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Impact of Paddy Field Expansion on Ecosystem Services and Associated Trade-Offs and Synergies in Sanjiang Plain

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Abstract: In recent decades, the integrity and security of the ecosystem in the Sanjiang Plain have faced severe challenges due to land reclamation. Understanding the impact of paddy field expansion on regional ecosystem services (ESs), as well as revealing the trade-offs and synergies (TOS) between these services to achieve optimal resource allocation, has become an urgent issue to address. This study employs the InVEST model to map the spatial and temporal dynamics of five key ESs, while the Optimal Parameter Geodetector (OPGD) identifies primary drivers of these changes. Correlation analysis and Geographically Weighted Regression (GWR) reveal intricate TOS among ESs at multiple scales. Additionally, the Partial Least Squares-Structural Equation Model (PLS-SEM) elucidates the direct impacts of paddy field expansion on ESs. The main findings include the following: (1) The paddy field area in the Sanjiang Plain increased from 5775 km^2 to 18,773.41 km^2 from 1990 to 2020, an increase of 12,998.41 km^2 in 40 years. And the area of other land use types has generally decreased. (2) Overall, ESs showed a recovery trend, with carbon storage (CS) and habitat quality (HQ) initially decreasing but later improving, and consistent increases were observed in soil conservation, water yield (WY), and food production (FP). Paddy fields, drylands, forests, and wetlands were the main ES providers, with soil type, topography, and NDVI emerging as the main influencing factors. (3) Distinct correlations among ESs, where CS shows synergies with HQ and SC, while trade-offs are noted between CS and both WY and FP. These TOS demonstrate significant spatial heterogeneity and scale effects across subregions. (4) Paddy field expansion enhances regional SC, WY, and FP, but negatively affects CS and HQ. These insights offer a scientific basis for harmonizing agricultural development with ecological conservation, enriching our understanding of ES interrelationships, and guiding sustainable ecosystem management and policymaking.

Keywords: land use change; paddy expansion; ecosystem services; Sanjiang Plain; trade-offs and synergistic

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1. Introduction

Ecosystem services (ESs) are the various functions and benefits that nature provides that are beneficial to humans [1]. As a bridge linking human society and natural ecosystems, researching ESs is crucial to enhance human well-being and foster regional sustainable development [2]. However, with ongoing human development, the ecological environment is deteriorating, leading to a decline in ESs, which seriously affects regional sustainable development.

Over the past half century, global ESs have declined to varying degrees [3]. The scientific understanding and management of ESs are therefore critical to attaining sustainable development goals. ESs are fundamental to sustainable development, supporting livelihoods and ensuring food security, which are essential for reducing poverty and hunger. They provide critical functions such as carbon sequestration in forests and oceans, which help mitigate climate change, and they protect forests and biodiversity, maintaining ecological balance and resource availability. An accurate understanding of the interactions among ESs is essential for effective management and the promotion of regional sustainable development [4,5].

In recent years, studies on the dynamics of ESs and their interrelationships have become a prominent focus. Growing emphasis has been placed on the assessment and evaluation of ESs due to their vital importance for human survival [6–8]. It has shown that changes in land use can have a significant impact on regional ESs [9,10]. Land use changes, including urban expansion [11], forest degradation [12], wetland loss [13], grassland degradation [14], and agricultural expansion [15], among others, have garnered increasing scholarly attention due to their impact on ESs. However, these studies usually address changes in the ESs of cropland as a whole, overlooking the impacts of changes within cropland (such as paddy and dryland) on regional ESs. Cropland is divided into two main categories, paddy, and dryland, with paddy land used for growing aquatic crops that are generally flooded during the growing season, and dryland used for growing crops that rely mainly on natural precipitation. Cultivated land can provide a variety of ESs, and food production, but the ESs provided by paddy fields and dryland differ functionally, with paddy fields significantly differing from dryland in terms of atmospheric regulation and water conservation [16]. Studies have shown that paddy fields can be considered a type of artificial wetland that fulfills some of the ecological functions of natural wetlands [17]. However, paddy fields also consume substantial amounts of irrigation water and are significant sources of methane (CH_4) emissions, with far-reaching impacts on global climate and the water circulation [18]. Thus, the area and spatial distribution of paddy fields impact not only human food security but also regional and global ecological changes. The Sanjiang Plain (SJP) in northeastern China is not only a major grain-producing region but also an area characterized by extensive swampy wetlands. Previous studies in this region have primarily addressed the effects of changes in swampy wetlands on regional ESs, with limited research on the impacts of changes within cropland. Rice paddies have shown a persistent growth trend in Northeast China since the 1970s [19]. Therefore, it is necessary to separate paddy fields from drylands in this region to quantify the impact of paddy field expansion on ESs.

As human activities increasingly disturb the ecological environment, the negative impacts also escalate, making the study of regional ESs and their trade-offs and synergies (TOS) a major research focus across various disciplines [20]. As research progresses globally, it has been found that various types of ESs are interconnected, often exhibiting TOS [21,22]. Trade-offs arise when the supply of certain ESs diminishes due to the increased utilization of other services, whereas synergies occur when two or more ESs are simultaneously enhanced [23]. ESs are intricately connected to sustainable economic and social development. It is crucial to thoroughly comprehend the changes in ESs and the complex relationships between TOS. Analyzing the relationships among various ecosystems, reducing unnecessary trade-offs, and promoting synergies are crucial for achieving the long-term provisioning of ESs and sustainable regional development. Achieving the long-term supply of ESs and sustainable regional development is of great significance [24]. In the early 20th century, studies on TOS were primarily presented in numerical terms. Research primarily focused on the theoretical aspects of TOS [25]. The research methods predominantly employed statistical techniques to reveal the quantitative relationships between ESs [26]. The study area focuses mainly on administrative areas, such as provinces, cities, and counties. With the progress of remote sensing technology and extensive research on ESs, a growing number of scholars are examining the temporal and spatial variations, driving factors, and regional disparities of ES—ESs TOS from various perspectives [27–29]. TOS and spatial changes among different ecosystems such as forests, lakes, wetlands, and croplands have also been examined [30–32]. Statistical techniques and models such as GWR are frequently employed to examine the relationships between them [33]. Some studies have also employed GeoDetector, random forests, and prediction models to further investigate the driving factors, formation mechanisms, and future projections of ES-ESS TOS [10,34,35]. Additionally, the research areas have expanded from single geographic units to large-scale regions with complex geographic relationships, such as the Tibetan Plateau of China [36], the Yellow River Basin [33], and the Karst region [37]. Some studies related to the SJP have focused on the impacts of wetland changes [38], land cover changes [39], and cropland expansion [17] on the ESs of the SJP. However, few of these studies provide quantitative analyses of the TOS among ESs. Most existing research has focused on the valuation of ESs [40], with limited attention given to the TOS relationships between ESs in the SJP. Therefore, studying the TOS of ESs in the SJP can help fill gaps in regional ES-ESs research and provide guidance for regional development.

The SJP, situated in northeastern China, is among the most crucial wetland and agricultural region. Its fertile soil and abundant water resources support a rich variety of crops, including rice, corn, and soybeans, making it one of China's primary grain-producing areas. In recent years, agricultural modernization has led to the development of highly efficient and intensive farming practices on the plains. Despite the rapid agricultural development in the SJP, ecological and environmental issues have become increasingly prominent. Over the past half-century of development, the SJP's ecological environment has deteriorated, with vegetation cover being destroyed, wetland areas shrinking, carbon storage (CS) declining, and other ecological issues arising frequently. Therefore, this study centers on the SJP in northeast China. Utilizing the InVEST model, OPGD, GWR, and correlation analysis, we investigated the expansion of rice paddies and the spatial and temporal dynamics of ESs from 1990 to 2020. Additionally, we explored the driving factors influencing ESs and analyzed the TOS relationships among various ESs. Finally, PLS-SEM was employed to examine the impact of paddy field expansion on ESs. The findings aim to provide insights for balancing agricultural development and ecological conservation in the SJP.

The objectives of this study are (1) to analyze the expansion of paddy fields and land use changes in the SJP over the past 30 years; (2) to quantify the spatial and temporal evolution characteristics of ESs in the SJP and to identify the driving factors influencing these services; (3) to uncover the changes in TOS relationships among the five ESs in the SJP; (4) and to assess the effects of paddy field expansion on ESs. Based on this study's findings, targeted recommendations can be made for ecological protection and spatial planning in the SJP region to promote sustainable environmental development.

2. Materials and Methods

In this study, we first assessed land use changes and five key ESs in the SJP by integrating multi-source data. Next, we analyzed the main factors influencing ESs. Finally, we explored the TOS between ESs and evaluated the impact of paddy field expansion on ESs. The detailed workflow of this study is shown in Figure 1.

2.1. Study Area

The SJP is located in northeastern China (Figure 2). It lies between longitude 130°13′~135°05′ E, and latitude 43°49′~48°27′ N, covering a total area of about 108,900 km^2. The region has a temperate humid and semi-humid continental monsoon climate, with an average annual temperature of 2.5–3.6 °C and average annual precipitation of 500–650 mm, predominantly falling between June and September. Soil types primarily include black soil, planosol soil, meadow soil, and swamp soil, with the latter two being the most widely distributed [17]. With warm summers, simultaneous rain and heat, and fertile land, the area is particularly suitable for agricultural production and is a key national food production area, especially for rice cultivation. Paddy fields are being expanded to meet the growing demand for food, but such expansion often has far-reaching impacts on local natural ecosystems. Therefore, studying how paddy expansion affects ESs can provide a scientific basis for balancing food security and ecological protection.

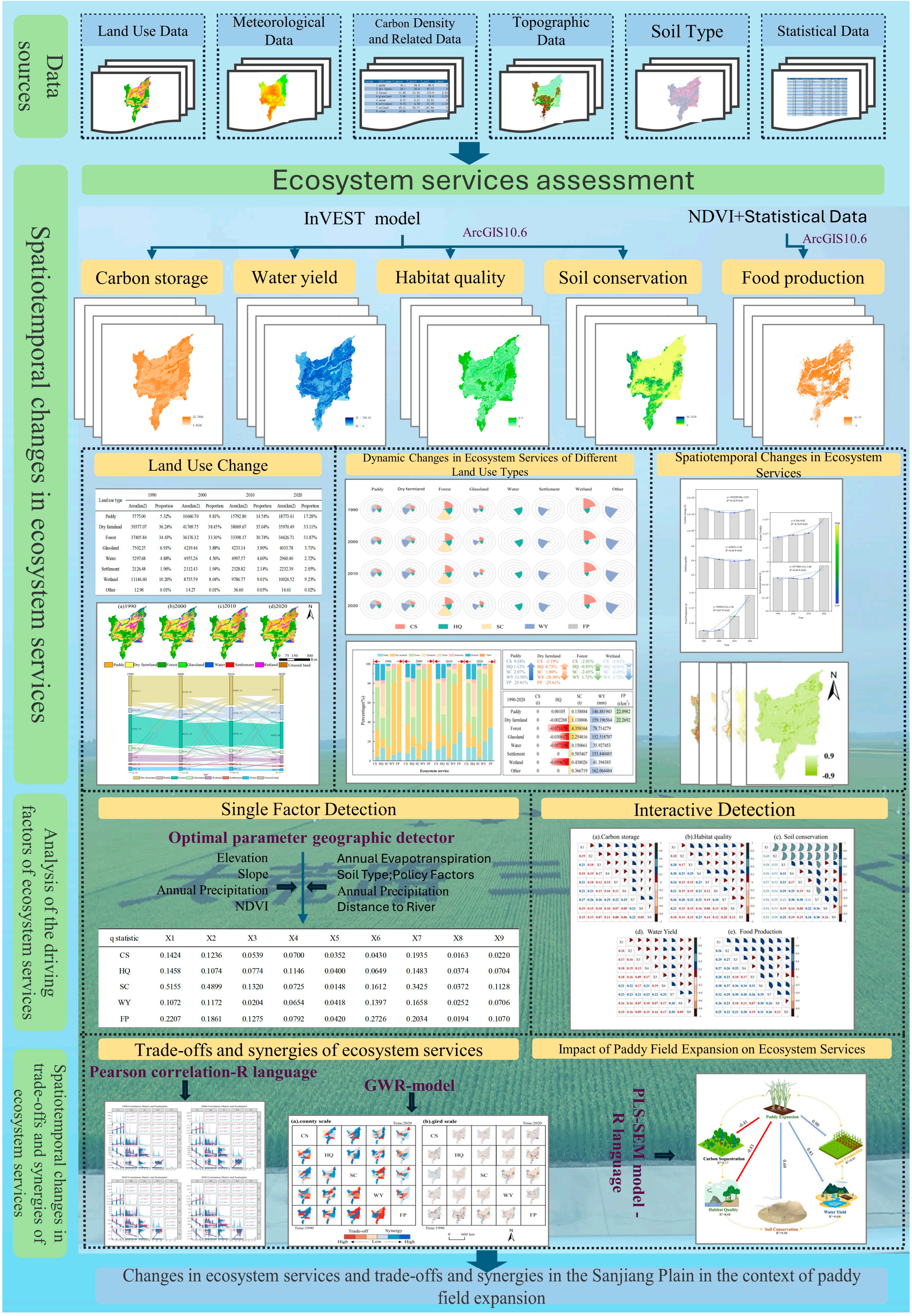

Figure 1. The flowchart of this study.

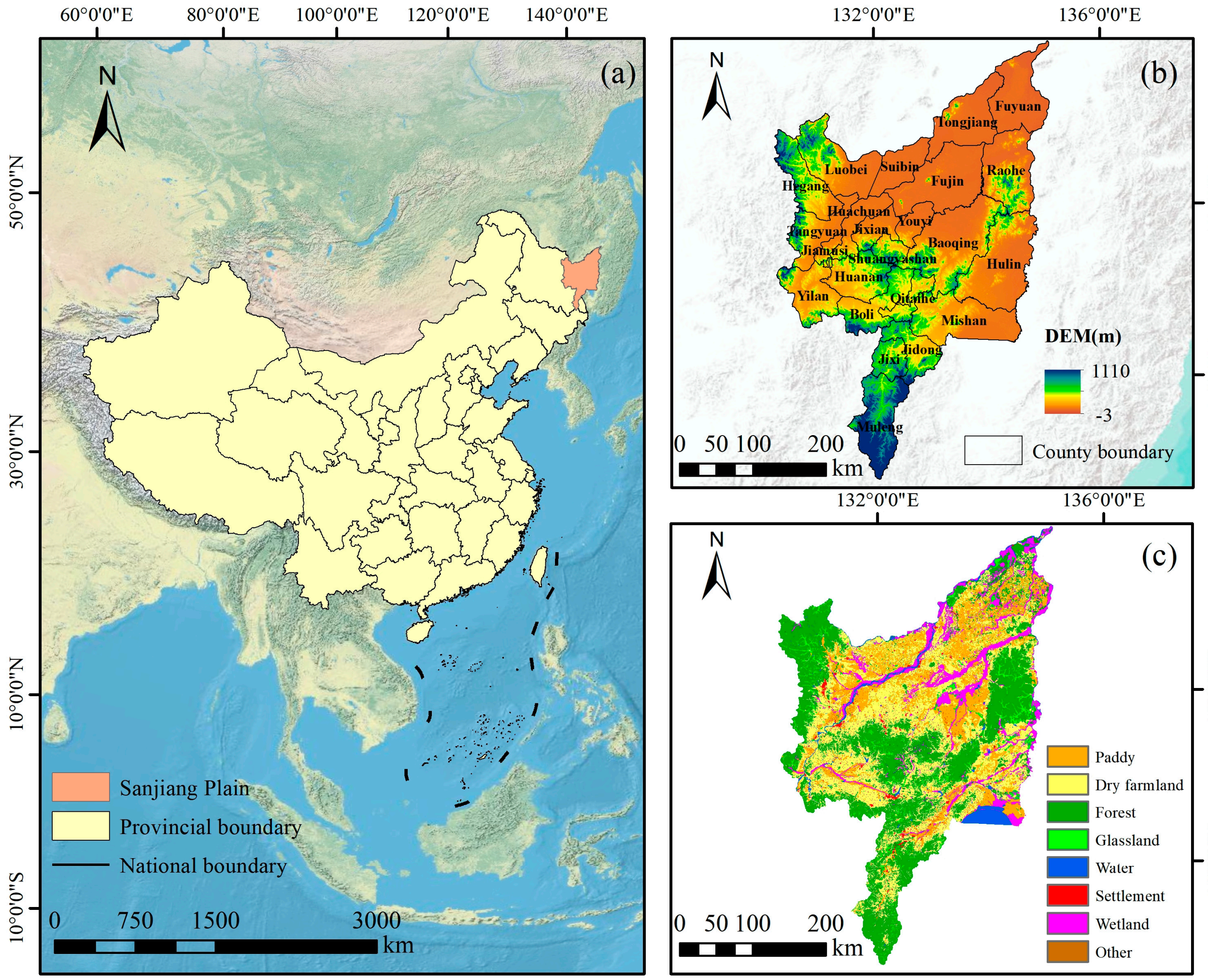

Figure 2. Study area. (**a**) Location of the study area. (**b**) Elevation and county boundaries. (**c**) Land cover/land use in 2020.

2.2. Data Source and Processing

The data utilized in this study include socio-economic, topographic, remote sensing imagery, and other data (Table 1). Data from various sources are resampled and projected in ArcGIS10.6, with the final projected coordinates standardized to the Albers Conic Equal Area projection.

Table 1. Data sources and descriptions.

Input Data	Resolution	Data Source and Processing
Digital elevation model (dem)	Raster, 30 m	https://srtm.csi.cgiar.org/srtmdata/ accessed on 20 May 2024.
Land use/land cover (LULC)	Raster, 30 m	Resource and Environment Science and Data Center (www.resdc.cn) accessed on 12 May 2024.
Carbon pools	Table	Supplementary S2
Threats table	Table	Supplementary S2
Sensitivity table	Table	Supplementary S2
Digital elevation model (DEM)	Raster, 30 m	https://srtm.csi.cgiar.org/srtmdata/ accessed on 20 May 2024.

Table 1. *Cont.*

Input Data	Resolution	Data Source and Processing
Precipitation	Raster, 1 km	National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn) accessed on 17 May 2024.
Watershed	Shapefile	Resource and Environment Science and Data Center (www.resdc.cn)
Biophysical table	Table	Supplementary S2
Potential evapotranspiration	Raster, 1 km	National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn) accessed on 17 May 2024.
Root restricting layer depth	Raster, 1 km	National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn) accessed on 17 May 2024.
Plant available water content	Raster, 1 km	National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn) accessed on 17 May 2024.
NDVI	Raster, 30 m	Resource and Environment Science and Data Center (www.resdc.cn) accessed on 12 May 2024.
Statistical data on grains	Table	China Agricultural Statistics Yearbook
Slope	Raster, 30 m	Obtained based on ArcGIS slope analysis tool
Potential evapotranspiration	Raster, 1 km	National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn) accessed on 20 May 2024.
Annual average temperature	Raster, 1 km	National Earth System Science Data Center (www.geodata.cn) accessed on 18 May 2024.
Soil type	Raster, 1 km	Resource and Environment Science and Data Center (www.resdc.cn) accessed on 20 May 2024.
Distance from the river	Raster, 1 km	Obtained through the buffer analysis tool in ArcGIS
The extent of farms and localities	Raster, 1 km	Obtained through the analysis tools in ArcGIS

2.3. Research Methods

2.3.1. ESs Quantification

Given regional conditions and data availability, we selected five ESs to quantify in this study. These services include carbon storage (CS), soil conservation (SC), habitat quality (HQ), water yield (WY), and food production (FP). The selection of these five ESs as key ESs for the Sanjiang Plain was primarily based on the region's ecological characteristics and the need for sustainable development. As a critically important wetland and agricultural area in China, research on CS helps address climate change, while HQ assessments support regional biodiversity conservation. WY is crucial for regional water resource management, SC ensures agricultural sustainability, and FP directly impacts the region's economy and livelihoods [41]. Overall, these five services comprehensively consider ecological health, economic development, and social needs, providing scientific support for the region's sustainable development.

These ESs were assessed using the InVEST model. The InVEST model integrates ESs and land use changes, helping decision-makers assess the impacts of different management scenarios on ecosystems and human well-being [42]. InVEST is highly open and flexible, allowing for the customization of model parameters according to the specific needs of different ecosystems and regions. Additionally, InVEST integrates GIS data, providing spatial analysis capabilities that make ESs assessments more intuitive and practical. Although the model's simplifications may overlook some ecological complexities, in this study, we calibrated the model results using previous research and field data to improve accuracy. Overall, InVEST provides an effective tool for evaluating ecosystem services and, through its flexibility and integration, bridges the gap between scientific research and practical decision-making. A summary of the modeling approach for quantifying these services is provided in (Table 2). For the rationale behind the model, please refer to the relevant literature [8,33]. For the basic formula related to this model, please see Supplementary S1.

Table 2. List of methods to quantify ESs.

Ecosystem Service	Methods	Formulas
Carbon storage (CS)	InVEST, Carbon module	$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead}$
Soil conservation (SC)	InVEST, SDR: Sediment Delivery Ratio module	$SC = RKLS - USLE = R \times K \times LS \times (1 - C \times P)$
Water yield (WY)	InVEST, Annual water yield module	$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x)$
Habitat quality (HQ)	InVEST, Habitat quality module	$Q_{xj} = H_j \times \left(1 - \frac{D_{xj}^z}{D_{xj}^z + K^z}\right)$
Food production (FP)	NDVI	$G_{fp} = \frac{NDVI_x}{NDVI_{sum}} \times G_{sum}$

2.3.2. OPGD (Optimal Parameter GeoDetector)

The GeoDetector is a spatial analysis method for detecting spatial stratified heterogeneity and revealing the driving forces behind it, and is widely used for driver and factor analysis [43]. Therefore, this paper utilizes factor detection in GeoDetector to reveal the driving factors affecting ESs in the SJP, based on the optimal parameters.

The attributes of the study area, data availability, and the more significant drivers identified in related research were considered. For this study, four main drivers were selected: topographic factors, meteorological factors, soil factors, and policy factors (Table 3). Additionally, the administrative affiliations of state farms and local farmers in this region differ, influencing land management practices. For this study, policy factors were categorized into individual farmers and state farms based on regional administrative distinctions. Using ArcGIS10.6, agricultural and reclamation areas were categorized into two groups based on policy criteria and assigned values of 0 and 1, respectively, for categorical differentiation as policy factors.

Table 3. Driver type selection.

Impact Factor	Indicator
X1	Elevation
X2	Slope
X3	Annual precipitation
X4	Annual mean temperature
X5	Annual evapotranspiration
X6	NDVI
X7	Soil type
X8	Distance to river
X9	Policy factors

2.3.3. ESs TOS Assessment Methods

Relationships between ESs can be categorized as trade-offs, synergies, and insignificant. Insignificant means that one ESs does not change with the other, trade-offs mean that one ESs decreases with the increase in the other, and synergies means that both ESs change simultaneously. In this study, the TOS relationships between ESs were quantified using Pearson analysis and GWR in R (4.3.3). The Pearson analysis reveals the linear relationships between the variables, and the GWR reveals the spatial heterogeneity among ESs. For formulas, please refer to [44,45].

2.3.4. PLS-SEM (Partial Least Squares-Structural Equation Model)

In this study, the PLS-SEM was used to measure the impact of paddy field expansion on ESs. First, the PLS-SEM can handle multivariate problems with small sample sizes. Second, the PLS-SEM has greater predictive power, less stringent data requirements, does not assume a normal distribution, and still produces robust outputs [46].

3. Results

3.1. Expansion of Paddy Fields and Land Use Change in the SJP

During the study period, the land use types in the SJP area were dominated by dry fields, forested lands, and paddy fields (Table 4). In 1990, 2000, 2010, and 2020, the total areas of drylands, forested lands, and paddy fields comprised 75.99%, 81.56%, 80.32%, and 82.26% of the SJP, respectively. Dryland area dominated the landscape during the study period, comprising 36.24%, 38.45%, 35.04%, and 33.11%, showing an increasing and then decreasing trend. Paddy fields have shown significant changes in area, comprising 5.32%, 9.81%, 14.54%, and 17.28% in 1990, 2000, 2010, and 2020, respectively. Paddy field area increased by 12,998.41 km^2 during the past 30 years, demonstrating a consistent annual increase.

Table 4. Areas and proportions of various LUTs.

Land Use Type	1990		2000		2010		2020	
	Area (km^2)	Proportion	Area (km^2)	Proportion	Area (km^2)	Proportion	Area (km^2)	Proportion
Paddy	5775.00	5.32%	10,660.70	9.81%	15,792.80	14.54%	18,773.41	17.28%
Dry farmland	39,377.07	36.24%	41,769.75	38.45%	38,069.67	35.04%	35,970.49	33.11%
Forest	37,405.84	34.43%	36,176.32	33.30%	33,398.17	30.74%	34,626.71	31.87%
Grassland	7502.25	6.91%	4219.46	3.88%	4233.14	3.90%	4033.78	3.71%
Water	5297.68	4.88%	4955.26	4.56%	4997.57	4.60%	2960.40	2.72%
Settlement	2126.48	1.96%	2112.43	1.94%	2328.82	2.14%	2232.39	2.05%
Wetland	11,146.60	10.26%	8735.59	8.04%	9786.77	9.01%	10,026.52	9.23%
Other	12.96	0.01%	14.27	0.01%	36.60	0.03%	16.61	0.02%

Throughout the study period, the areas of forest, grassland, wetland, and water exhibited a consistent decline, decreasing by 2.56%, 3.19%, 2.15%, and 1.03%, respectively, by 2020. The area of settlement decreased and then rose, resulting in an overall increase of 0.10%. The "other" category had the smallest proportion of the area and exhibited minimal change over the period. The rates of change for each land use types from 1990 to 2020, in descending order, were as follows: paddy fields, grasslands, drylands, forests, water, wetlands, settlements, and other categories.

During the study period, the spatial distribution of land use types in the SJP was basically consistent, but there was a strong transition between different land use types (Figure 3). Drylands and paddy fields are mainly distributed in the central plains of the study area, with large changes in area and a clear trend of expansion. Forested land is mainly distributed in areas with higher terrain; wetlands are mainly distributed near rivers and water, and grasslands are sporadically distributed around wetlands and forested. Little spatial change is observed in settlements, water and other.

Figure 3 shows the changes between different land use types in 1990–2000, 2000–2010, and 2010–2020. Changes in paddy fields and drylands are the most obvious, with paddy fields increasing by 12,998.41 hm^2 during the 30 years; drylands decreased by 3406.59 hm^2. It was caused by the conversion within the cropland and the policy of returning farmland to forests. Areas of forest, grassland, wetland, and water decreased due to the continuous expansion of cropland areas. Settlement and other unutilized land showed minimal change. Overall, the conversion of the various land use types in the study area is more dramatic over the 2000–2020 period.

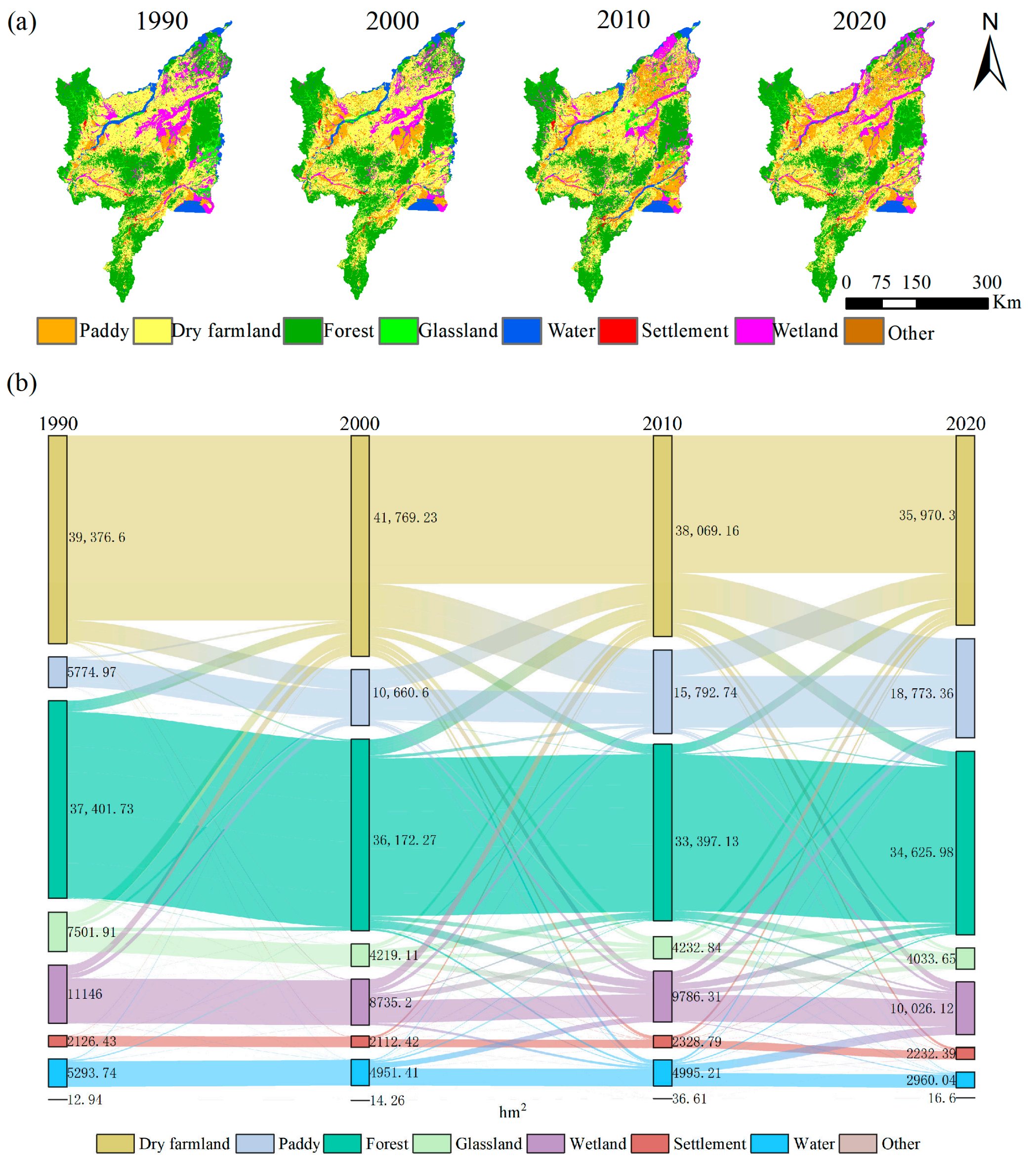

Figure 3. (**a**) Land use changes in the SJP from 1990 to 2020. (**b**) Land use transition chord diagram in the SJP from 1990 to 2020.

3.2. The Spatiotemporal Changes in ESs

In this study, five ESs in the SJP were assessed. The results showed that the SJP exhibited significant spatial heterogeneity in ESs during the study period (Figure 4). The spatial distribution patterns of CS and HQ were similar and closely related to the LUTs in the study area, with the high-value areas all located in woodlands and wetlands in the study area. Additionally, watersheds like Xingkai Lake were in low-value CS areas but high-value HQ areas. Areas where CS and HQ changed were generally consistent over the study period. The areas of increased CS were mainly located near water bodies, and the areas of decreased CS were mainly where wetlands, forests, and grasslands had been encroached upon. The changes in HQ align with those in wetland, woodland, and grassland areas. From 1990 to 2020, significant changes in SC were primarily observed in the higher-terrain areas of the SJP, while SC in the central plains and areas with low topography decreased to varying extents. Rainfall and evapotranspiration are the primary factors influencing WY, which has shown a noticeable upward trend during the study period alongside increasing precipitation in the SJP. The areas with significant changes in WY from 1990 to 2020 correspond closely with changes in wetlands and grasslands. High-value FP is concentrated in the central area where cropland is contiguous and extensive, whereas low-value areas are predominantly found in fragmented cultivated lands surrounding this central area. FP has generally shown a notable upward trend throughout the study period, with only a small portion of croplands experiencing declines.

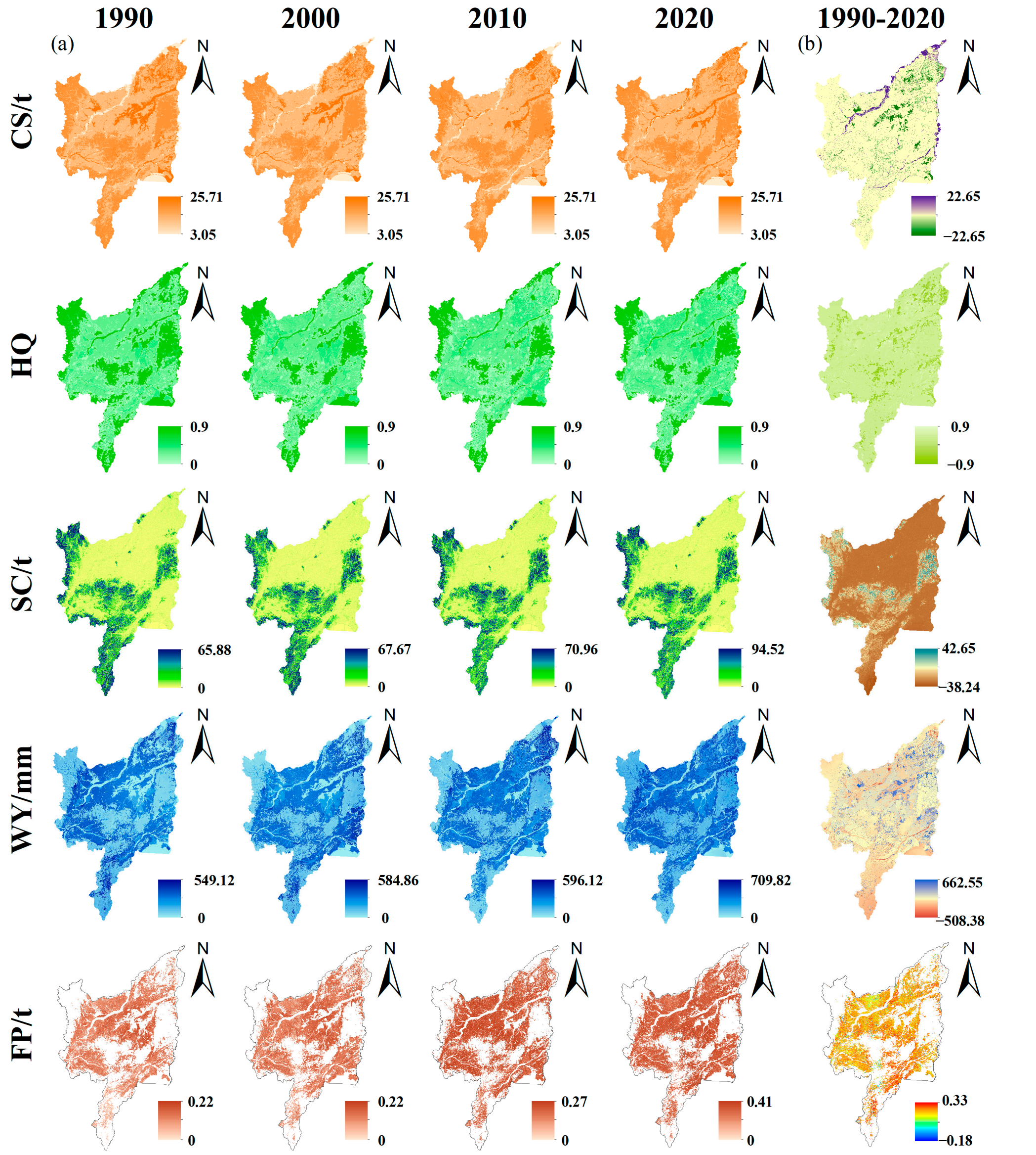

Figure 4. (**a**) Spatiotemporal distribution of ESs in the SJP from 1990 to 2020. (**b**) Spatiotemporal changes in ESs in the SJP.

From 1990 to 2020, ESs in the SJP exhibited varying trends (Figure 5). CS, HQ, and SC initially showed decreases followed by increases, with CS decreasing by 0.01×10^9 t and HQ by 0.04. SC decreased from 1990 to 2010 and significantly increased from 2010 to 2020, resulting in SC increasing by 1.78×10^8 t over the 30 years. WY increased by 1.32×10^{10} t over 30 years. Grain production increased by 2.32×10^7 t over the last 30 years, attributed to the cultivation of improved varieties, the rational use of fertilizers and pesticides, and advancements in agricultural mechanization.

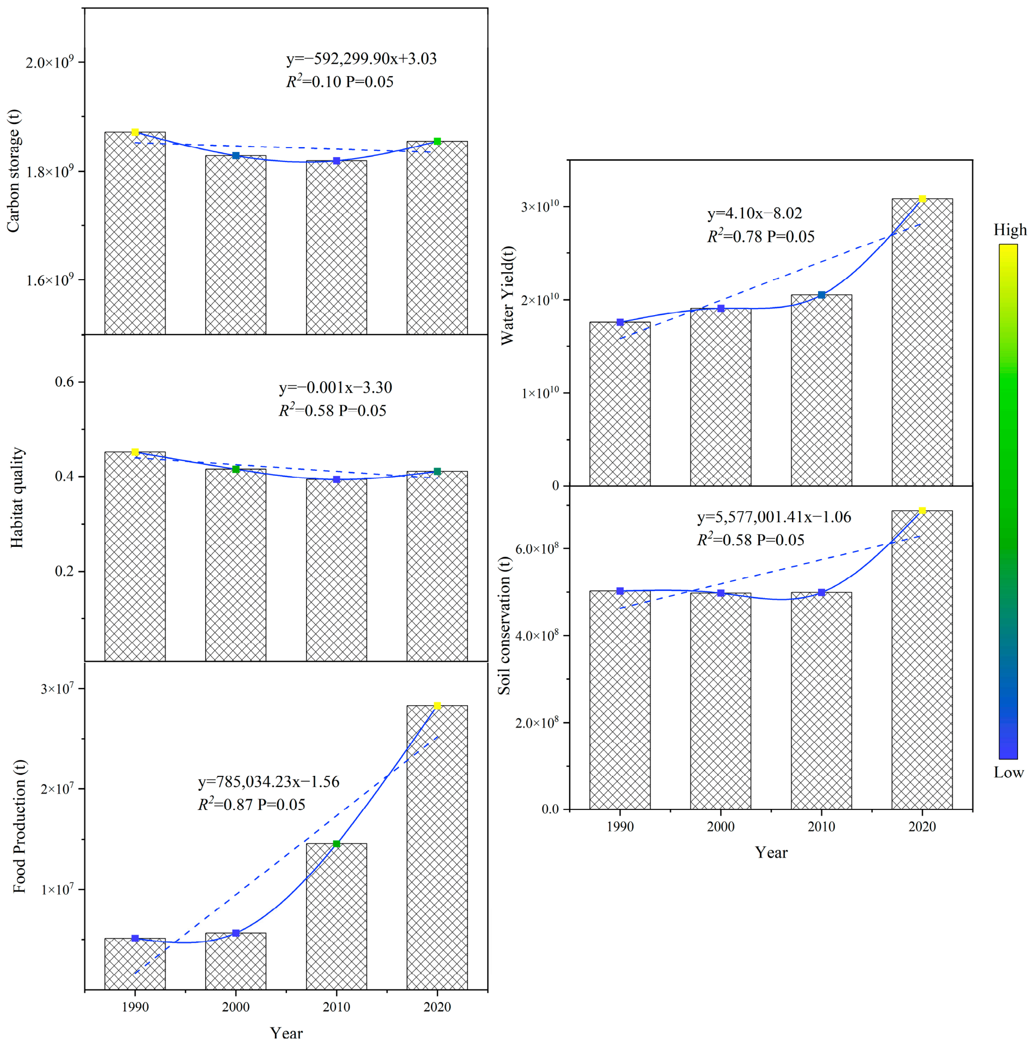

Figure 5. Interannual changes in the total ESs of the SJP.

3.3. Changes in ESs Across Land Use Types

In this study, the mean ESs value for each land category was calculated separately using spatial statistics tools in ArcGIS10.6, and the ESs of each land category were normalized and plotted in a rose diagram (Figure 6). The results showed that forests and wetlands had the highest CS from 1990 to 2020, reaching 25.71 t and 19.68 t, respectively. Forests and water primarily provide regional HQ functions, and changes in HQ reveal significant decreasing trends for each category from 1990 to 2020. Forests and grasslands, as the largest regional providers of SC functions, exhibit fluctuating upward trends in their SC levels. WY is the most important ecosystem service for settlement and other land uses. FP activities are generally carried out only on cropland; thus, paddy fields and drylands contribute most significantly to regional FP functions. As the largest land use types in the SJP, paddy fields and drylands not only perform all five ESs functions, but also deliver relatively high levels of ESs. Grasslands, forests, and wetlands, as important ecological barriers in the region, also assume most of the ESs functions. Water, settlement, and other land uses, on the other hand, contribute relatively singular ESs functions.

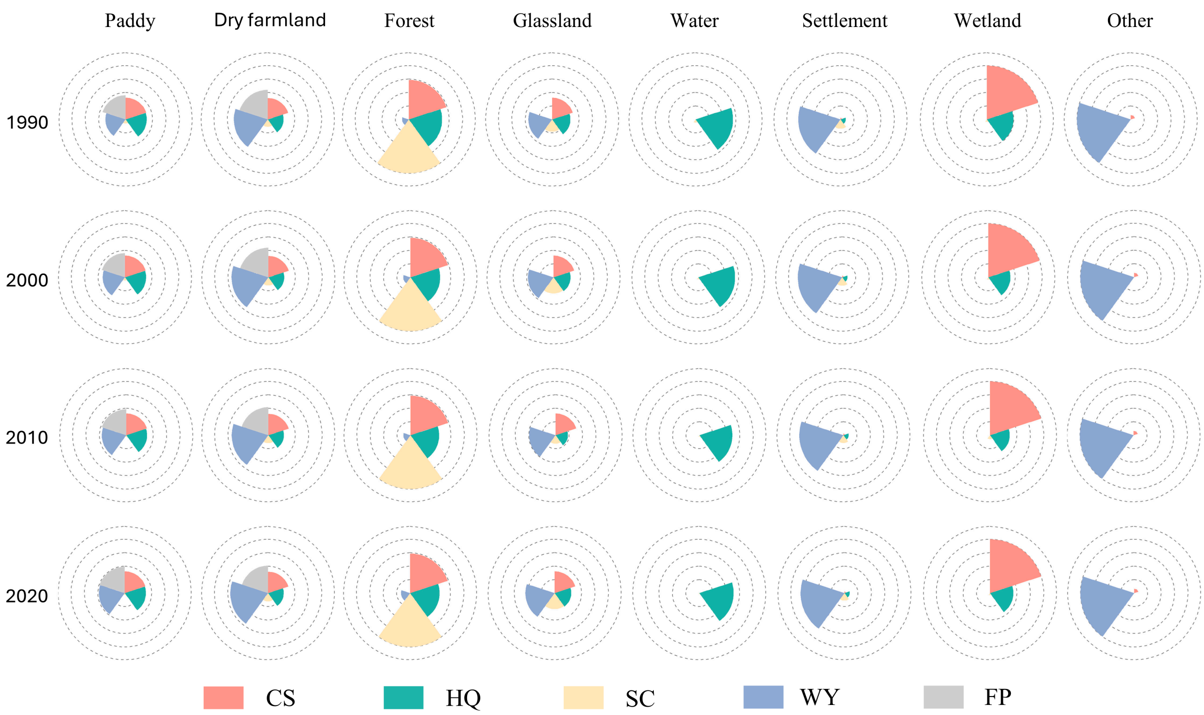

Figure 6. Nightingale rose charts of ESs by eight LUTs for 1990, 2000, 2010, and 2020.

In terms of the proportion of ESs provided by each LUT in the SJP (Figure 7), paddy fields, drylands, and forests have strong ESs provisioning capacity, and the proportion of ESs provided by these three land use types consistently exceeds 50%. Overall, the proportion of ESs provided by each land use types in the SJP remained relatively stable from 1990 to 2020. Additionally, the ESs capacity of paddy fields increased during this period due to the expansion of paddy fields and the increase in grain production per unit area. Conversely, due to the implementation of the drought-to-water conversion policy, some of the dryland was converted to paddy land or other land types, resulting in a decreasing trend in CS, WY, and FP functions. Wetlands and forests exhibited a decreasing trend in all services except for WY, which increased. The ESs functions represented by each of the land classes changed over the 1990–2020 period, with CS remaining unchanged, while the other four services fluctuated. There was a small increase in HQ for paddy fields, and HQ services for all other land classes showed a constant or decreasing trend, while SC, WY, and FP services primarily exhibited increasing trends over the 30-year period.

3.4. Impact of Drivers on ESs

A total of nine indicators, including topography, climate, soil, and policy, were selected as the driving factors for this study. Compared with some studies that use the simple natural segment point method to discretize the data, this paper uses OPGD to discretize the data with optimal parameters, which is more robust and scientific. For the single factor detected of the factors affecting ESs in the SJP from 1990 to 2020 (Table 5), it was evident that the elevation, slope, and soil type, were the top three among in the explanatory power of ESs changes. The results showed that in the case of CS, HQ, and SC, the explanatory power of soil and topographic factors for these three ESs was notably stronger, and soil type, DEM, and slope were the main drivers of changes in CS, HQ, and SC. For WY and FP services, soil type and NDVI had higher explanatory power. The main drivers affecting WY were soil type, NDVI, and slope, with 16.58%, 13.97%, and 11.72%, respectively. The main drivers affecting FP were NDVI, soil type, elevation and slope, where the explanatory power of policy factors on FP was also stronger at 10.70%. Overall, topography, soil type, and NDVI were the main drivers affecting the spatial heterogeneity of ESs in the SJP.

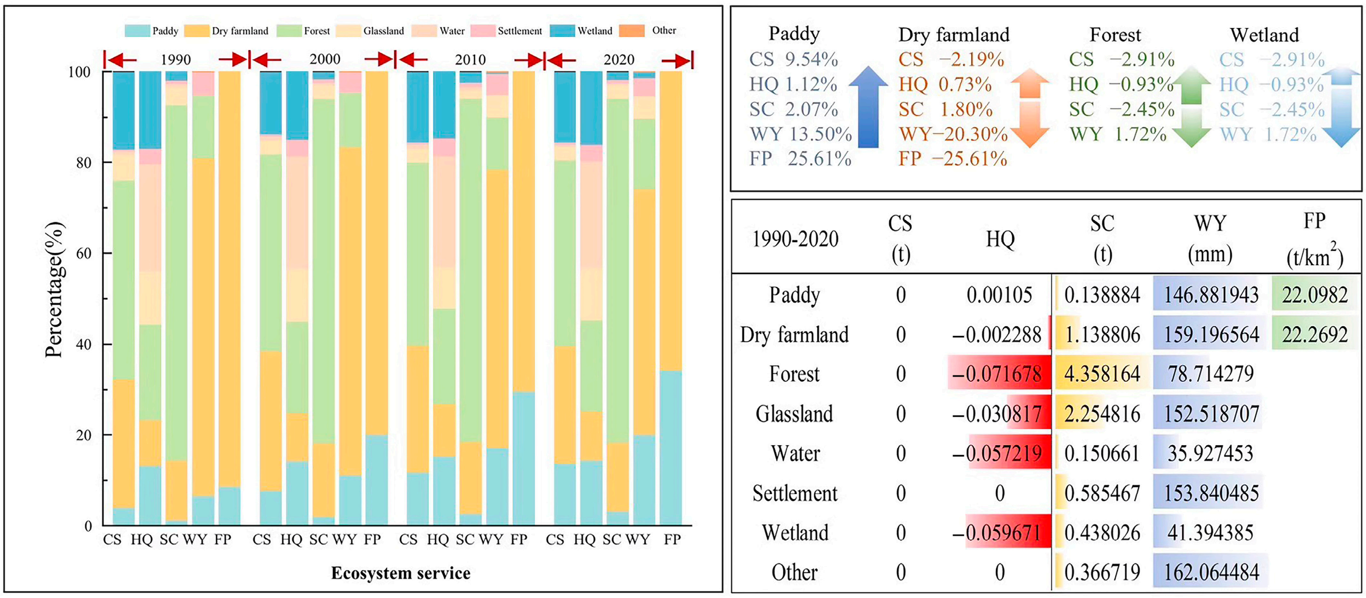

Figure 7. Percentage of and change in the total supply of ESs by eight LUTs for 1990, 2000, 2010, and 2020.

Table 5. Ecosystem services factor detection results.

q Statistic	X1	X2	X3	X4	X5	X6	X7	X8	X9
CS	0.1424	0.1236	0.0539	0.07	0.0352	0.043	0.1935	0.0163	0.022
HQ	0.1458	0.1074	0.0774	0.1146	0.04	0.0649	0.1483	0.0374	0.0704
SC	0.5155	0.4899	0.132	0.0725	0.0148	0.1612	0.3425	0.0372	0.1128
WY	0.1072	0.1172	0.0204	0.0654	0.0418	0.1397	0.1658	0.0252	0.0706
FP	0.2207	0.1861	0.1275	0.0792	0.042	0.2726	0.2034	0.0194	0.107

This study showed that the interactive effects of two indicators affecting the regional heterogeneity of ESs in the SJP had stronger explanatory power than a single factor (Figure 8). The significant increase in the explanatory power after interaction suggests that no single factor can completely determine the variations in ESs in the SJP. The explanatory power of the interaction between elevation∩soil type on the spatial heterogeneity of CS was the largest, at 19.39%, larger than that between soil type∩other factors. And all factors were greater than 21%. The interactions involving elevation, annual mean temperature, and soil type were stronger, with the interaction between annual mean temperature∩soil type having the most significant effect on HQ, with an explanatory power of 31.64%. For SC service, it had the greatest explanatory power, at 59.51% between elevation∩slope, followed by the interaction of slope∩elevation alone on other factors. For WY service, it was 25.11% between NDVI∩soil type. In FP, it was generally greater than 20%, and the explanatory power of the interaction between NDVI∩other factors was relatively strong, all greater than 30%. The interaction between NDVI∩soil type had the greatest explanatory power for the spatial heterogeneity of FP, which was 38.88%. It was also above 10% between policy factors∩other factors. Overall, the interaction detection revealed that soil type, NDVI, slope, DEM, and policy factors are important factors for understanding the changes in ESs in the SJP.

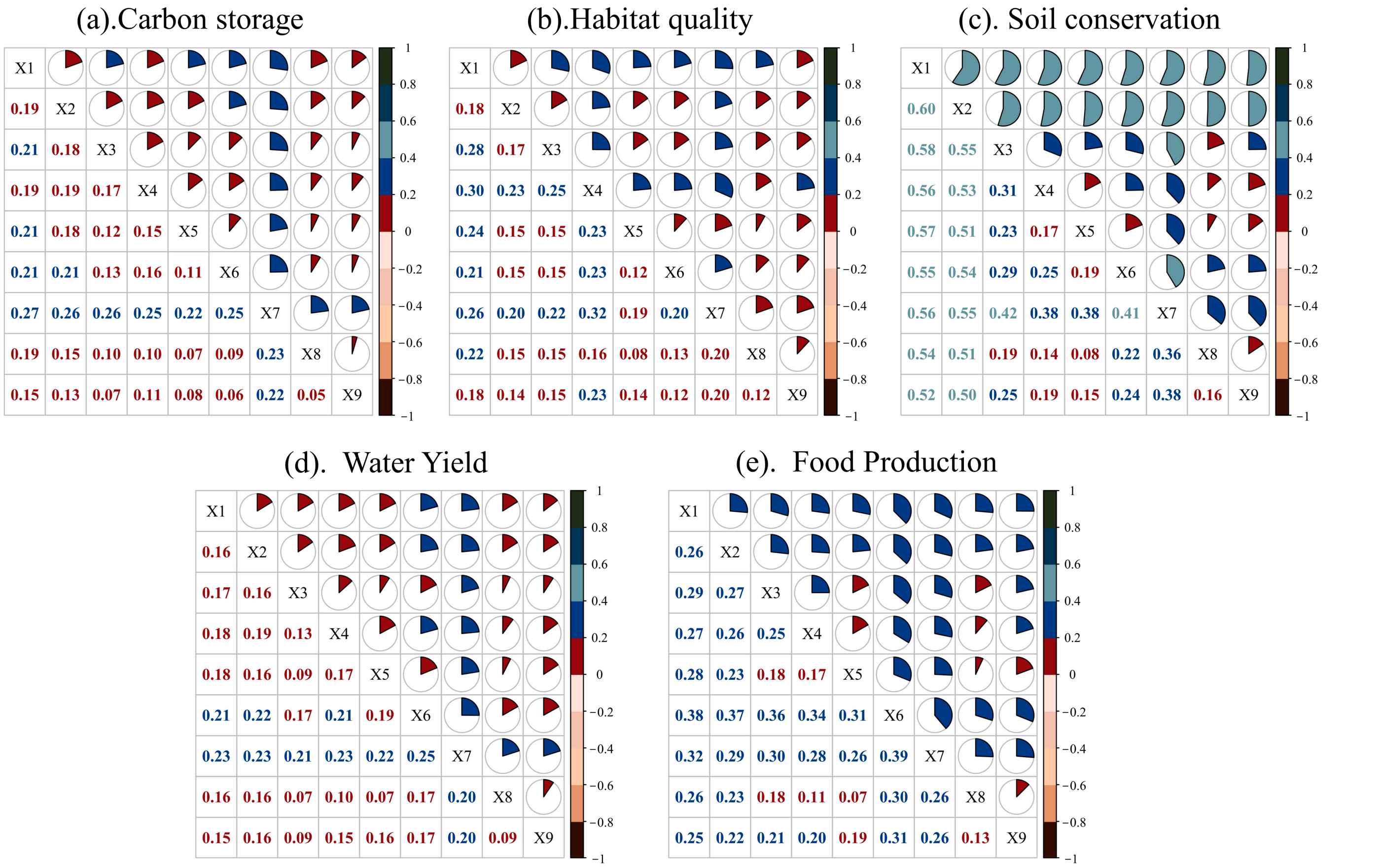

Figure 8. Interactive detection of influencing factors of ESs in SJP. Note: X1, elevation; X2, slope; X3, annual precipitation; X4, annual mean temperature; X5, annual evapotranspiration; X6, normalized difference vegetation index; X7, soil type; X8, distance to river; X9, policy factors.

3.5. Spatial and Temporal Characteristics of Ecosystem Services Trade-Offs and Synergies in the Sanjiang Plain

The results showed significant relationships between ESs in the SJP, with a *p*-value of <0.001 (Figure 9). From 1990 to 2020, there were varying degrees of correlation between each pair of ESs, and their correlation coefficients showed notable similarities. CS was positively correlated with HQ and SC, indicating synergy relationships with their respective increases and decreases. Conversely, CS was negatively correlated with WY and FP, indicating trade-offs. HQ had a significant synergy relationship with SC and notable trade-offs with both WY and FP. SC also exhibited trade-offs with WY and FP, while WY demonstrated a significant synergy relationship with FP.

To understand the spatial TOS among different ESs in SJP, the GWR was employed to illustrate the spatial heterogeneity of these relationships (Figure 10). The results are presented in Figure 10. Overall, the TOS relationships among various ESs exhibited significant spatial heterogeneity and scale effects. The TOS at raster and county scales showed inconsistencies and notable differences among subregions. From the spatial changes in ESs TOS from 1990 to 2020, the areas of CS and HQ trade-offs were predominantly in the western and southeastern regions, while the areas of synergy were primarily in the central region. The trade-offs between CS and SC, HQ and SC, and CS and WY were mainly located in the central region around the city of Jiamusi and the southeastern region, with synergy areas localized in the central region.

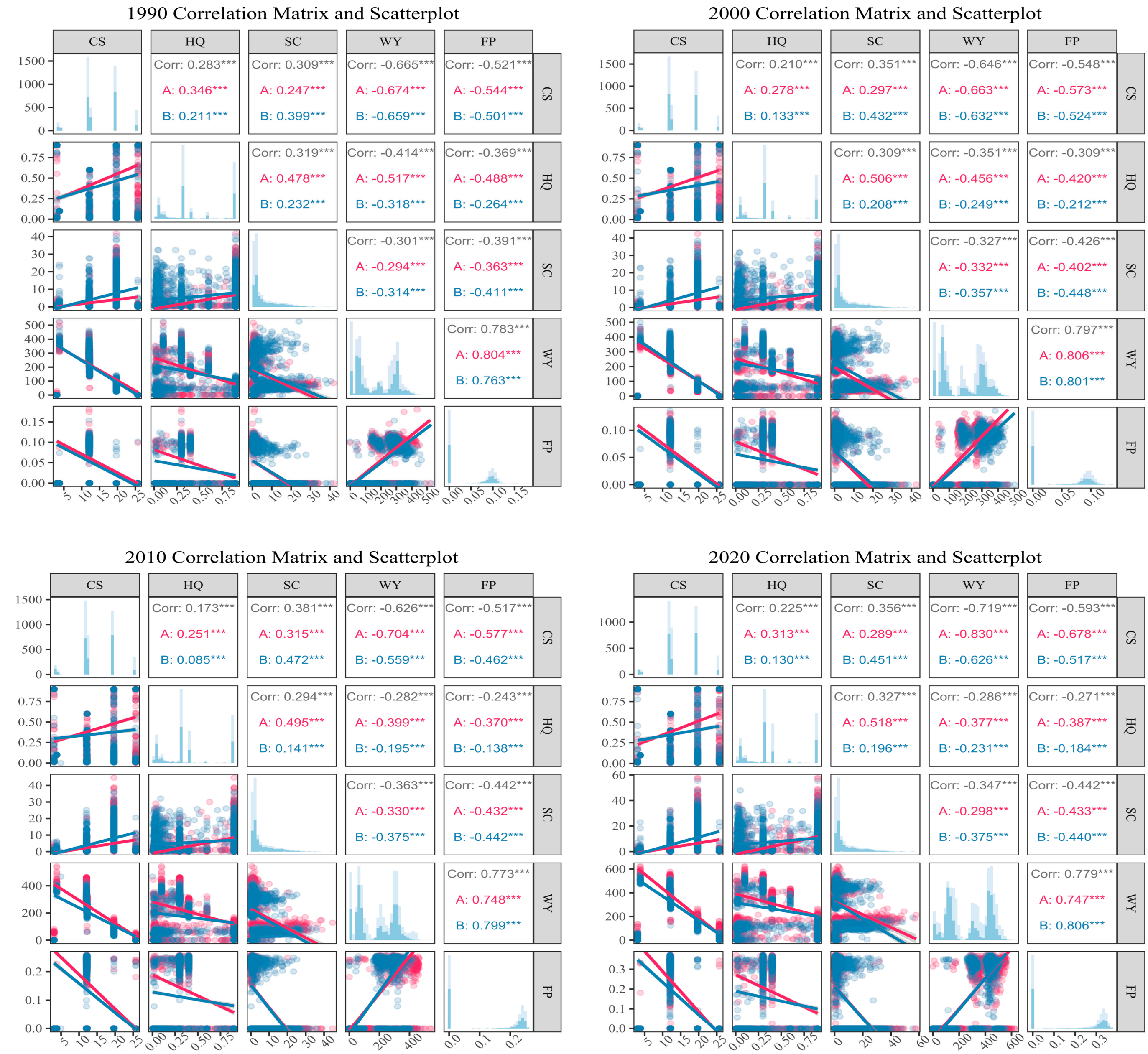

Figure 9. Correlation matrix and scatterplot of TOS of ESs in the SJP from 1990 to 2020. *** Indicating a highly significant $p < 0.001$. A, B represents the correlation demonstrated by dividing the data in the study area into two groups on average.

The areas of HQ and WY trade-offs are mainly clustered in the northwestern and southeastern counties and cities, while the synergy areas are scattered across a few counties and cities in the northeast and southwest. The TOS relationships between SC and WY are dominated by trade-offs, with the majority of the eastern part of the region characterized by trade-offs. In contrast, the TOS relationships between CS, HQ, SC, WY, and FP exhibit pronounced spatial heterogeneity. In 1990, the relationships among CS, HQ, and FP were predominantly synergies, whereas those among SC, WY, and FP were predominantly characterized by trade-offs. By 2020, weak trade-off relationships dominated most areas between CS, HQ, SC, WY, and FP. At the raster scale, the TOS relationships among the five ESs from 1990 to 2020, although differing in small regions, showed spatial similarities at a larger regional scale. In conclusion, the TOS relationships among ESs in the SJP exhibit significant scale effects as well as spatial heterogeneity.

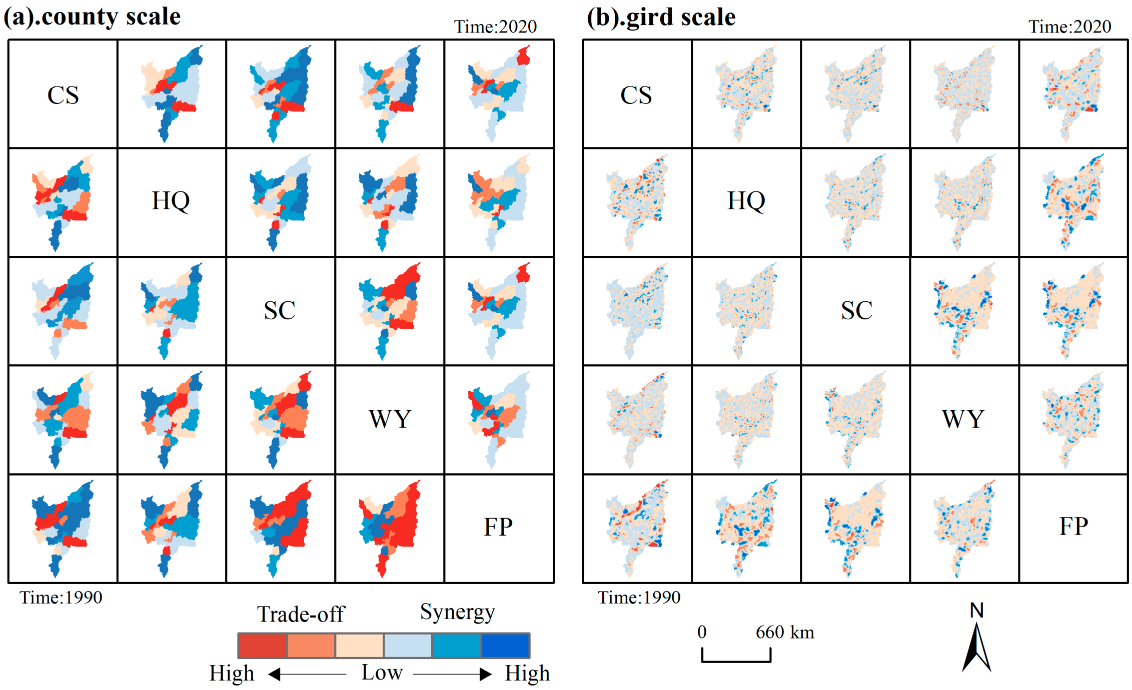

Figure 10. Spatial distribution of TOS of ESs in the SJP.

3.6. Impacts of Paddy Field Expansion on ESs

We analyzed the effects of paddy field expansion on five ESs using the PLS-SEM (Figure 11). Since this study explored the relationship between paddy field expansion and five ESs, we analyzed only the path coefficients of paddy field area on these services and the R^2 values. Between 1990 and 2020, paddy field expansion negatively impacted regional CS and HQ, with the greatest impact on HQ (path coefficient: −0.83) and a significant impact on CS (path coefficient: −0.41). Paddy field expansion positively contributed to SC, WY, and FP, having the greatest impact on FP (path coefficient: 0.90). It also significantly impacted SC and WY, with path coefficients of 0.69 and 0.83, respectively.

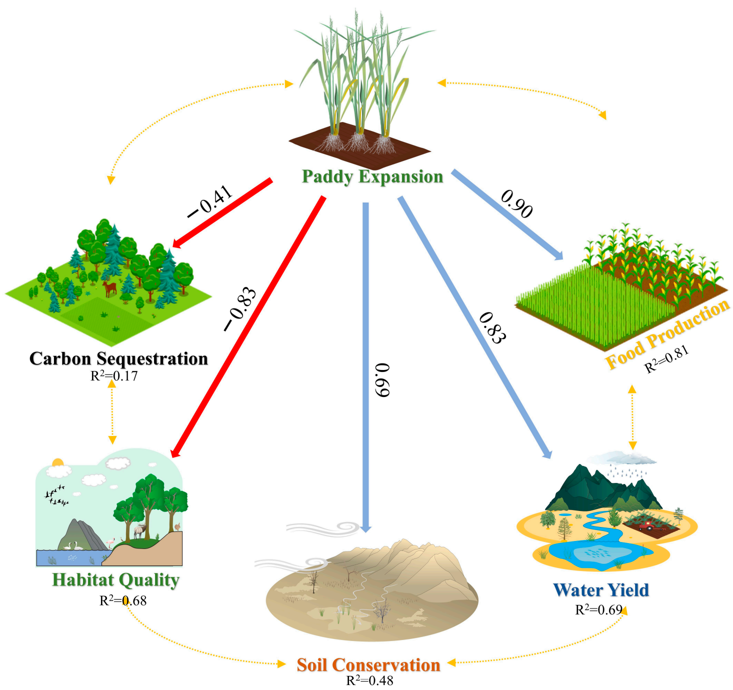

Figure 11. Impact of paddy field expansion on ESs in the SJP.

4. Discussion

4.1. Dynamics and Drivers of ESs in the SJP

The distribution pattern of ESs is closely linked with the land use pattern [47]. The southwest and a small part of the east are mountainous areas with higher terrain, minimal human disturbance, high vegetation cover, and rich biodiversity, which are areas with high values of CS, HQ, and SC. Conversely, WY is strongly influenced by rainfall and evapotranspiration and is mainly distributed in plains with lower terrain, and FP is concentrated in cropland. From 1990 to 2020, CS and HQ in the SJP generally declined, while SC, WY, and FP generally increased, consistent with existing studies [38]. At the same time, the conversion of farmland to forest and grassland, wetland protection policies, and the establishment of nature reserves increased vegetation cover [48]. Consequently, the ecological environment was restored, and the water demand for vegetation and water retention on the ground increased, resulting in an increase in WY. The areas of high value for CS, SC, and HQ were mainly dominated by woodlands, grasslands, and wetlands. The protection policies contributed to the restoration of vegetation cover and the ecological environment. Studies indicated that photosynthetic carbon sequestration and root sequestration by vegetation enhanced carbon sink capacity [49,50], and regional HQ was influenced by vegetation cover, with CS and HQ recovering in the last 10 years. Good vegetation cover slows runoff and absorbs precipitation, reduces soil erosion, and increases SC capacity [51]. Factors such as advances in agricultural science and technology, policy support, and infrastructure development have led to a significant increase in FP.

Changes in ESs are caused by a range of factors, such as topography, climate change, and human activities [52]. Studies have shown that changes in CS are mainly influenced by land use patterns [44]. Over the past 30 years, the CS capacity of forest land, grassland, and wetland has decreased due to the expansion of cropland, resulting in a decreasing trend in CS. Simultaneously, the reduction in forest and grassland areas diminished biological habitats, and the construction of irrigation reservoirs exacerbated the negative impacts on HQ, leading to a decline in HQ and SC. Between 2010 and 2020, policies drove the restoration of woodland and grassland areas, leading to increased vegetation cover and the subsequent recovery of HQ and SC. These findings are consistent with recent studies indicating that fallow forest programs improved SC in the Loess Plateau and Liaohe River Basin [53,54]. Precipitation is the primary source of water recharge in temperate regions, and precipitation patterns directly determine changes in WY. Over the past 30 years, the climate of the SJP has become progressively warmer and wetter (Figure 12), with increased precipitation and temperature contributing to higher WY. FP is strongly influenced by meteorology, topography, and soil type. Appropriate precipitation, suitable temperature, and sufficient light directly affect crop yields; topography affects precipitation distribution and soil erosion, which in turn impacts FP; and different soil types influence crop suitability and yields. This study also found that policy factors significantly impact FP.

4.2. TOS Relationships Between ESs in the SJP

In this paper, the relationship between ESs TOS in the SJP was investigated using Pearson analysis and GWR in R. It was found that there were trade-offs between WY and CS, and HQ and SC; similar trade-offs were observed between FP and these three services. Synergy relationships were found between CS and HQ and SC, HQ and SC, and WY and FP. Additionally, the spatial heterogeneity of ESs within the region was analyzed using the GWR.

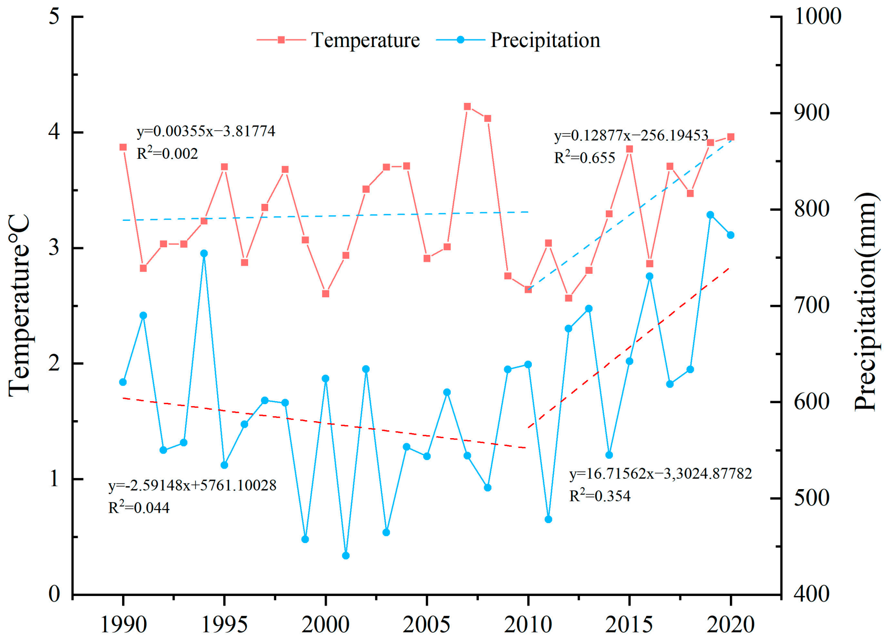

Figure 12. Changes in annual mean temperature and annual precipitation in the SJP from 1990 to 2020.

It was found that there are trade-offs between ESs due to the limited nature of resources and the mutual exclusion of ESs. Due to the finite nature of regional water resources, trade-offs exist between WY and CS, HQ, and SC, because these services jointly utilize limited water resources. An increase in WY reduces the amount of water in the soil, affecting vegetation growth and CS changes in the region [55,56]. Additionally, regional land resources are limited; FP requires a large amount of land. Land used for food cultivation cannot maintain HQ or increase CS. Agricultural activities often necessitate the clearing of cropland and the use of fertilizers and pesticides, which can harm HQ and reduce SC functions [57]. On the other hand, trade-offs between ESs may also occur due to the mutual exclusion of the functions of each ESs [58]. CS are generally associated with areas of forest or other high vegetation cover, which may not be suitable for agricultural production. Thus, increasing CS and HQ may necessitate a reduction in the area of arable land. Agricultural production frequently leads to ecosystem disturbances, such as soil erosion and pesticide pollution, which can reduce SC and HQ. Several studies have shown that complementarities and co-facilitators of ESs lead to synergy relationships between ESs [59]. The synergy relationship between CS, HQ, and SC is due to the combined effects of vegetation. Healthy vegetation not only stores significant amounts of carbon but also protects habitats and maintains soil stability [60]. For example, forests and grasslands reduce soil erosion through their root structure while providing habitat for organisms. Healthy ecosystems typically exhibit multiple functions that support each other. High-quality habitats promote soil retention, while stable soils help maintain vegetation cover and CS. Moreover, some ecological restoration programs initiated by the government often enhance multiple ESs [61]. For example, reforestation projects not only increase CS but also enhance HQ and soil retention. For agricultural production, the adoption of sustainable agricultural practices can enhance FP while protecting soil and HQ. Simultaneously, differences in geographic conditions and the impact of some human activities lead to significant spatial heterogeneity among ESs. Mountainous areas are ideal for forest cover and CS accumulation, while plains are suitable for agricultural production. Differences in soil type and fertility across different regions can also lead to spatial heterogeneity in ESs. High-intensity agricultural activities may concentrate in some areas, while nature reserves may be concentrated in others. The phenomenon of TOS among ESs in the SJP results from a combination of multiple natural factors and human activities. These factors interact to form a complex dynamic relationship within ESs. Comprehending these factors is essential for developing effective ecological management and sustainable development strategies.

4.3. Causes of Paddy Field Expansion and Impacts on ESs

Over the past 30 years, the paddy field area in the SJP has expanded from 5775 km^2 in 1990 to 18,773 km^2 in 2020, nearly quadrupling in size. Some studies have shown that policy support plays a crucial role in promoting agricultural plantation restructuring [62]. Since the reclamation of the SJP, policy support has underpinned every large-scale expansion of paddy fields (Figure 13). Between 1956 and 1996, wetlands were primarily cultivated, and many were drained and converted into rice paddies. In the 21st century, a series of national policies and related laws have led to the implementation of strategies such as "curing floods with rice and enriching the people with rice." Furthermore, projects such as "converting drought to water" and "converting wetland to water" have been executed [63]. Driven by food market prices, some farmers have spontaneously converted drylands into paddy fields. This series of initiatives has significantly facilitated the conversion of drylands into paddy fields.

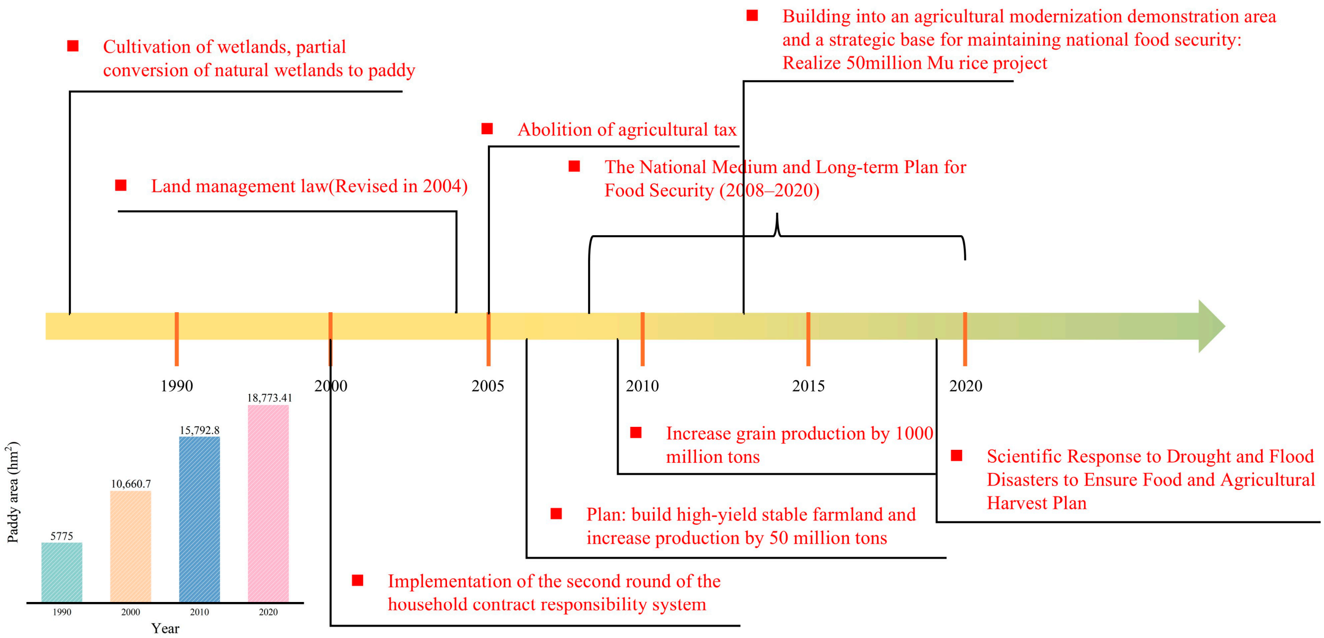

Figure 13. Changes in paddy area in the SJP and policy-driven paddy area expansion.

Although paddy field expansion promotes FP, it also affects regional ESs. We analyzed the effects of paddy field expansion on five ESs using the PLS-SEM model, and the results showed that paddy field expansion had a negative effect on CS and HQ, with coefficients of −0.409 and −0.827, respectively. Paddy field expansion directly contributed to SC, WY, and FP, with coefficients of 0.689, 0.828, and 0.898. Our study found that paddy field expansion leads to a reduction in the area of wetlands, forests, and grasslands, and that ecosystems such as wetlands and forests have high CS capacity. Converting these ecosystems to paddy fields reduces the vegetation cover and leads to a decrease in the regional CS. In addition, paddy field expansion can lead to the destruction of natural ecosystems such as wetlands and forests, reducing wildlife habitat and biodiversity, resulting in a decline in HQ [64]. Although paddy field expansion has a negative effect on CS and HQ, Paddy field expansion has a positive effect on the other three ESs. On the one hand, paddy farming can reduce soil erosion and improve soil retention through the root system of rice and soil moisture conditions. Irrigation systems and water management practices in paddy fields can increase WY in the region and promote water recycling. On the other hand, paddy field expansion directly increases the area under rice cultivation and enhances FP. In conclusion, paddy field expansion has had a complex impact on the ESs of the SJP, yielding both positive and negative effects.

To balance agricultural production and ecological protection, the following measures should be taken: first, optimize land use patterns by prioritizing land with low ecological value and avoiding important wetlands and forest resources for agriculture. Second, implement ecological compensation measures for transformed wetlands and forests, such as establishing nature reserves and ecological restoration projects, to restore and maintain ES functions. Finally, actively promote sustainable and smart agriculture by adopting techniques like water-saving irrigation, ecological planting, and variable fertilizer application to minimize environmental impacts and protect water resources and soil quality. These measures can safeguard FP, minimize negative ecosystem impacts, and promote the sustainable development of the SJP.

4.4. Limitations

This study comprehensively examines the changes in paddy field expansion and five ESs in the SJP from 1990 to 2020, discusses the drivers influencing these ESs, and explores their TOS, with the aim of contributing to regional ESs research. However, this study has the following shortcomings: (1) Although the study used 30 years of data, these data may have temporal and spatial limitations of ecosystem changes. For instance, external influences such as climate change and policy shifts can significantly affect ESs, yet these factors were not sufficiently addressed and measured. (2) Although the InVEST model, the OPGD, the GWR model, and the PLS-SEM were used, each model has its limitations and assumptions. The choice of models and their parameter configurations may impact the precision and dependability of the results. Future research might utilize alternative models or refine current ones to improve analytical accuracy. (3) Five ESs were selected for analysis in this paper. However, other significant services, such as cultural and regulatory services, may have been overlooked. Future studies should consider additional ESs indicators to achieve a more comprehensive assessment of ecosystem health. (4) Although spatial heterogeneity was explored in this paper, the heterogeneity analysis across different scales and regions may not be sufficiently detailed. Future research could explore the heterogeneity in its driving mechanisms across regions and scales in greater detail. (5) Paddy fields are important sources of methane emissions. Due to a series of limitations, greenhouse gas emissions were not considered an ESs in this study. Future research should include the contribution of greenhouse gasses as a crucial ESs, especially since rice cultivation plays a substantial role in methane emissions, which may have important implications for climate change and regional environmental dynamics.

5. Conclusions

This study analyzes the expansion of paddy fields from 1990 to 2020 and quantifies five representative ESs in the SJP using the InVEST model. The main drivers of ESs changes were examined using OPGD, while TOS relationships among ESs were explored through Pearson analysis in R and the GWR. Moreover, the effects of paddy field expansion on regional ESs were evaluated using PLS-SEM, with the goal of reconciling agricultural output and ecological conservation in the SJP. The primary findings are as follows:

(1) From 1990 to 2020, the area of rice paddies in the SJP increased by 12,998.41 km^2, nearly quadrupling. With the exception of rice paddies and settlements, all other land categories exhibited an overall decline.

(2) Regional ESs showed a recovery trend. CS, HQ, and SC initially showed decreases followed by increases, with CS decreasing by 0.01×10^9 t and HQ by 0.04. SC decreased from 1990 to 2010 and significantly increased from 2010 to 2020, resulting in SC increasing by 1.78×10^8 t over the 30 years. WY increased by 1.32×10^{10} t over 30 years. The ecosystem service functions of different land types varied significantly, with paddy fields, drylands, forests, and wetlands being the main providers. Soil type, topography, and NDVI

were the primary drivers of ESs changes, with elevation and slope explaining 59.51% of spatial variation in SC, and soil type and NDVI explaining 38.88% of spatial variation in FP.

(3) There were varying degrees of correlation among ESs. CS showed synergy relationships with HQ and SC, as well as with WY and FP. However, there were trade-offs between CS and WY and FP, HQ and WY and FP, and SC and WY and FP. These TOS exhibited significant spatial heterogeneity and scale effects, with large variations across different subregions.

(4) The expansion of paddy fields promoted increases in SC, WY, and FP, but had negative effects on CS and HQ.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14112063/s1, Table S1. Carbon Pools; Table S2. Threats; Table S3. Sensitivity; Table S4. Biophysical Table. References [38,65–72] are cited in supplementary materials.

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