Spatiotemporal Characteristics of Vegetation Net Primary Productivity and Its Major Driving Factors in the Yellow River Delta over the Past 30 Years: Postprint

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Abstract

China possesses abundant coastal blue carbon sinks. Accurately understanding the status of Net Primary Productivity (NPP) in coastal blue carbon ecosystems and identifying the spatiotemporal distribution characteristics of NPP in these ecosystems under different anthropogenic disturbances are of great significance. Taking the Yellow River Delta as the study area and a recent 30-year period (1987, 1995, 2005, 2016-2017) as the temporal scale, this study investigates the spatiotemporal variation characteristics of NPP and its main influencing factors in the Yellow River Delta through remote sensing and field surveys. The results show: (1) Over the past 30 years, the mean and total NPP in the study area exhibited a pattern of initial decline followed by slight increase. The average NPP for 2016-2017 was 294.38 g C m^{2} a^{1}, with a total amount of 710.05 Gg C/a, showing significant seasonal differences. (2) NPP in the study area exhibited obvious spatial heterogeneity among administrative districts, protected areas, and land cover types. The NPP zoning results for 2016-2017 showed that the areas of different zones, from largest to smallest, were medium productivity zone (49.5%), low productivity zone (38.3%), and high productivity zone (12.1%). (3) The spatiotemporal heterogeneity of NPP in the study area is the result of combined influences from land cover types and vegetation growth conditions. Land-sea interaction, development and utilization activities, and ecological restoration in recent years are the main influencing factors of NPP spatiotemporal variation. (4) Wetland vegetation and cropland are the main contributors to carbon sinks in the study area. Since the 1990s, the mean NPP of both has gradually increased, reaching 570.28 g C m^{2} a^{1} and 335.92 g C m^{2} a^{1}, respectively, in 2016-2017. Over the past 30 years, the total NPP of wetland vegetation has gradually decreased, while that of cropland has gradu-

ally increased. Wetland vegetation is a typical carrier of coastal blue carbon. Cropland, as a carbon sink type located in coastal areas that has been converted from wetland vegetation and possesses high carbon sequestration capacity and potential, can serve as an important supplement to coastal blue carbon.

Full Text

Preamble

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Spatio-temporal Characteristics and Main Influencing Factors of Vegetation Net Primary Productivity in the Yellow River Delta in Recent 30 Years

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Abstract

Coastal salt marsh vegetation, mangroves, and seagrass beds are highly efficient carbon sinks, and the carbon sequestered by these ecosystems is termed coastal blue carbon. China has an extensive coastline with widely distributed coastal blue carbon ecosystems. With rapid economic development and consistently increasing CO emissions, exploring the potential of coastal blue carbon has become an important pathway to enhance carbon sequestration capacity and mitigate CO emission pressure. Accurately identifying the spatio-temporal distribution characteristics of net primary productivity (NPP) in coastal blue carbon ecosystems under various and complex anthropogenic disturbances is of great significance.

Using remote sensing and field investigations, this study examined the Yellow River Delta as the research area, analyzing spatio-temporal variation characteristics and main influencing factors of NPP over the recent 30-year period (1987, 1995, 2005, and 2016–2017). The results indicated that: (1) The mean value and total amount of NPP decreased initially and then increased slightly over the past 30 years. The mean NPP values in summer for 1987, 1995, 2005, and 2016 were 94.93, 63.90, 64.56, and 69.54 g C m ^{2} month ^{1}, respectively. The annual mean value and total amount of NPP for 2016–2017 were 294.38 g C m ^{2} a ^{1} and 710.05 Gg C a ^{1}, respectively, showing distinct seasonal differences. (2) Obvious spatial heterogeneity existed across different administrative districts, nature reserves, and land cover types. Among the three districts, Lijin County showed greater temporal fluctuation in NPP than the other two districts. The mean NPP inside nature reserves was higher than outside, and higher in the experimental zone than in the buffer and core zones. The mean NPP values were similar between old and new estuary areas in 2016–2017. (3) Among different land cover types, wetland vegetation had the highest mean value and total amount of NPP, followed by farmland, while other land cover types showed low values. (4) Partitioning results for 2016–2017 showed that the medium NPP area accounted for the largest proportion (49.5%), followed by low NPP (38.3%) and high NPP (12.1%). The spatio-temporal heterogeneity of NPP resulted from the combined influence of land cover types and vegetation growth conditions. Land-sea interaction, exploitation activities, and recent ecological restoration were the main factors influencing spatio-temporal NPP variations.

Wetland vegetation and farmland were the main contributors to carbon sinks in the study area. Their mean NPP values increased steadily since the 1990s, reaching 570.28 g C m ^{2} a ^{1} and 335.92 g C m ^{2} a ^{1} in 2016–2017. Over the 30-year period, the total NPP amount continuously decreased in wetland vegetation while increasing in farmland. Wetland vegetation is the typical carrier of coastal blue carbon. Meanwhile, farmland located in coastal areas, transformed from wetland vegetation and possessing high carbon sequestration ability and potential, can serve as an important supplement to coastal blue carbon.

Keywords: coastal blue carbon; net primary productivity (NPP); spatio-temporal characteristics; human activities; Yellow River Delta

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1. Introduction

Global warming has become a worldwide concern, with rising greenhouse gas concentrations considered the fundamental cause [1–2]. Coastal salt marshes, mangrove wetlands, and seagrass beds in coastal zones are hotspots of efficient carbon sequestration on Earth. The carbon fixed by these ecosystems is called coastal blue carbon, and these ecosystems are termed coastal blue carbon ecosystems. Carbon burial rates per unit area for salt marshes, mangroves, and seagrass beds are (218±24), (226±39), and (138±38) g C m ^{2} a ^{1}, respectively, far exceeding those of deep-sea and terrestrial forest ecosystems [4, 7]. China has a long coastline with widely distributed coastal blue carbon ecosystems. As economic and social development accelerates and CO emissions increase daily, tapping into the potential of coastal blue carbon has become an important means to enhance carbon sink capacity and reduce emission pressure. Pollutant discharge and other anthropogenic disturbances have severely impacted coastal blue carbon ecosystems [7].

Net primary productivity (NPP) represents the remaining organic matter produced by plants through photosynthesis after subtracting autotrophic respiration. It reflects plant community productivity [4-6], forms the basis for ecosystem member survival and reproduction, regulates ecological processes, and serves as a primary indicator for determining whether an ecosystem is a carbon source or sink [8-9]. Investigating the spatio-temporal distribution characteristics of NPP in typical coastal blue carbon ecosystems under different human disturbances is crucial for revealing China' s coastal blue carbon potential and its variation patterns, and for providing a basis for regulating coastal exploitation activities and enhancing blue carbon capacity.

The Yellow River Delta is one of China' s three major river deltas and represents the most complete and largest newly-formed salt marsh wetland in China's warm temperate zone [10]. Due to its special geographic location and abundant sediment supply, the Yellow River Delta ecosystem not only has rich and complete wetland vegetation but also serves as an important habitat for many rare and endangered birds. However, it also exhibits obvious vulnerability characteristics [11-12]. Human disturbances in the Yellow River Delta have intensified, with large-scale farmland and salt pond reclamation continuously encroaching on wetland vegetation, causing natural wetland areas to decrease year by year [13-15]. The establishment of nature reserves and various ecological protection and management measures have had significant impacts on natural ecosystems [15-16]. Under complex natural factors and human activities, the Yellow River Delta has become one of the world' s most active estuarine regions with rapid ecological and environmental evolution [17]. Numerous scholars have conducted extensive research on the Yellow River Delta ecosystem, including studies on ecosystem carbon processes, soil carbon content, and spatial distribution [10, 18-20]. However, research on spatio-temporal NPP evolution characteristics at larger temporal and spatial scales remains insufficient, particularly lacking analysis of variation characteristics under anthropogenic disturbance and regulation impacts.

Based on the modern Yellow River Delta extent, this study uses remote sensing and field investigations to examine temporal changes and spatial characteristics of NPP over the past 30 years, and to analyze the main influencing factors of spatio-temporal NPP variations, aiming to reveal patterns at larger temporal and spatial scales and provide references for enhancing China' s coastal blue carbon.

2. Study Area Overview

The Yellow River Delta is located on the southern coast of Bohai Bay and the western coast of Laizhou Bay. The modern Yellow River Delta refers to the area with Yuwa in Kenli County as the vertex and Tiaohe River mouth and Songchunrong Gully mouth as endpoints. This study is based on the modern Yellow River Delta extent, extending the southern endpoint to the Hongguang Fishing Port at the southern end of the Binhai Avenue in Kenli County. Considering geographic integrity and actual conditions, the study area is slightly larger than the modern Yellow River Delta.

The study area is located in a warm temperate monsoon climate zone with an average annual temperature of 12.1°C and average annual precipitation of 551.6 mm, showing large seasonal differences. Most of the study area is within Dongying City, belonging to Kenli District and Hekou District (49% and 44% of the area, respectively), with the remainder in Lijin County (7%). The elevation is below 15 m, with soil types mainly consisting of fluvo-aquic soil and saline soil. Vegetation is dominated by halophytes that are widely distributed and show obvious gradient patterns.

The Yellow River Delta National Nature Reserve was established with State Council approval to protect newly-formed wetland ecosystems and rare/endangered birds. The reserve can be divided into core, buffer, and experimental zones, mainly distributed at the current and old Yellow River estuaries. The reserve has implemented active ecosystem restoration and construction projects and a series of control measures. Over the past 30 years, intensifying human exploitation activities have caused dramatic changes in land cover types [15], affecting NPP and its spatial distribution.

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3. Data Sources and Processing

Given the characteristics of available data, this study uses the recent 30-year period as the time span and selects 1987, 1995, 2005, and 2016–2017 as time intervals to analyze NPP variation patterns and main influencing factors.

3.1 Remote Sensing Images

Cloud cover significantly affects NPP estimation accuracy. Based on available data, cloud-free or low-cloud LANDSAT 5 and LANDSAT 8 remote sensing images covering the study area over the past 30 years were selected for 1987, 1995, 2005, and 2016–2017. Using ENVI 5.3 and ArcGIS 10.0, original images underwent radiation calibration, atmospheric correction, and band fusion. The coastline served as the sea-land boundary, and the outer edge of contiguous vegetation distribution areas defined the land boundary, forming study area outlines for different periods. After image clipping and band calculation, Normalized Difference Vegetation Index (NDVI) was obtained for different periods.

Based on remote sensing images from August 1987, 1995, 2005, and 2016, land cover types were classified through visual interpretation into wetland vegetation, farmland, water area, salt ponds and aquaculture ponds, bare land, building land, traffic land, and industrial land. Wetland vegetation is dominated by *Phragmites australis* and *Tamarix chinensis*, interspersed with *Suaeda salsa* and other plants. Farmland mainly consists of rice paddies, wheat fields, and lotus root ponds, with corn, cotton, and other crops also planted. Water areas include the Yellow River, old river courses, and reservoirs such as Gudong Reservoir. Salt ponds and aquaculture ponds are concentrated in nearshore areas, dominated by salt ponds. Bare land includes tidal flats in nearshore areas and bare land within the study area. Building land refers to urban and rural construction areas, including towns like Huanghe Town and Xianhe Town and numerous scattered rural settlements. Traffic land includes highways and ports, mainly the Dongying Port Expressway and provincial roads S312, S310, and S228. Industrial land refers to factory areas such as oil refineries.

[Figure 1: see original paper] Remote sensing images and outlines of study area in different years

3.2 Meteorological Data

Meteorological data were obtained from observations at meteorological stations in Dongying and surrounding areas, including multi-year average data for different months. Solar total radiation and sunshine hours were derived from relevant studies in the Dongying area.

3.3 Field Survey and Sampling

Field surveys were conducted in 2016–2017 to verify land cover types. Based on representativeness and accessibility, sampling points were established, recording latitude/longitude, community type, and plant species. In concentrated wetland vegetation areas, 30 plant sampling points were established, with plant sampling conducted in August 2016 and 2017. At each site, three 1 m^2 parallel quadrats were randomly established using grid methods. All aboveground plant material within quadrats was harvested, and biomass dry weight was calculated.

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4. Calculation and Analysis

4.1 NPP Calculation

The Carnegie-Ames-Stanford Approach (CASA) model [23] was used to calculate NPP in the study area based on remote sensing, meteorological, and field survey data:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t)$$

where $NPP(x,t)$ is the net primary productivity at point x in month t; $APAR(x,t)$ is the photosynthetically active radiation absorbed at point x in month t; and $\varepsilon(x,t)$ is the actual light use efficiency at point x in month t.

$$APAR(x,t) = PAR(x,t) \times FPAR(x,t)$$

where $PAR(x,t)$ is the photosynthetically active radiation at point x in month t; and $FPAR(x,t)$ is the fraction of photosynthetically active radiation absorbed by vegetation.

$$\varepsilon(x,t) = \varepsilon_{max} \times T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t)$$

where ε_{max} is the maximum light use efficiency (g C/MJ); $T_{\varepsilon 1}(x,t)$ and $T_{\varepsilon 2}(x,t)$ are temperature stress factors; and $W_{\varepsilon}(x,t)$ is the water stress factor.

FPAR Calculation: Both NDVI and Simple Ratio Vegetation Index (SRVI) show clear linear relationships with FPAR [25-26]. FPAR is calculated as:

$$FPAR_1(x,t) = \frac{NDVI(x,t) - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \times (FPAR_{max} - FPAR_{min}) + FPAR_{min}$$

$$FPAR_2(x,t) = \frac{SRVI(x,t) - SRVI_{min}}{SRVI_{max} - SRVI_{min}} \times (FPAR_{max} - FPAR_{min}) + FPAR_{min}$$

$$SRVI(x,t) = \frac{1 + NDVI(x,t)}{1 - NDVI(x,t)}$$

To eliminate extreme value effects, $NDVI_{max}$ and $NDVI_{min}$ were set at 0.001 and 0.99 percentiles of all NDVI values, respectively. $SRVI_{max}$ and $SRVI_{min}$ were calculated accordingly. $FPAR_{max}$ and $FPAR_{min}$ were set at 0.95 and 0.001, respectively. The final FPAR is the average of $FPAR_1$ and $FPAR_2$, which provides higher accuracy [9, 27].

Temperature Stress Factors: $T_{\varepsilon 1}$ reflects the limitation of plant biochemical processes on photosynthesis under extreme temperatures:

$$T_{\varepsilon 1}(x,t) = \frac{1}{1 + e^{0.3 \times (T(x,t) - T_{opt}(x,t))}}$$

where $T(x,t)$ is the actual average temperature for month t; and $T_{opt}(x,t)$ is the optimal temperature (average temperature of the month with highest NDVI).

$T_{\varepsilon 2}$ indicates light use efficiency reduction when actual temperature is above or below optimal:

$$T_{\varepsilon 2}(x,t) = e^{8\times(T(x,t)-T_{opt}(x,t))}$$

Water Stress Factor: W_ε reflects the impact of available water conditions on light use efficiency:

$$W_\varepsilon(x,t) = 0.5 + 0.5 \times \frac{E(x,t)}{E_p(x,t)}$$

where $E(x,t)$ is actual evapotranspiration and $E_p(x,t)$ is potential evapotranspiration.

Potential evapotranspiration is calculated as:

$$E_p(x,t) = 1.6 \times \left(\frac{R_n(x,t) \times (n/N)}{L \times (T_k + 273)}\right) \times \left(\frac{e_d}{T_k + 273}\right)^{0.5}$$

where R_n is net radiation (MJ m ²); n/N is the ratio of sunshine hours to possible sunshine hours; T_k is average temperature (K); e_d is vapor pressure (hPa); and L is latent heat of vaporization.

Maximum Light Use Efficiency (ε_{max}): This parameter critically affects NPP estimation accuracy and varies significantly among plant types [32]. The Yellow River Delta wetland vegetation is dominated by *Phragmites australis*, which has the largest area. However, specialized studies on maximum light use efficiency for wetland vegetation are limited. Chen et al. [33] simulated a value of 1.667 g C/MJ for *Phragmites* communities in the Liao River Estuary wetland. Based on field measurements and model parameter back-calculation, this study derived a value of 0.859 g C/MJ. Since plant sampling points were relatively limited, to minimize error, this study used the average of the measured value and Chen et al.' s [33] result: 1.257 g C/MJ for wetland vegetation.

For other land cover types, values from Running et al. [36] and Zhu et al. [32] were applied. Running et al. [36] modeled global vegetation types based on ecological-physiological processes, yielding ε_{max} values of 0.389–0.985 g C/MJ. Zhu et al. [32] simulated Chinese vegetation types using forestry census data, obtaining values of 0.604–1.259 g C/MJ. Farmland ε_{max} used the average of these two studies: 0.573 g C/MJ. Non-vegetation land cover types (salt ponds, aquaculture ponds) theoretically have ε_{max} of 0. However, due to inevitable interpretation errors and mixed pixels at 30 m resolution, these areas contain some vegetation, so the minimum ε_{max} of 0.389 g C/MJ was adopted.

4.2 Spatio-temporal Characteristics Analysis

The 2016 remote sensing image had some cloud cover in the northern study area, causing errors in NPP estimation. Using Inverse Distance Weighted (IDW) interpolation based on surrounding NPP values, cloud and shadow areas were corrected.

To analyze seasonal NPP characteristics and differences across units, the study area was divided into high productivity zones (NPP 600 g C m ^{2} a ^{1}), medium productivity zones (200 NPP $<$ 600 g C m ^{2} a ^{1}), and low productivity zones (NPP $<$ 200 g C m ^{2} a ^{1}) using ArcGIS 10.0. Temporal variation characteristics were examined for the entire study area, administrative districts, nature reserves, and land cover types.

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5. Results

5.1 Temporal Variation Characteristics

NPP estimation results showed that mean summer NPP values for 1987, 1995, 2005, and 2016 were 94.93, 63.90, 64.56, and 69.54 g C m ^{2} month ^{1}, respectively, with total amounts of 143.96, 149.88, 167.75, and 214.76 Gg C. Over the past 30 years, mean NPP values and total amounts showed a pattern of initial decline followed by slight increase. The 2016-2017 annual mean NPP was 294.38 g C m ^{2} a ^{1} with a total of 710.05 Gg C a ^{1}, showing distinct seasonal differences —summer was far higher than other seasons, followed by spring and autumn, while winter values were low and negligible.

[Figure 4: see original paper] Variation characteristics of NPP in whole study area and different districts

5.2 Spatial Variation Characteristics

Administrative Districts: Different districts showed consistent overall patterns. Lijin County exhibited greater fluctuation than the other two districts, with more pronounced declines and increases. Due to its smaller area, Lijin' s total NPP was lower than other districts. Kenli and Hekou districts showed temporal variation patterns consistent with the entire study area.

Nature Reserves: Mean NPP inside nature reserves was significantly higher than outside. Both internal and external areas showed initial decline followed by increase, with the difference more pronounced in summer. Within reserves, the experimental zone had higher mean NPP than buffer and core zones. The 1987-1995 decline was more severe inside reserves, while the 2005-2016 increase was more pronounced. The old estuary area had lower NPP than the new estuary in 2005, but they became equivalent by 2016-2017.

Land Cover Types: Wetland vegetation and farmland showed clear spatial heterogeneity. Wetland vegetation had the highest mean NPP and total amount, followed by farmland, while other types were low. Wetland vegetation and farmland mean NPP showed initial decline followed by increase, reaching 570.28 g C m ^{2} a ^{1} and 335.92 g C m ^{2} a ^{1} in 2016-2017, respectively. Over 30 years, wetland vegetation total NPP continuously decreased while farmland total NPP increased. Seasonal differences were significant, especially for farmland.

[Figure 5: see original paper] Spatio-temporal characteristics of NPP in recent 30 years

NPP results of different land cover types in recent 30 years

5.3 NPP Partitioning Results

Partitioning results for 2016–2017 showed that medium productivity zones accounted for the largest area proportion (49.5%), followed by low productivity zones (38.3%) and high productivity zones (12.1%). Among administrative districts, Hekou District had more low productivity zones, while Kenli District had more medium productivity zones. Lijin County was mostly medium productivity. Within nature reserves, the proportion of high productivity zones was significantly higher than non-reserve areas, and higher in experimental zones than in buffer and core zones. The old and new estuary areas showed similar productivity partitioning.

Among land cover types, wetland vegetation was relatively evenly distributed between medium and high productivity zones, while farmland was mostly in medium productivity zones. Other types were primarily in low productivity zones.

[Figure 6: see original paper] Spatio-temporal characteristics of NPP in different seasons

NPP results of different land cover types in different seasons and whole year in 2016–2017

[Figure 7: see original paper] Variation characteristics of NPP about the nature reserve

Statistics results of NPP partitioning in 2016–2017

[Figure 8: see original paper] NPP partitioning in 2016–2017

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6. Discussion

6.1 NPP Level and Variation Characteristics

The study area' s wetland vegetation is dominated by *Phragmites australis*, showing high carbon sequestration capacity (570.28 g C m ^{2} a ^{1} in 2016-2017) with obvious seasonal patterns. This demonstrates the important value of Yellow River Delta wetlands as coastal blue carbon. However, this value is lower than results from similar regions using the same method (e.g., 1016 g C m ^{2} a ^{1} in some studies [39]), possibly because this study used seasonal remote sensing images to calculate annual NPP, fully considering seasonal differences, while other studies often used only summer half-year images, potentially overestimating results.

Farmland NPP (335.92 g C m ^{2} a ^{1}) is lower than wetland vegetation but higher than some regional farmland values [32, 38, 40], indicating considerable improvement potential. The widespread soil salinization in the Yellow River Delta and its historical impact on crop growth [46] may explain lower values compared to other regions. However, since the 1990s, improved vegetation growth conditions have led to steadily increasing farmland NPP.

6.2 Driving Factors of Spatio-temporal Variations

NPP spatio-temporal heterogeneity results from combined natural and anthropogenic factors, with land cover type and vegetation growth condition as determinants [41]. The Yellow River carries massive sediment loads, and intense land-sea interactions including coastal erosion continuously change delta morphology [42-43], affecting land cover types. Outline changes mainly involve wetland vegetation loss or gain at different locations. From 1987-1995, the advancing river mouth created new wetlands, while coastal erosion reduced wetlands elsewhere. From 1995-2005, reclamation increased salt ponds, aquaculture ponds, and bare land. From 2005-2016, while reclamation continued, nature reserve restoration projects increased water areas.

Internally, land cover composition changed dramatically. In 1987, wetland vegetation dominated (68.9%), followed by bare land (11.4%), with human disturbance relatively minor. By 1995, wetland vegetation decreased significantly while farmland increased to 31.2%. By 2005, wetland vegetation further decreased to 25.1% and farmland became the dominant type (45.9%). By 2016, wetland vegetation dropped to 17.8% while salt ponds and aquaculture ponds increased to 9.1%. Human disturbance gradually became the main factor influencing land cover [14, 44].

NDVI, as an important indicator of vegetation growth, showed different land cover types had varying patterns. Wetland vegetation and farmland had higher NDVI values, while salt ponds and water areas were significantly lower. Wetland vegetation and farmland NDVI showed initial decline followed by obvious increase, dropping to lowest values in 1995 and peaking in 2016. This reflects: (1) severe water resource conflicts and frequent flow interruptions in the Yellow River during 1987-1995 that damaged the delta ecosystem [12]; (2) initial stages of large-scale farmland reclamation with serious soil salinization limiting crop growth [46]; and (3) since the 2000s, unified water resource management, nature reserve establishment, ecological water regulation, and salinization control measures [12, 47] that improved vegetation growth conditions.

Changes in land cover type and vegetation growth condition drove NPP variations. During 1987-1995, wetland vegetation area shrank and vegetation condition declined, causing obvious NPP decrease. During 1995-2005, land cover transformation continued but improved vegetation condition offset these changes, keeping mean NPP relatively stable. During 2005-2016, vegetation condition improvement led to overall NPP recovery despite continued land cover changes.

Administrative districts and nature reserves showed different NPP patterns due to varying land cover composition and growth conditions. Lijin County's greater fluctuation resulted from its small area and land cover transitions from wetland vegetation to farmland. Within nature reserves, higher NPP inside than outside, and higher NPP in experimental zones than buffer/core zones, reflects better vegetation protection and management. The old estuary area, though lower than the new estuary in 2005, recovered to equivalent levels by 2016-2017 due to strengthened protection and management, including ecological water supplementation projects in old river courses.

6.3 Coastal Blue Carbon and Farmland Carbon Sink

Wetland vegetation is a crucial component of coastal blue carbon, providing important ecological functions including biodiversity maintenance and landscape aesthetics [11, 48]. Farmland reclamation destroys original wetland ecosystems, causing vegetation loss, habitat fragmentation, and landscape disruption [49]. However, based on current farmland development status, recognizing its positive ecological effects is important for balancing conservation and exploitation to maximize economic, social, and ecological benefits.

Since large-scale farmland reclamation began in the 1990s, farmland NPP has gradually increased. Farmland in coastal areas, transformed from wetland vegetation with high carbon sequestration capacity and potential, can be considered an important supplement to coastal blue carbon—potentially termed "secondary blue carbon" or "derived blue carbon." While not typical blue carbon in the strict sense, it can be included in the broad concept of blue carbon. Original salt marsh vegetation, mangroves, and seagrass can be termed "primary blue carbon." This study shows that wetland vegetation and farmland are the main carbon sink contributors, accounting for 94.2% of total NPP in 2016-2017. Although wetland vegetation total NPP has decreased, farmland total NPP has increased, making farmland an important blue carbon supplement.

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7. Conclusions

1. Over the past 30 years, mean NPP values and total amounts in the Yellow River Delta showed initial decline followed by slight increase. Summer mean NPP values for 1987, 1995, 2005, and 2016 were 94.93, 63.90, 64.56, and 69.54 g C m ^{2} month ^{1}, respectively. The 2016-2017 annual mean NPP was 294.38 g C m ^{2} a ^{1} with a total of 710.05 Gg C a ^{1}, showing obvious seasonal differences (summer » other seasons).

2. Significant spatial heterogeneity existed across administrative districts, nature reserves, and land cover types. Lijin County showed greater temporal fluctuation than other districts. Nature reserve internal NPP was higher than external, with experimental zones > buffer/core zones. Wetland vegetation had the highest NPP, followed by farmland.

3. Partitioning results for 2016–2017 showed medium productivity zones accounted for 49.5% of area, followed by low productivity zones (38.3%) and high productivity zones (12.1%). Spatio-temporal heterogeneity resulted from combined effects of land cover type and vegetation growth condition. Land-sea interaction, exploitation activities, and recent ecological restoration were main driving factors.

4. Wetland vegetation and farmland were the main carbon sink contributors, with mean NPP values of 570.28 g C m^{2} a^{1} and 335.92 g C m^{2} a^{1} in 2016–2017, respectively, accounting for 94.2% of total NPP. Over 30 years, wetland vegetation total NPP continuously decreased while farmland total NPP increased. Wetland vegetation is the typical carrier of coastal blue carbon. Coastal farmland, transformed from wetland vegetation with high carbon sequestration capacity and potential, serves as an important supplement to coastal blue carbon.

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[45] [Chinese reference on NDVI as growth indicator]

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[48] [Chinese reference on wetland ecosystem functions]

[49] [Chinese reference on farmland reclamation impacts]

Note: Figure translations are in progress. See original paper for figures.