Factors (EVF) Method

Xie et al. proposed the equivalent value factors of ESs applicable to China [27] (Table S1). Some researchers [34,35] poorly understood the regional differences and directly adopted the EVF. Referring to correlational research [27,36], this paper performed unit value equivalent correction in the YRD based on grain price changes.

First, we made the correction through grain prices. Many scholars considered natural grain production as equal to 1/7 of actual grain production [36,37]. In this paper, the average prices of three major food grains were used as the basis, and the average net profit of farmlands excluding human input costs was used as the standard equivalence factor. The ratio of urban unit grain production in the YRD to national unit area grain production in the same period was used as the correction factor [38], which was further corrected for grain prices using the consumer food price index for residents to take inflation into account. Eventually, the economic value of equivalent factors for the YRD was determined.

$$\delta = \frac{1}{7} \times \frac{R + M + N}{3} \times \frac{\alpha}{\beta} \times \lambda \tag{1}$$

where δ is the equivalent value of a standard unit; R, M, and N are the prices of wheat, corn, and rice, respectively (yuan); α and β are the local food production per unit area and the national food production per unit area in the same time, respectively; and λ is the consumer food price index for residents.

In this paper, according to the corrected grain price and the equivalent value factors of ESs applicable to China [27] (Table S1), we compiled the ES value factor equivalents per unit area for each LULC in the YRD, which was used to estimate the value of Re, WT, FP, CR, GR, and RW.

2.3.2. WY

The WY of each grid is the difference between the input water (precipitation) and output water (evapotranspiration and surface runoff) of each grid unit. The WY is calculated with Equation (2) [39].

$$WY_i = \left(1 - \frac{ARE_i}{P_i}\right) \times P_i$$
$$V_8 = WY_i \times P_y \tag{2}$$

where WY_i is the WY in cell i; ARE_i is the mean reference evapotranspiration every year; P_i is the mean precipitation every year; V_8 is the value of WY; and P_y is the cost of unit reservoir capacity [33]. The calculation methods of related factors are presented in the Supplementary Materials.

2.3.3. Ca

The Carbon Storage and Sequestration model multiplies the area of each LULC by its carbon density and then sums them to obtain the total carbon storage of the study area, as shown in Equation (3).

$$C = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{3}$$

where C is the total carbon density (kg/km^2); C_{above} is the carbon density of aboveground carbon storage (kg/km^2); C_{below} is the carbon density of underground carbon storage (kg/km^2); C_{soil} is the carbon density in soil (kg/km^2); and C_{dead} is the carbon density of litter (kg/km^2). The carbon densities of the YRD were adopted from the correction equation, which is presented in the Supplementary Materials.

The Ca. value is as follows.

$$V_4 = C \times P_c \tag{4}$$

where V_4 is the value of Ca. (CNY); C is the total carbon density (kg/km^2); and P_c is the carbon fixation price (kg/CNY) [31].

2.3.4. SC

The seduction delivery ratio module mainly makes use of universal soil loss equation (USLE), as shown in Equation (5) [40].

$$USLE_i = R_i \times K_i \times LS_i \times C_i \times P_i$$
$$PSA_i = R_i \times K_i \times LS_i \tag{5}$$
$$SCA_i = RKLS_i - USLE_i$$

where R_i is rainfall erosion; K_i is soil erodibility; LS_i is the factor of slope and slope length; C_i is the vegetation coverage factor; P_i is the management factor; and $USLE_i$, PSA_i and SCA_i are the soil erosion amount every year, the potential soil erosion amount and the soil conservation amount, respectively. The calculation methods of the above-mentioned factors are presented in the Supplementary Materials.

Wetland soil loss takes away a large amount of nutrients, and the value of wetland conservation soil can be replaced by the value of wetland reduction of soil fertility loss. In this paper, we mainly selected nutrients such as nitrogen, phosphorus, and potassium, which are easily soluble in water or easily separated from the soil by external forces, and cannot be recovered with the lost soil. The average values of nutrient contents of soils in the YRD [28] are shown in Table 3.

Table 3. Average nutrient content of soils in the Yellow River Delta.

Category	Nitrogen	Phosphorus	Potassium	Total
Content (%)	0.050	0.055	2.65	2.755

The value of soil fertility was used to estimate the value of SC.

$$V_3 = SCA_i \times nut \times P_s \tag{6}$$

where *nut* is total nitrogen, phosphorus, and potassium nutrients in unit mass of soil [28,29]; and P_s is average price of nitrogen, phosphorus, and potassium fertilizers [30].

2.3.5. GR

In the ecosystem, vegetation synthesizes organic matter through photosynthesis and also releases O_2. According to the equation of photosynthesis and respiration of plants, 1.19 g of O_2 is released for every 1 g of dry matter produced. In this study, we downloaded the NPP data of ecosystems in the study area (http://www.geodoi.ac.cn) (accessed on 3 February 2023), and the material masses of O_2 released from 1980 to 2020 were converted separately.

$$V_6 = NPP \times 1.16 \times P_o \tag{7}$$

where V_6 is the value of GR (CNY); *NPP* is the annual net primary productivity (kg/km^2); and P_o is the price of oxygen (CNY/kg) [32].

2.4. Quantification of Correlations between ESs

2.4.1. Correlation Analysis

Since data on various types of ESs showed a non-normal distribution, we used Spearman's non-parametric correlation analysis to determine trade-offs/synergies between ESs [41,42]. A positive correlation between ESs indicates a synergy, while a negative correlation indicates a trade-off.

2.4.2. CCD Model

The CCD model was used to analyze the coordinated development level of things [43]. It is widely used in studying the coupling coordination relationship of multiple systems, and can also be used to discuss the coupling coordination relationship between ESs and economic development [43].

Although correlation can reflect the interaction between ESs, it is difficult to reflect the overall coordination level of the two systems. The CCD refers to the degree of coordinated development between systems, which reflects the state of the coupling degree. Consequently, CCD was introduced to reflect the overall coordination level of ESs. In order to eliminate differences in scales, ESs were standardized, followed by the above-mentioned model analysis to analyze the level of synchronization and coordination of the two ESs.

The standardized formula is as follows.

$$ESV_i' = \frac{(ESV_i - ESV_{\min})}{(ESV_{max} - ESV_{\min})} \tag{8}$$

where ESV_i demotes the value of ES i; ESV_i' demotes the standardized data; and ESV_{max} and $ESV_{\min}$ are the maximum and minimum values, respectively.

The formula of the CCD model is as below [44,45]:

$$D = \sqrt{C \cdot T}$$

$$C = 2 \cdot \sqrt{\frac{(U_1 \cdot U_2)}{(U_1 + U_2)^2}} \tag{9}$$

$$T = a \cdot U_1 + b \cdot U_2$$

where D is the CCD, taking the value of [0, 1], with a larger D indicating a more coordinated development level of the two ESs; C is the coupling degree, taking the value of [0, 1], with a larger C indicating a better coupling state of the two systems, and a smaller C indicating the worse, which will tend to disorderly development; T is the composite coordination index of the two systems; and U_1 and U_2 are the values of two ESs, whose weights are a and b. In this study, we have no prejudice on the importance of ESs, each of which is equally important to human beings, so $a = b = 0.5$ [43–45].

In order to study the development stage of the CCD clearly, according to the relevant study [43,46], we determined the 10 grading standards of the degrees (Table 4).

Table 4. Classification of coupling coordination degrees.

D Value Interval	Coupling Coordination Type
0.0 < D ≤ 0.19	Serious disorder
0.2 < D ≤ 0.29	Moderate disorder
0.3 < D ≤ 0.39	Mild disorder
0.4 < D ≤ 0.49	Almost disorder
0.5 < D ≤ 0.59	Slight coordination
0.6 < D ≤ 0.69	Primary coordination
0.7 < D ≤ 0.79	Moderate coordination
0.8 < D ≤ 0.89	High coordination
0.9 < D ≤ 1.00	Extreme coordination

2.5. Social–Ecological Drivers of ESs

2.5.1. Selection of Social–Ecological Drivers

The ESs in the YRD are not only affected by local drivers, but also by the huge amount of water and sediment brought by the Yellow River and the influence from the ocean [19]. According to the relevant literature [16] and the particularity of the study area, three types of drivers were considered, for which 11 specific drivers were proposed, which are shown in Table 5. Meteorological conditions are the basis for the stability of the structure and function of the coastal wetland ecosystem, whose environmental bases are soil and hydrological conditions, while social–economic development is the external driver for the evolution of

the coastal wetland. The formulae and reference studies for specific indicators are shown in the Supplementary Materials.

Table 5. Social–economic drivers and their sources in the Yellow River Delta.

Type of Drivers	Data
Meteorological conditions	Precipitation Temperature
Soil and hydrological conditions	Salinization Runoff Sediment load Hydrographic net
Social–economic development	GDP Population Landscape disturbance Traffic roads Shoreline use intensity

2.5.2. PCA

PCA can transform a group of related variables into a group of unrelated PCs, which reduces the calculation workload and increases the accuracy of subsequent analysis [26]. Through ArcGIS10.2, 11 multivariate drivers in the YRD from 1980 to 2020 were extracted. On account of the large number of drivers and the correlation between them, it was necessary to reduce the dimensionality of these 11 drivers as well as the interference of data redundancy.

2.5.3. The GTWR Model

The GTWR model introduces the time dimension into the geographically weighted regression (GWR) model, which can obtain the dual information of time and space, making the estimation results more effective [13,47]. The formula of the GTWR model is as follows [48]:

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i, t_i)x_{ik} + \varepsilon_i \tag{10}$$

where u_i and v_i are the latitude and longitude coordinates of the center of gravity; (u_i, v_i, t_i) is the spatiotemporal coordinate of the ith sample point; $\beta_0(u_i, v_i, t_i)$ is the regression constant at point i; $\beta_k(u_i, v_i, t_i)$ is the kth regression parameter at point i; x_{ik} is the value of the independent variable x_k at point i; and ε_i is the residual term of the model.

PCA of multiple drivers was performed using ArcGIS 10.2, whose results were used to identify spatial interactions with ESs by the GTWR model.

3. Results

3.1. Spatiotemporal Variations of ESs

3.1.1. Spatiotemporal Variations

The temporal variability and change rate of ESs in the YRD from 1980 to 2020 is shown in Figure 3. ESs in the YRD in 1980, 1990, 2000, 2010, and 2020 were CNY 37.01, 48.89, 42.47, 48.30, and 50.49 billion, respectively, with an overall fluctuating upward trend, where RS generated the largest share, followed by SS, which was consistent with previous studies [13,49]. In RS, GR accounted for the largest share, followed by WY and WT. PS and CS showed a fluctuating upward trend, while RS and SS remained relatively unchanged, which indicated that the ESs provided by artificial ecosystems increased. The change rates of SS and CS from 2000 to 2010 were relatively high, while WY had the highest rate between 1980 and 1990, followed by SC between 2010 and 2020.
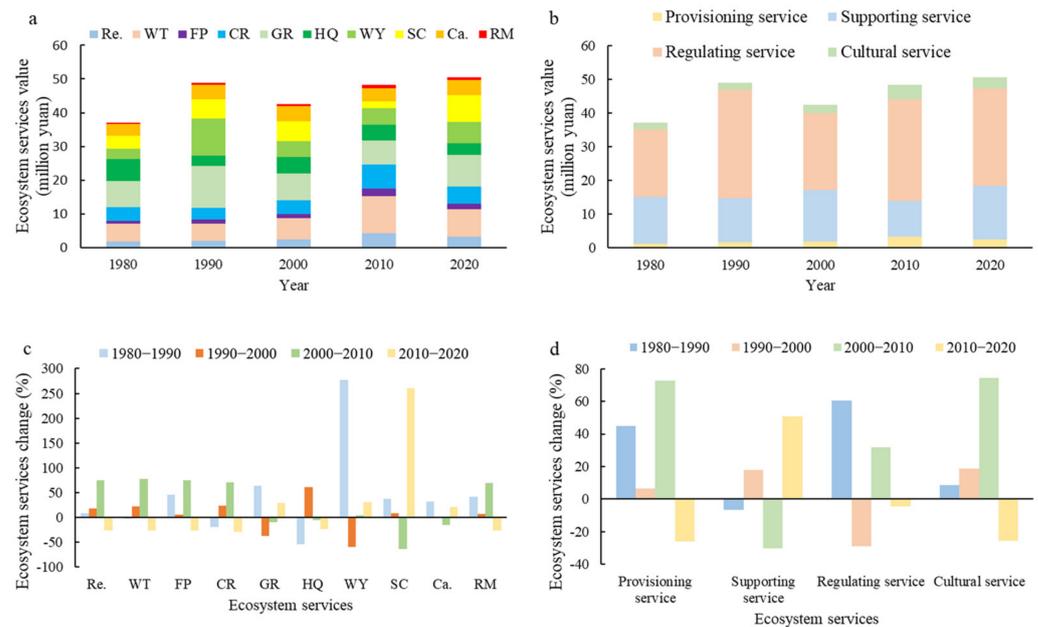
Figure 3. The temporal variability and change rate of ecosystem services (ESs) in the Yellow River Delta (YRD) from 1980 to 2020. (**a**,**b**) The temporal variability of ESs in the YRD from 1980 to 2020. (**c**,**d**) The change rate of ESs in the YRD from 1980 to 2020. (FP: food production, RM: raw material, SC: soil conservation, Ca.: carbon storage, HQ: habitat quality, GR: gas regulation, CR: climate regulation, WY: water yield, WT: waste treatment, Re.: relaxation.)

The results indicated that the pattern of ESs in the YRD showed spatial heterogeneity, while remaining relatively similar and stable (Figure 4). The high supply areas of PS and SS were mainly located in the southwest of the croplands, while the high supply areas of RS and CS were mainly located in the wetlands. Specifically, the spatial pattern of RS showed a gradient distribution from southwest to northeast.
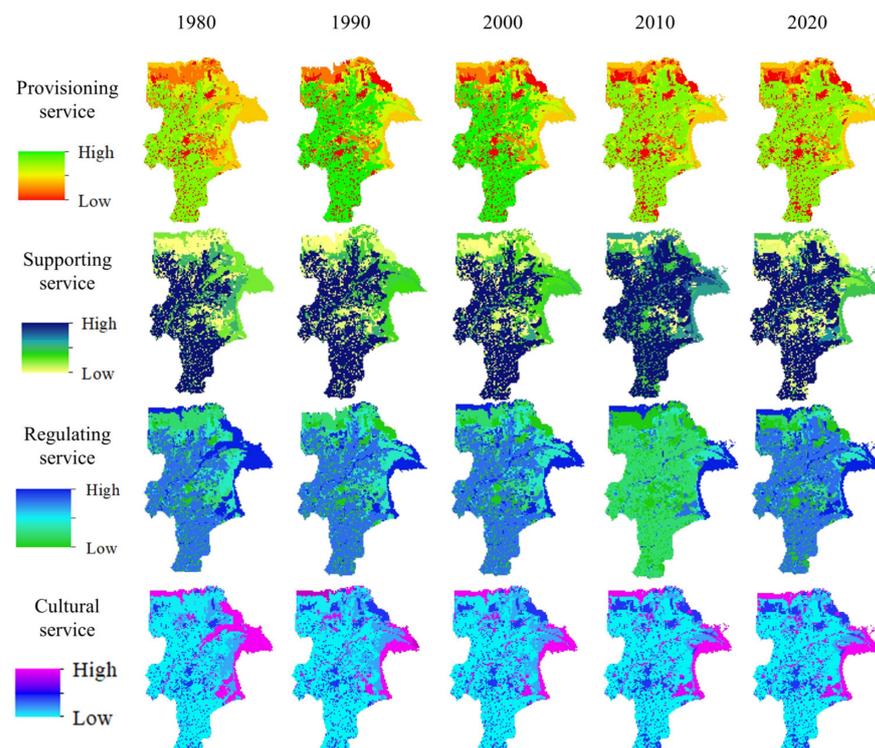
Figure 4. The spatiotemporal patterns of ecosystem services in the Yellow River Delta from 1980 to 2020.

3.1.2. Trade-Offs and Synergies between ESs

A total of 45 correlations were identified between 10 ESs per year, whose correlations were statistically significant ($p < 0.05$) (Figure 5). There were similarities in the correlations in all 5 years. First of all, the relationships between Re. and other ESs were basically negative, with higher trade-offs between FP, RM, CS, and WY. Secondly, other ES were basically positive correlations, among which WT, FP, CR, RM, HQ, and CS had high synergies.

a.1980

	Re.	WT	FP	CR	RM	HQ	Ca.	SC	GR
WT	-0.220**								
FP	-0.822**	0.661**							
CR	0.222**	0.721**	0.345**						
RM	-0.819**	0.631**	0.982**	0.350**					
HQ	0.122**	0.633**	0.368**	0.888**	0.367**				
Ca.	-0.468**	-0.018	0.548**	0.269**	0.617**	0.315**			
SC	-0.196**	0.238**	0.367**	0.198**	0.361**	0.164**	0.317**		
GR	-0.178**	-0.097*	0.084**	-0.183**	0.079**	0.177**	0.079**	0.096**	
WY	-0.816**	0.413**	0.869**	0.139**	0.877**	0.196**	0.602**	0.421**	0.139**

b.1990

	Re.	WT	FP	CR	RM	HQ	Ca.	SC	GR
WT	-0.519**								
FP	-0.875**	0.832**							
CR	0.049**	0.586**	0.355**						
RM	-0.890**	0.768**	0.977**	0.354**					
HQ	-0.068**	0.475**	0.375**	0.851**	0.381**				
Ca.	-0.848**	0.611**	0.904**	0.228**	0.944**	0.289**			
SC	-0.146**	0.232**	0.272**	0.148**	0.266**	0.101**	0.362**		
GR	-0.093**	0.028**	0.067**	-0.128**	0.056**	-0.138**	0.076**	0.128**	
WY	-0.809**	0.585**	0.844**	0.213**	0.862**	0.279**	0.862**	0.346**	0.153**

c.2000

	Re.	WT	FP	CR	RM	HQ	Ca.	SC	GR
WT	-0.490**								
FP	-0.876**	0.817**							
CR	0.058**	0.602**	0.352**						
RM	-0.888**	0.751**	0.971**	0.354**					
HQ	-0.073**	0.481**	0.379**	0.842**	0.386**				
Ca.	-0.849**	0.586**	0.895**	0.221**	0.942**	0.290**			
SC	-0.159**	0.245**	0.284**	0.168**	0.280**	0.120**	0.369**		
GR	-0.363**	0.304**	0.398**	0.036**	0.395**	0.005	0.422**	0.349**	
WY	-0.817**	0.564**	0.845**	0.205**	0.861**	0.290**	0.861**	0.351**	0.433**

d.2010

	Re.	WT	FP	CR	RM	HQ	Ca.	SC	GR
WT	-0.394**								
FP	-0.914**	0.718**							
CR	-0.095**	0.766**	0.435**						
RM	-0.901**	0.687**	0.967**	0.456**					
HQ	-0.237**	0.603**	0.473**	0.787**	0.473**				
Ca.	-0.638**	0.184**	0.600**	0.432**	0.700**	0.476**			
SC	-0.141**	0.144**	0.198**	0.125**	0.192**	0.082**	0.188**		
GR	-0.412**	0.250**	0.419**	0.074**	0.415**	0.039**	0.247**	0.305**	
WY	-0.814**	0.456**	0.818**	0.265**	0.816**	0.336**	0.622**	0.266**	0.483**

e.2020

	Re.	WT	FP	CR	RM	HQ	Ca.	SC	GR
WT	-0.393**								
FP	-0.912**	0.720**							
CR	-0.094**	0.766**	0.437**						
RM	-0.900**	0.689**	0.967**	0.458**					
HQ	-0.234**	0.608**	0.475**	0.791**	0.475**				
Ca.	-0.638**	0.184**	0.600**	0.430**	0.700**	0.472**			
SC	-0.141**	0.143**	0.198**	0.124**	0.192**	0.079**	0.190**		
GR	-0.399**	0.235**	0.403**	0.073**	0.402**	0.035**	0.252**	0.295**	
WY	-0.815**	0.460**	0.819**	0.263**	0.818**	0.331**	0.619**	0.284**	0.496**

Legend:

- 0.819 – 1.000
- 0.637 – 0.818
- 0.456 – 0.636
- 0.274 – 0.455
- 0.092 – 0.273
- -0.090 – 0.091
- -0.272 – -0.091
- -0.454 – -0.273
- -0.635 – -0.455
- -0.817 – -0.636
- -1.000 – -0.818

FP: Food production
RM: Raw material
SC: Soil conservation
Ca.: Carbon storage
HQ: Habitat quality
GR: Gas regulation
CR: Climate regulation
WY: Water yield
WT: Waste treatment
Re.: Relaxation

Figure 5. Correlations among 10 types of ecosystem services (** represents $p < 0.01$) in the Yellow River Delta, 1980–2020. The lower left part of each panel shows the Spearman's correlation coefficients. The blue and red symbols represent positive and negative correlations, respectively.

3.2. CCD Evaluation

The CCD of ESs in the YRD from 1980 to 2020 is shown in Figure 6. The results showed that the mean values of CCD among ESs from 1980 to 2020 fluctuated slightly in the range of 0.4–0.6 and 0.1–0.3, respectively. The average CCD of the PS–SS was the highest, followed by RS–SS and PS–RS, both between 0.4 and 0.6, indicating that these ESs were in the high coupling, generally in a moderate coordination state. The average CCD of the PS–CS was the lowest, followed by CS–SS and RS–CS, which were both between 0.1 and 0.3, indicating that the CS and other ESs were generally in a low coordination state, leading to a dysfunctional state. Combined with the results of the correlation analysis, it showed that the CS was always strongly associated with other ESs while the coordination effect was weak.
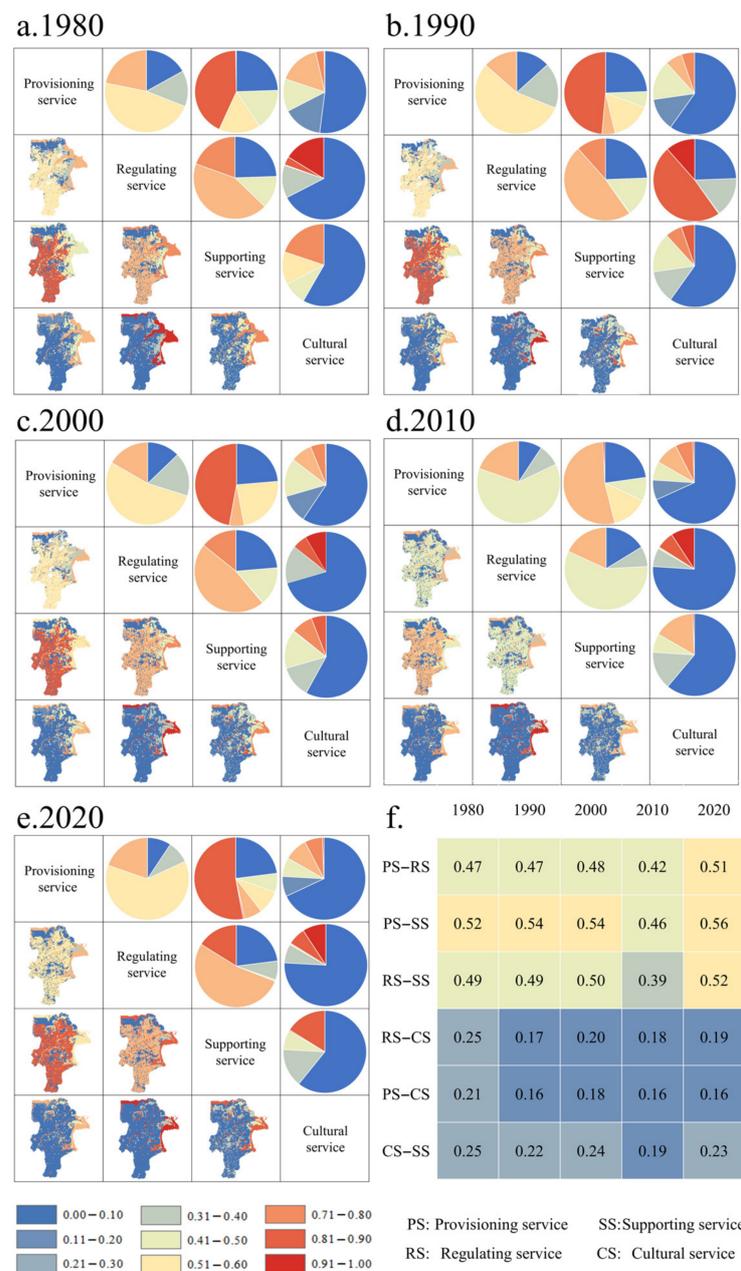
Figure 6. The coupling coordination degree (CCD) of ecosystem services (ESs) in the Yellow River Delta from 1980 to 2020. (**a**–**e**) The pie charts showed the area share of different CCD between ESs. (**f**) The temporal variability of mean value of CCD between ESs.

The spatial heterogeneity of CCD between ESs was obvious, while the trend was relatively stable, and the difference had a great relationship with LULC.

3.3. GTWR Analysis of Multiple Drivers and ESs

3.3.1. PCA

Firstly, the Kaiser–Meyer–Olkin (KMO) and Bartlett tests for the 11 drivers showed that the KMO value was >0.5 and the *p* value of the Bartlett test was <0.001, indicating that these 11 indicators could be analyzed by PCA. Secondly, the cumulative contribution of the first five eigenvalues reached 73.484%, as shown in Table 6, which generally indicated a more satisfactory cumulative above 70%.

Table 6. Total variance explained.

Principal Component	Eigenvalue	Contribution Rate (%)	Cumulative Contribution Rate (%)
1	1.851	16.824	16.824
2	1.834	16.668	33.493
3	1.700	15.450	48.943
4	1.633	14.847	63.791
5	1.066	9.693	73.484

It can be seen from Table 7 that, in the first PC, the absolute value of the hydrographic net and runoff loads was relatively large, indicating that these variables had high correlation coefficients with the first PC, which can be named hydrologic conditions. In the second PC, the absolute value of temperature and sediment loads were relatively large. Since temperature is one of the important factors for vegetation growth, which is an important factor for sediment transport, the second PC can be called vegetation influence. In the third PC, the absolute value of population, GDP, traffic roads, and shoreline use intensity loads were large, so the third PC was called social economy. In the fourth PC, the absolute values of precipitation and salinization loads were large. Considering that the cause of salinization is strongly associated with precipitation, the fourth PC was consequently called water–salt balance. In the fifth PC, the absolute value of landscape disturbance load was large, so the fifth PC was called landscape disturbance. The spatial pattern of PCs of social–economic drivers in the YRD from 1980 to 2020 is shown in Figure 7.

Table 7. Component matrix.

| Driver	Principal Component				
	1	2	3	4	5
Hydrographic net	0.926	0.231	0.029	0.000	−0.008
Temperature	−0.058	0.834	0.026	0.388	0.142
Precipitation	−0.246	0.222	0.308	0.683	−0.068
Traffic roads	0.438	−0.238	−0.550	0.222	−0.173
Landscape disturbance	−0.042	−0.062	0.022	0.011	0.956
Population	−0.020	−0.161	0.650	−0.019	0.005
GDP	0.168	0.002	0.795	0.174	0.024
Shoreline use intensity	0.418	−0.061	−0.478	−0.268	0.188
Salinization	0.025	0.044	−0.049	0.879	0.047
Runoff	−0.726	0.494	−0.075	0.296	0.128
Sediment load	0.068	0.836	−0.102	−0.066	−0.209

3.3.2. GTWR Analysis

Using the GTWR plug-in for ArcGIS 10.2 (with automatic optimal settings for bandwidth) produced by Huang et al. [48], the regression results can explain the relation between PCs and ESs. A parameter greater than 0 indicated that the explanatory variables were driving ESs, with a larger parameter indicating a stronger driving effect, while a parameter less than 0 indicated that the explanatory variables were inhibiting ESs, with a larger absolute value indicating a stronger inhibiting effect. The natural breakpoint method was used to classify the effects of each PC on ESs into six categories: weak positive effect, middle positive effect, strong positive effect, weak negative effect, middle negative effect, and

strong negative effect, and finally the spatiotemporal variation was plotted, as shown in Figure 8.
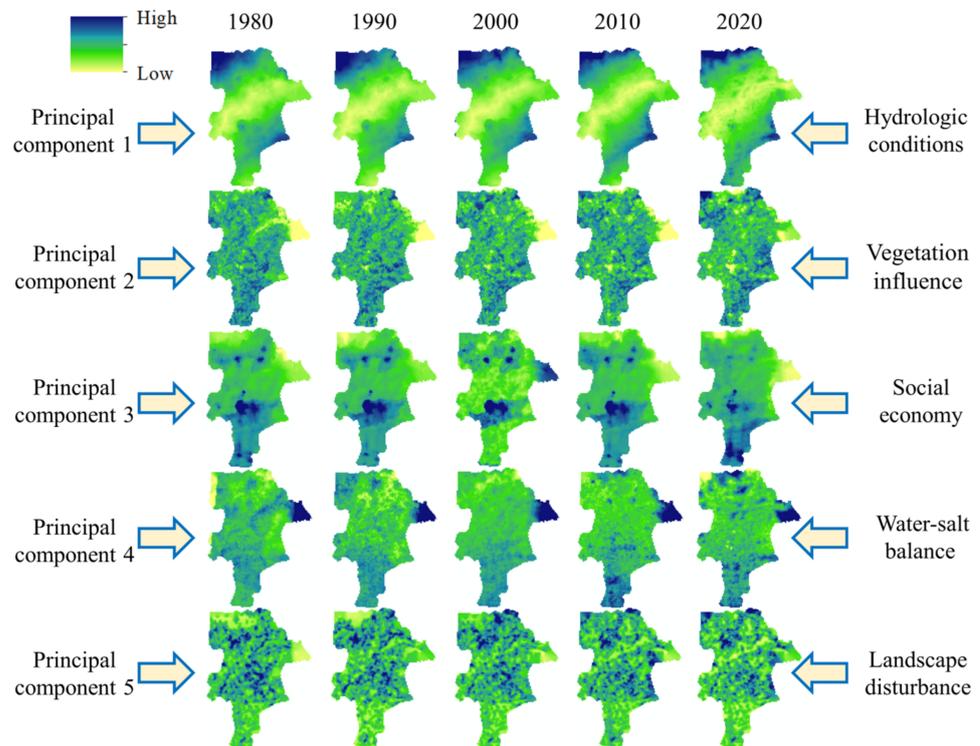
Figure 7. Principal components of social–economic drivers in the Yellow River Delta, 1980–2020.
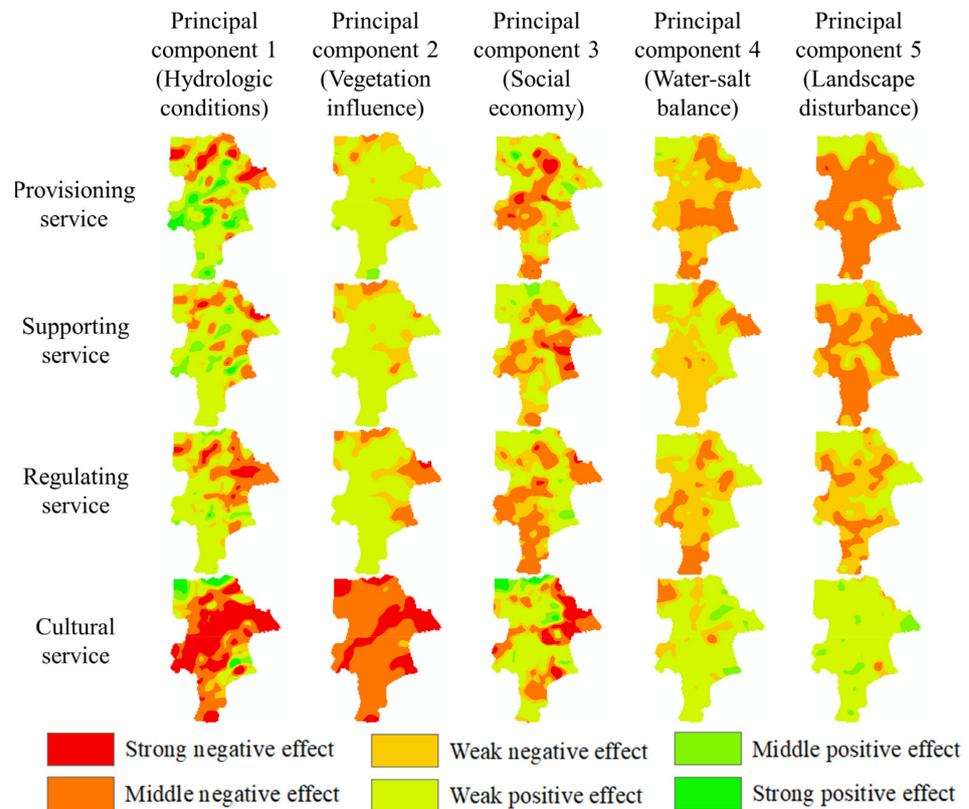
Figure 8. Spatiotemporal variation in the impact of principal components on ecosystem services.

For SS, PS, and RS, the vegetation influence was a positive driver while water–salt balance and landscape disturbance were basically negative drivers. The driving effect of hydrographic net was opposite to that of social economy. The former had a strong negative driving effect in the northeast and a strong positive driving effect in the southwest, while the latter had an opposite effect. The role of each PC for CS was opposite to that of the other ESs. Landscape disturbance and water–salt balance on CS were the positive drivers, while vegetation influence was negative.

4. Discussion

4.1. Reasons for Spatiotemporal Variation of ESs

From 1968 to 2020, the precipitation in Dongying City decreased by 66.31 mm/a, especially in the late 20th century, when the annual precipitation was the lowest. The precipitation in 1990 reached 893.76 mm, which was the extreme value of precipitation during this period [50]. Moreover, parallel with that, there were fewer urban-up lands but more forest and grasslands, so the value of WY was high, which in turn affected the total ES value in 1990. Previous studies have shown that vegetation has a deep connection with RS [11,47]. From 1996 to 2001, the unified water transfer in the Yellow River basin was initiated, resulting in the decrease of bare lands and the increase of croplands [51]. Dongying City took this opportunity effectively to restore a large number of wetlands, which not only increased carbon storage, but also reduced soil erosion and flooding [52]. To sum up, the change of vegetation and wetlands led to an overall fluctuating upward trend in RS in Dongying City.

### 4.2. Trade-Offs/Synergies Based on the CCD Model and Correlation

The trade-offs/synergies between ESs were identified by the CCD model and correlation in our research, which showed that CS and other ESs were basically in a state of trade-off and imbalance, while the other ESs were basically in a state of synergy and coordinated development. We found large similarities between the results of the CCD model and correlation (Figures 6 and 9) while there was little discrepancy in the respective change, which suggested that the relationships between ESs were relatively stable [53].

The spatial pattern of the CCD of ES in the YRD from 1980 to 2020 showed spatial heterogeneity. CS and the other ESs were basically in a state of coordination in wetlands, which in other LULCs were in a state of imbalance, which is generally consistent with previous studies [54,55]. In wetlands, all kinds of ESs can basically develop in a coordinated way, while in build-up lands and barren they cannot. Consequently, Dongying City needs to control urbanization and industrialization to maintain the sustainable supply of key ESs [56], which is consistent with previous studies [57,58]. To sum up, the results indicate that there is still more room to improve the ES status in urban and bare lands for sustainable development of regional ESs. The results of the correlation analysis lack spatial description, while the CCD model can remedy the flaw, providing a new way of thinking the relationships between ESs and monitoring the sustainable supply of ESs, because of the deep connection between the spatial distribution and temporal dynamics of ESs [59,60]. Hence, long-term monitoring of the supply of ESs is essential to identify the development relationship between ESs in different regions, to avoid unnecessary trade-offs and ensure the sustainable supply of ESs [61].

4.3. Response of ESs to Multiple Drivers

We found that the responses of PS, SS, and RS to multiple drivers were parallelism because of their similarities [62], while the response of CS was opposite to other ESs. Playing a pivotal role in ESs, vegetation was a positive driver for ESs. Social economy played a positive driver for CS and a negative driver for other ESs in the southwest where the Dongying District is located, a region with high economic development and population concentrations. Landscape disturbance had a deep connection with the intensity of human

activities, so that it was positive driver for CS and a negative driver for the other ESs in areas where human activities were more frequent, such as build-up lands and croplands.
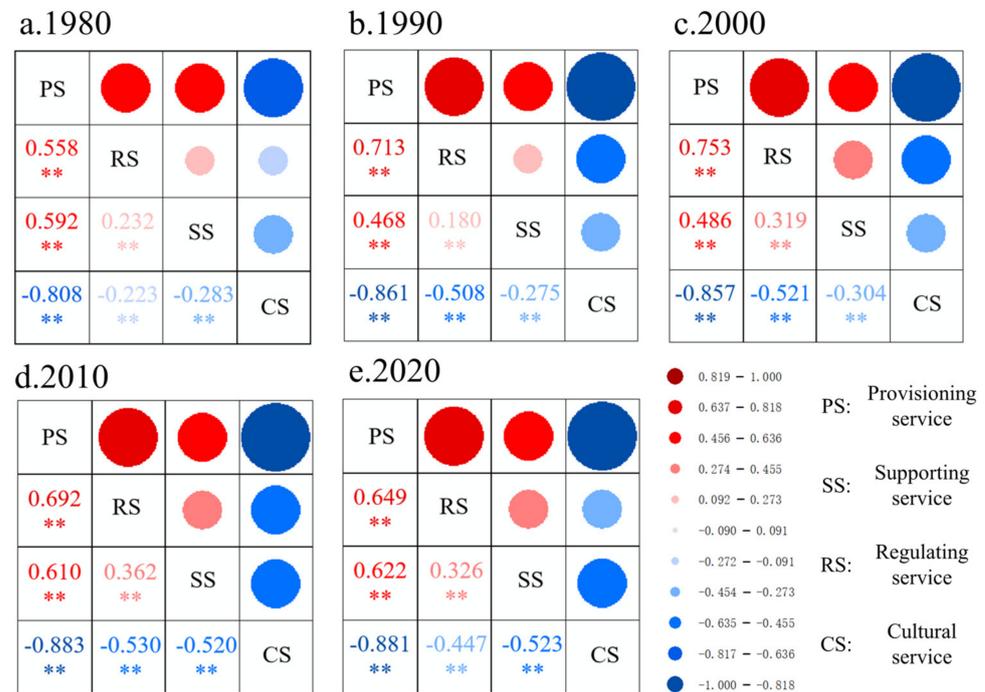
Figure 9. Correlations of four categories of ecosystem services (** represents *p* < 0.01) in the Yellow River Delta, 1980–2020. The lower left part of each panel shows the Spearman's correlation coefficients. The blue and red symbols represent negative and positive correlations, respectively.

The results suggest that there are three main aspects of sustainable supply about ESs, which are limiting the expansion of artificial landscapes, improving agricultural techniques, and promoting wetland conservation and restoration [63,64].

4.4. Spatial Planning and Management

Accurately identifying the social–ecological drivers of ESs will not only help to formulate corresponding spatial management and planning strategies [65,66], but also provide insights for improving the versatility of territorial space and regional sustainable development.

The structure of ESs in the YRD is shown in Figure 10. We integrated the above-mentioned results to propose spatial planning and development strategies for each district in Dongying City. Located in inland areas, Lijin County is largely consistent with Guangrao County, both having few ES values and more croplands, which suggest that measures should be taken to protect basic farmland and improve agricultural water facilities and soil quality. Hekou District has large similarities with Kenli District, which are both in the coastal area, with few croplands, more grasslands, and high ES values. Consequently, the industrial structure and the treatment of saline land should be improved. Dongying District, which has large build-up lands, is the central urban area and the location of Shengli Petroleum Administration organs, whose treatment measures should be mainly focused on industrial development, oil–land integration, innovation, and improvement of people's livelihoods.
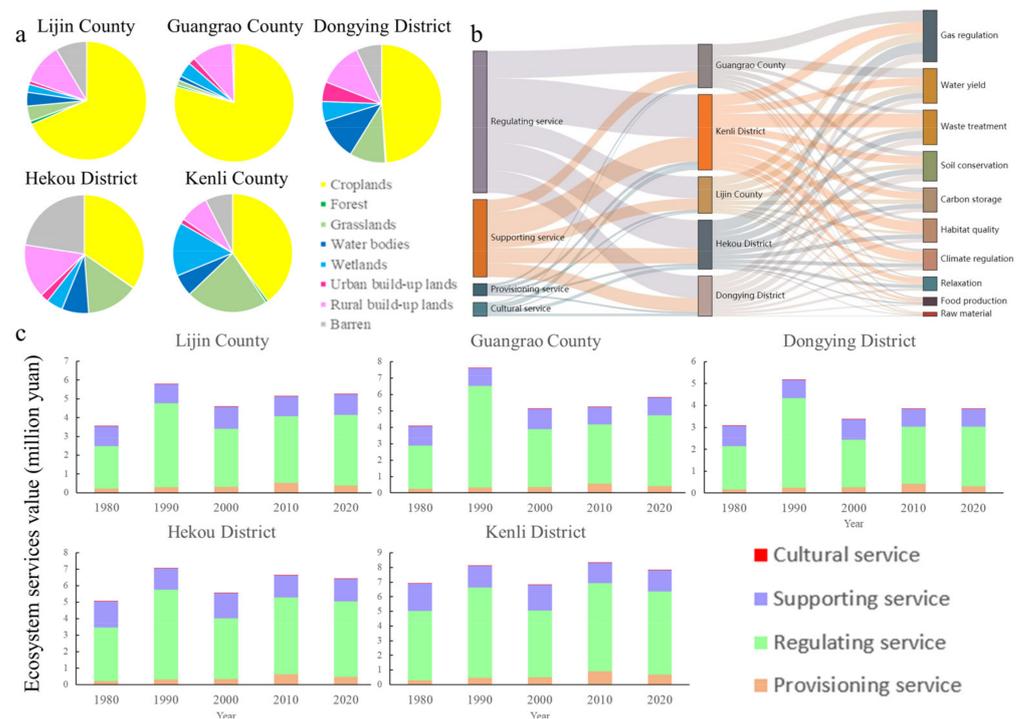
Figure 10. Structure of ecosystem services (ESs) in the Yellow River Delta (YRD). (**a**) Average share of land use/land cover in different administrative regions of the YRD, 1980–2020. (**b**) Sankey diagram of ESs in different administrative regions of the YRD, 1980–2020. (**c**) Temporal changes of ESs in different administrative regions of the YRD, 1980–2020.

4.5. Limitations and Prospects

While this study has provided insights into the interaction of ESs in the YRD and the response of ESs to social–ecological drivers, it is necessary to pay attention to the following limitations: (1) some ecological processes in the InVEST model are comparatively simple [67], being an important question for future investigation, so that our next challenge is to find more suitable ecological models to estimate ESs. (2) In the WY module, the water quantity only takes into account two factors: precision and evapotranspiration [68], while no consideration is given to groundwater [69,70], which will be our understudied and important potential next frontier. (3) The seduction delivery ratio module mainly makes use of USLE, whose effect is limited although widely used [70]. Only water erosion is taken into account to estimate soil loss, while no consideration is given to the other types of soil erosion [71]. Inevitably, more empirical studies are needed to obtain applicable data of soil erosion to the study area in future research. (4) The carbon storage module assumes that the only change of carbon storage is due to LULCs [69,70], without considering the variability of carbon storage in specific LULCs and soil type [72]. Hence, more accurate data will be important for future investigation.

5. Conclusions

Threatened by natural and human disturbances, coastal wetland ecosystems face the risk of uncoordinated development. Accordingly, it is necessary to evaluate dynamic changes of coastal wetland ESs scientifically, identify their coordinated development status, and explore the spatial heterogeneity about response of ESs to social–ecological drivers, to ensure the better sustainable use of coastal resources.

The key findings that emerged from this study were that: (1) from 1980 to 2020, the ESs of YRD showed an overall upward trend, which were mainly affected by the GR, WY, and WT of RS. (2) CS was disordered with other ESs, but, even so, various ESs could basically develop in a coordinated manner in wetlands. The empirical results of this study provide a new understanding about the role of wetlands in ESs, which showed that wetlands not

only provide a variety of resources for human beings, but also have huge environmental functions and benefits. We should protect wetlands better and use the prominent role of wetlands in coordinating ESs. (3) Through PCA, 11 social–economic drivers were integrated into 5 PCs, namely hydrologic conditions, vegetation influence, social economy, water–salt balance, and landscape disturbance, which reduced the information redundancy and the calculation workload for the subsequent analysis, increasing the accuracy and stability of the results. (4) This study provides a deep insight into the response of wetland ESs to social–economic drivers through the GTER model, which has spatial heterogeneity, suggesting that ES management in different regions should have its own priority rather than generalization.

The knowledge gained in this study can be of help to provide a basis for the sustainable development of the regional ESs and the improvement of human well-being. Despite the limitations, to a large extent, our results cast a new light on more comprehensive management for ESs, to achieve more efficient and rational decision-making.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs15071866/s1, The method of ecosystem services assessment and social–ecological drivers of ESs. Table S1: Equivalent value factors of ecosystem services per unit area in China. Table S2: The root depth and evapotranspiration coefficient of each land use/land cover. Table S3: The carbon density of each land use/land cover (Mg·ha^{-1}). Table S4: The management factor expressed by P of different LULCs. References [15,25,27,72–96] are cited in the supplementary materials.

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Data Availability Statement: Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

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