remote sensing

Technical Note

Spatio-Temporal Variation and Prediction of Carbon Storage in Terrestrial Ecosystems in the Yellow River Basin

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Abstract: The accurate estimation of a regional ecosystem's carbon storage and the exploration of its spatial distribution and influencing factors are of great significance for ecosystem carbon sink function enhancements and management. Using the Yellow River Basin as the study area, we assessed the changes in regional terrestrial ecosystem carbon storage through geographically weighted regression modeling based on a large number of measured sample sites, explored the main influencing factors through geographic probe analysis, and predicted the carbon sequestration potentials under different scenarios from 2030 to 2050. The results showed that (1) the total carbon storage in the Yellow River Basin in 2020 was about 8.84×10^9 t. Above-ground biological carbon storage, below-ground biological carbon storage, and soil carbon storage accounted for 6.39%, 5.07%, and 89.70% of the total ecosystem carbon storage, respectively. From 2000 to 2020, the carbon storage in the basin showed a trend in decreasing and then increasing, and the carbon storage in the west was larger than in the east and larger in the south than in the north. (2) Forest ecosystem was the main contributor to the increase in carbon storage in the Yellow River Basin. Elevation, temperature, and precipitation were the main factors influencing the spatial pattern of carbon storage. (3) The ecological conservation scenario had the best carbon gain effect among the four future development scenarios, and appropriate ecological conservation policies could be formulated based on this scenario in the future to help achieve the goals of carbon sequestration and sink increase.

Keywords: carbon storage; the Yellow River Basin; terrestrial ecosystem; geographically weighted regression; prediction

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1. Introduction

The massive use of fossil fuels by humans over the past century has caused global temperatures to rise significantly. To cope with climate change and stop the trend in global warming, the United Nations formulated the United Nations Framework Convention on Climate Change in 1992 to reduce emissions and control the rise of global temperature. The Paris Agreement proposed to control the increase in global average temperature within 2 degrees Celsius and strive to limit it to 1.5 degrees Celsius [1]. In 2020, in response to the Paris Agreement, UN Secretary-General Antonio Guterres called on major emitters to target net-zero greenhouse gas emissions by 2050; the Chinese government has proposed to peak carbon emissions before 2030 and strive to achieve "carbon neutrality" by 2060 [2,3]. Ecosystem carbon storage mainly includes above-ground biomass carbon storage, below-ground biomass carbon storage, soil organic carbon storage, and dead organic matter carbon storage [4], which are important indicators of terrestrial ecosystem service functions and play a very important role in global climate change and carbon cycle [5]. It was found that terrestrial ecosystems absorbed 31% of the net CO_2 released by human activities during the same period from 2010 to 2019 [6], and increasing terrestrial ecosystem carbon storage is considered one of the most environmentally friendly and economically feasible ways to mitigate the greenhouse effect. Therefore, it is important to accurately estimate the carbon storage of the Yellow River Basin ecosystem and identify its spatial distribution and driving factors to scientifically guide regional ecological management and achieve the carbon peaking and carbon neutrality goals.

The Yellow River Basin is an important ecological barrier in China, an ecological corridor connecting the Qinghai–Tibet Plateau, Loess Plateau, and North China Plain, and an important carbon sink and storage area for China's terrestrial ecosystem. Significant changes in land use and spatial and temporal patterns of carbon storage have occurred in the basin since the 21st century, with profound impacts on the ecosystem service functions of the basin [7–11]. Based on measured sample points, multi-source remote sensing data modeling, and ecosystem modeling [12–14], studies have been conducted to estimate and predict the carbon storage potential [15–17] of individual ecosystems [18–20] or individual carbon pools [21–23] in the Yellow River Basin. In estimating carbon storage based on measured sample points' carbon densities, the spatial distribution of the study area is demanding and mostly needs to be further combined with model estimation [17,24–26]. At present, there are few studies on the unified estimation of carbon storage in terrestrial ecosystems in the Yellow River Basin [27]. The spatial heterogeneity of the basin is large [21], and the mode of action of different factors and the main control factors are still unclear, leading to the variable distribution of carbon density in the region, and the existing studies only considered the carbon density differences between different ecosystems [28] or estimated the basin by simple zonal modeling [29], which is not sufficient to well solve the not-well-addressed problem of spatial heterogeneity. In recent years, a geographically weighted regression model to explore the spatial characteristics of data came into being, which incorporated the spatial characteristics of data into the estimation of the model, considered the spatial heterogeneity of the data, and achieved good application results in the fields of meteorology, forestry, and ecology [30–32].

In this study, the Yellow River Basin was taken as the study area, and the spatial heterogeneity model of carbon density of different ecosystems was established by using the geographical weighted regression model, combining a large number of sample data and a variety of remote sensing indicators. In this paper, we estimated carbon stocks from 2000 to 2020, determined the spatial and temporal distribution of carbon stocks and their drivers, and predicted the carbon sequestration potential from 2030 to 2050. This study can provide scientific basis for the evaluation of carbon sequestration benefits and management decisions of terrestrial ecosystems in the Yellow River Basin.

2. Study Area and Data Sources

2.1. Study Area

The Yellow River Basin is located at 32°N~42°N, 95°E~120°E. The total length is about 5464 km, and the basin area is about 795,000 square kilometers. The Yellow River Basin is high in the west and low in the east, spanning three major topographic gradients in the east and west, including the Tibetan Plateau, Inner Mongolia Plateau, Loess Plateau, North China Plain, Shandong hills, and other topography [17,24]. The basin contains arid, semi-dry early, semi-humid areas; the annual temperature difference is evident; and the average annual precipitation is 200~600 mm. In the role of the east Asian monsoon, the average annual temperature and rainfall are decreasing from the southeast to the northwest (Figure 1).

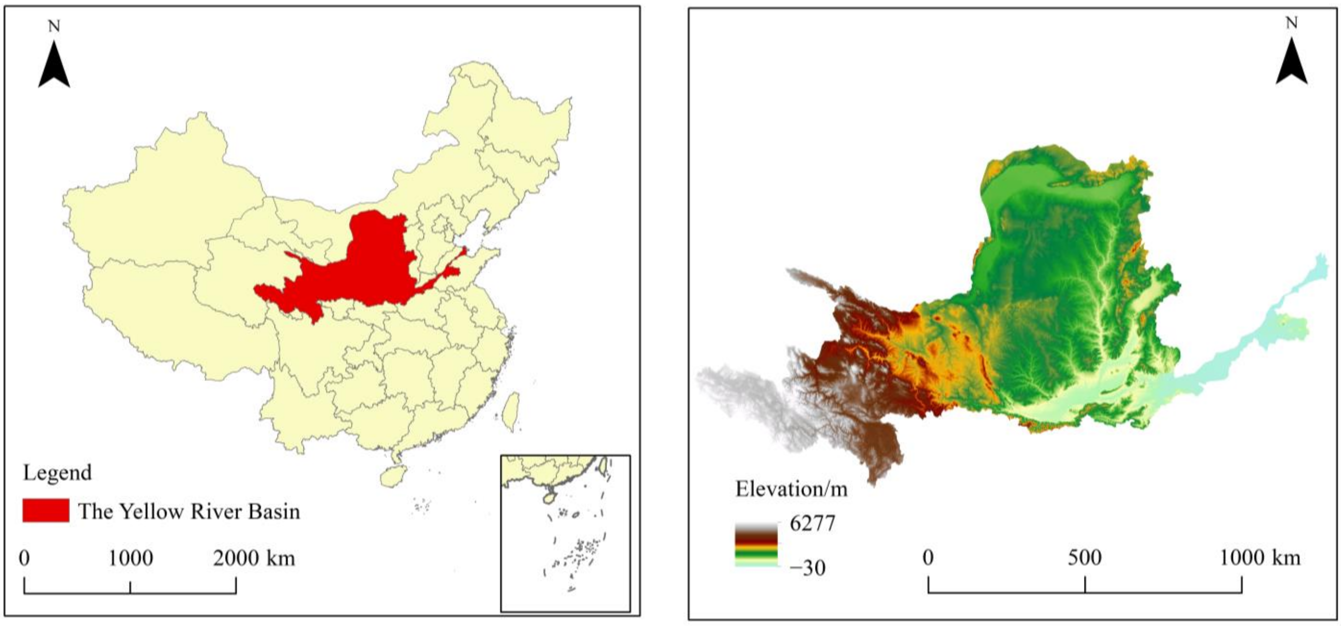

Figure 1. Overview of the geographical location of the study area.

2.2. Data Sources

The land use data were derived from the China 30 m Land Cover Product (CLCD) (80% accuracy), which was based on LANDSAT images, combined with automatic stabilization samples of existing products and visual interpretation samples. Vegetation type data were derived from the MCD12Q1 product (spatial resolution 500 m). Geomorphology, population, GDP, road traffic, night lights, and ecogeographic regionalization data were obtained from the Resources and Environmental Sciences and Data Center (resolution 1000 m). Precipitation and temperature data were from the National Earth System Science Data Center (spatial resolution 30 m). The carbon density data were derived from the measured data in the published literature, including 703 above-ground biological samples, 708 underground biological samples, and 878 soil samples. Soil organic matter data were derived from the spatiotemporal tripolar environment big data platform (spatial resolution 1000 m). Evapotranspiration data were obtained from GLEAM v3 (spatial resolution 0.25°). Vegetation index, topography, and slope data were obtained by atmospheric correction and band calculation of LANDSAT images (resolution 30 m). NPP data acquisition using MOD17A3HGF products (resolution 250 m). GDP and population data for future climate change scenarios were based on the Shared Socio-economic Pathways (SSPs) Population and Economy lattice dataset (resolution 1000 m).

3. Methods

3.1. Carbon Storage Estimation Method

Using the property that remotely sensed vegetation indices could well reflect the prosperity of surface vegetation, remote sensing indices with high correlations, biological above-ground and below-ground carbon densities, and 0–100 cm soil carbon densities were selected and modeled based on a geographically weighted regression model combined with sample point data, respectively. Among them, the remote sensing indices contained 20 vegetation indices, 7 single-band factors, 56 texture bands, and 2 topographic factors [30,31] (Table 1). Three kernel functions (Gaussian, Bi-square, and Exponential), two bandwidths (Akaike information criterion and cross-validation), and a total of six geographically weighted regression models were constructed using the R language GWmodel function package, and the cross-validation and Moran index were used to evaluate the fitting accuracy of the six models and filter the best-fit model. The optimal model was used for inversion to obtain carbon storage datasets of three carbon pools from different ecosystems in the Yellow River Basin.

Table 1. Formulas for calculating vegetation indices used in the study.

Serial Number	Vegetation Index	Calculation Formula *
1	Normalized difference vegetation index (NDVI)	NDVI = NIR − RED/NIR + RED
2	Ratio vegetation index (RVI)	RVI = NIR/RED
3	Difference vegetation index (DVI)	DVI = NIR − RED
4	Ratio vegetation index 1 Ratio vegetation index 1 (RVI54)	RVI54 = SWIRI/NIR
5	Ratio vegetation index 2 (RVI64)	RVI64 = SWIR2/NIR
6	Soil-adjusted vegetation index (SAVI)	SAVI = (1 + L)(NIR − RED)/NIR + RED + L
7	Non-linear vegetation index (NLI)	NLI = NIR2 − RED/NIR2 + RED
8	Atmospherically resistant vegetation index (ARVI)	ARVI = (NIR − RED + r(BLUE − RED))/(NIR − RED − r(BLUE − RED))
9	Enhanced vegetation index (EVI)	EVI = G × (NIR − RED)/(NIR + C1 × RED − C2 × BLUE + I)
10	RGVI	RGVI = RED − GREEN/RED + GREEN

* BLUE, GREEN, RED, NIR, SWIR1, and SWIR2 are the blue, green, red, near-red, short-wave infrared 1, and short-wave infrared 2 bands, respectively; in the SAVI index, the value of L is 0.5; in the ARVI index, r is the correction parameter and is set to 1.0; in the EVI index, the values of the gain factor G, the soil adjustment factor I, and the two correction factors C1 and C2 are 2.5, 0.10, 6.0, and 7.5 [30].

3.2. Carbon Storage Change Analysis Method

Based on the trend in statistical analysis, the changes in carbon stocks in different ecogeographical regions of the Yellow River Basin were analyzed in both time and space, and the changes in carbon stocks in different ecosystems were investigated by using spiral graph analysis [9,17].

3.3. Carbon Storage Impact Factor Analysis Method

According to the ecological geography and socio-economic development of the study area, the influencing factors, such as precipitation, temperature, altitude, terrain, slope, NPP, population, and GDP, were selected for classification (Table 2) [32]. The influence of each factor on carbon storage was analyzed with geographical detectors (including factor_detector, risk_detector, ecological_detector, and interaction_detector), and the influence degree of each factor on the spatial distribution of carbon storage and the high-value area of carbon storage were analyzed.

Table 2. Impact factor classification.

Factor	Classification Level				
	1	2	3	4	5
Elevation/m	0~200	200~500	500~1500	1500~3500	>3500
Landforms	Plain	Terrace	Hilly	Small undulating hills	Middle-rolling hills
GDP/yuan·km^{-2}	0~1 million	1~2 million	2~5 million	5~10 million	>10 million
NPP/kg·m^{-2}	0~1000	1000~2000	2000~3000	3000~4000	>4000
Precipitation/mm	0~200	200~400	400~600	600~800	>800
Population/persons·km^{-2}	0~100	100~200	200~500	500~1000	>1000
Slope/°	0~5	5~15	15~25	25~35	>35
Temperature/°C	<−5	−5~0	0~5	5~10	>10

3.4. Future Carbon Storage Prediction Methods

Using Patch-generating Land Use Simulation (PLUS) and a Markov model to predict future development scenarios of land use change in the Yellow River Basin during 2030–2050, the VEST model (Integrated Valuation of Ecosystem Services and Tradeoffs) was further used to estimate carbon reserves in the Yellow River Basin during 2030–2050 [12]. In order to meet different future development needs, this paper set four future development scenarios (Table 3), which comprehensively considered the land use transfer situation in the Yellow River Basin from 2000 to 2020, the Outline of Ecological Protection and High-quality Development Plan in the Yellow River Basin, the middle road scenario of socio-economic development, and the moderate level of greenhouse gas emissions (SSP245).

Table 3. Four future development scenarios.

Types of Future Development Scenarios	Features
Natural development scenario	This scenario considers only the natural variation in land use types in the Yellow River basin according to the existing rate of change.
Arable land conservation scenario	Under the "natural development scenario", the arable land is not transferred and the restricted development area is the water area.
Ecological conservation scenario	Using the nature reserve as a limit in 2021, the probability of converting forest, grassland, scrub, and wetland to construction land is reduced by 20%; the probability of converting arable land and unused land to forest, grassland, scrub, and wetland is increased by 50%; and the probability of converting construction land to forest, grassland, scrub, and wetland is increased by 30%.
Urban restricted development scenario	Grassland, arable land, and unused land to construction land probability reduced by 20%, restricting the development area for impervious surface area.

4. Results

4.1. Spatial and Temporal Changes in Carbon Storage

The estimated terrestrial carbon storage in the Yellow River Basin in 2020 is 8.84 × 109 t, and the spatial distribution of carbon density ranges from 0.02 to 62.27 kg C·m^{-2}, with an average value of 8.81 kg C·m^{-2}. The carbon storage in western basin is larger than that in eastern basin, and that in southern basin is larger than that in northern basin. Soil carbon storage is greater than biological carbon storage. The total carbon reserves mainly exist in the Qingdong Qilian mountains (20.15%) and the highlands in the Shaanxi Gandong plateau hills (19.83%), mainly because these regions occupy a large proportion of the basin area and have a high carbon density. Aboveground biological carbon reserves mainly exist in the Jinzhong North Shaanxi Gandong plateau hills (35.00%) and the Jinan Guanzhong basin (17.00%). The underground biological carbon reserves mainly exist in the Jinzhong North Shaanxi Gandong plateau hills and the Qingdong Qilian mountains, accounting for 20.89% and 20.36% of the total above biological carbon pool, respectively. Soil carbon storage was mainly distributed in the western and southern parts of the basin, especially in the Qingdong Qilian mountains and the Guoluo Naqu hill-like plateau (Figure 2).

Over the past 20 years, the total carbon storage in the Yellow River Basin decreased by 7.15%. The total carbon storage showed a trend in decrease followed by increase, with an average decrease of 1.84 × 10^8 t per year from 2000 to 2010 and an average increase of 1.17 × 10^8 t per year from 2010 to 2020 (Figure 3). The carbon storage changes differed in different ecogeographic regions, among which the total carbon storage decreased the most in the eastern part of the basin in the North China Plain and the hills in south central Lu.

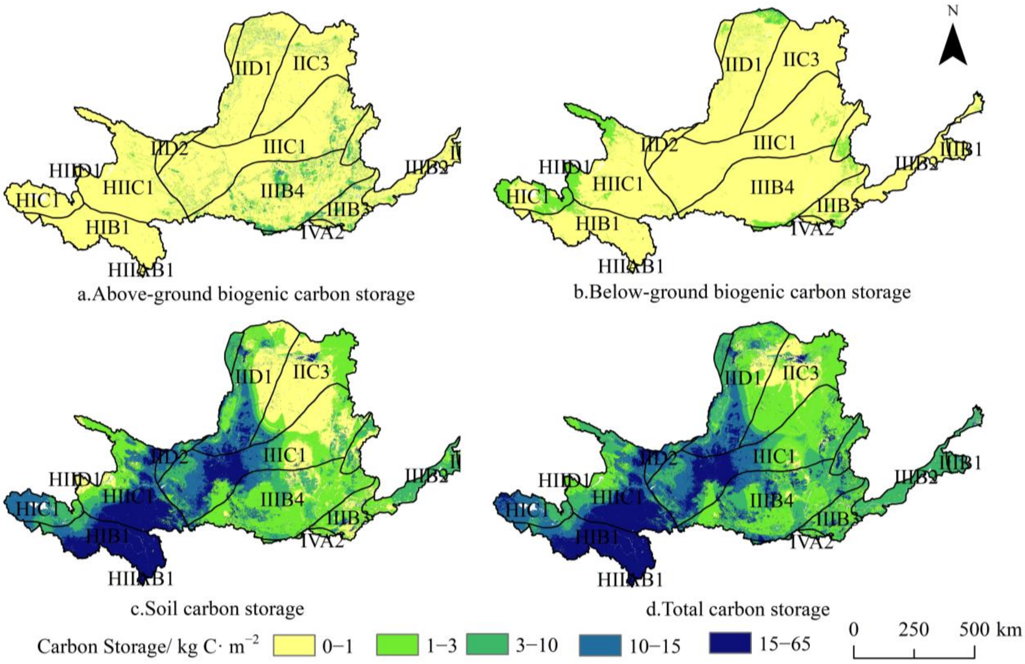

Figure 2. Carbon storage distribution in the Yellow River Basin in 2020. Diagrams of the (**a**) above-ground biogenic carbon storage; (**b**) below-ground biogenic carbon storage; (**c**) soil carbon storage; (**d**) total carbon storage. (II Middle Temperate Zone, III Warm Temperate Zone, IV Northern Subtropical Zone, HI Plateau Subtropical Zone, HII Plateau Temperate Zone; A Humid Region, B Semi-Humid Region, C Semi-Arid Region, D Arid Region; IIC3 Eastern Inner Mongolia High Plain, IID1 Western Inner Mongolia High Plain, IID2 Alashan and Hexi Corridor, IIIB3 North China Mountain Hills, IIIB2 North China Plain, HIID1 Qaidam Basin, IIIC1 Jinzhong North Shaanxi Gandong plateau hills, HIIC1 Qingdong Qilian mountains, IIIB1 Luzhong mountain hills, IIIB4 Jinan Guanzhong basin, HIC1 Qingnan plateau wide valley, HIB1 Guoluo Naqu hill-like plateau, IVA2 Hanzhong basin, and HIIA/B1 Sichuan–Xizang East high mountain deep valley).

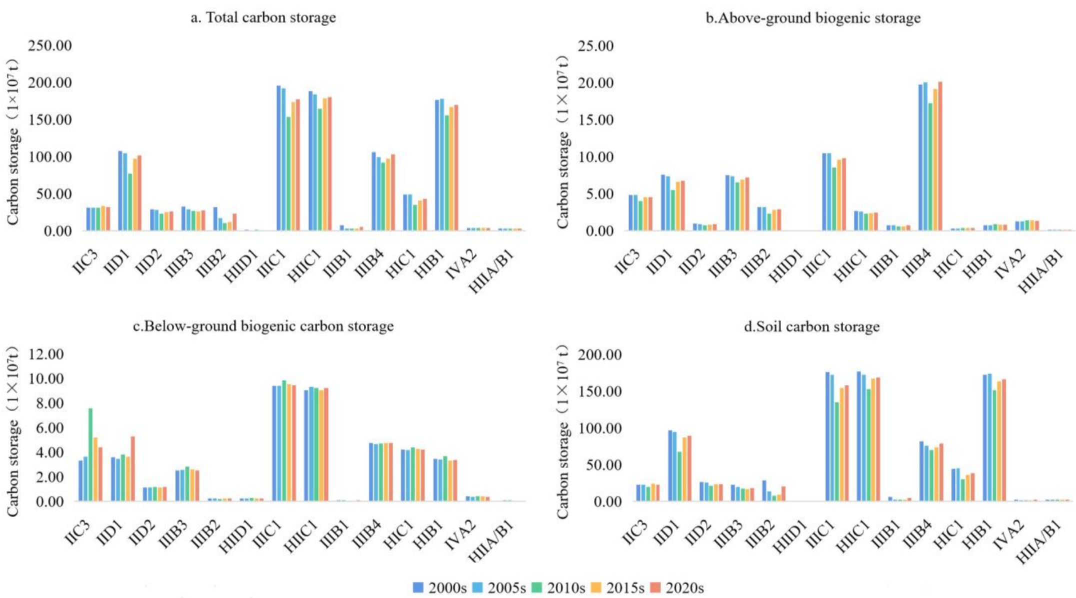

Figure 3. Changes in carbon storage in the Yellow River Basin from 2000 to 2020. Diagrams of the (**a**) total carbon storage; (**b**) above-ground biogenic carbon storage; (**c**) below-ground biogenic carbon storage; (**d**) soil carbon storage.

4.2. Carbon Storage Changes in Different Ecosystems

The carbon storage of each ecosystem in the Yellow River Basin changed more drastically between 2000 and 2020. If we do not consider the increase or decrease in carbon density before and after ecosystem transformation, due to ecosystem change only, the forest ecosystem is the main contributor to the increase in carbon storage in the Yellow River basin, accounting for 63.61% of the total carbon storage enhancement, and the carbon storage mainly comes from the grassland ecosystem (Figure 4). At the same time, the changes in carbon storage in different ecosystems are also directly related to the changes in carbon density (Figure 5).

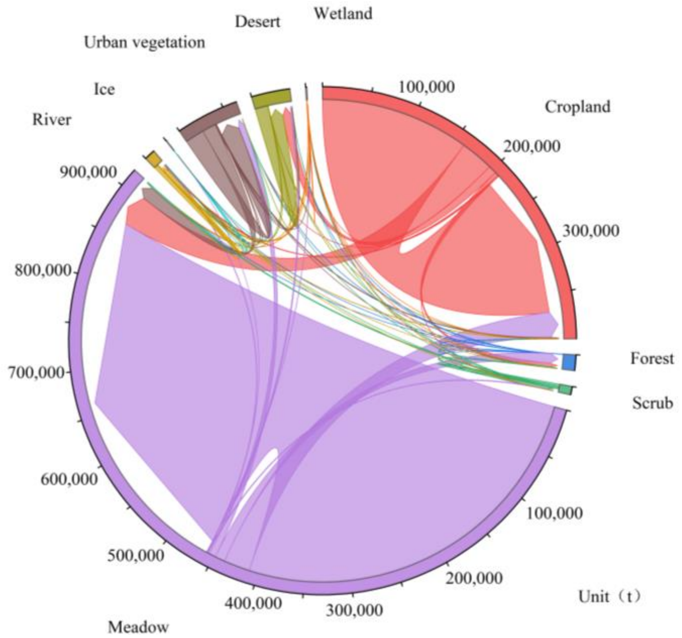

Figure 4. Carbon storage of different ecosystem types from 2000 to 2020.

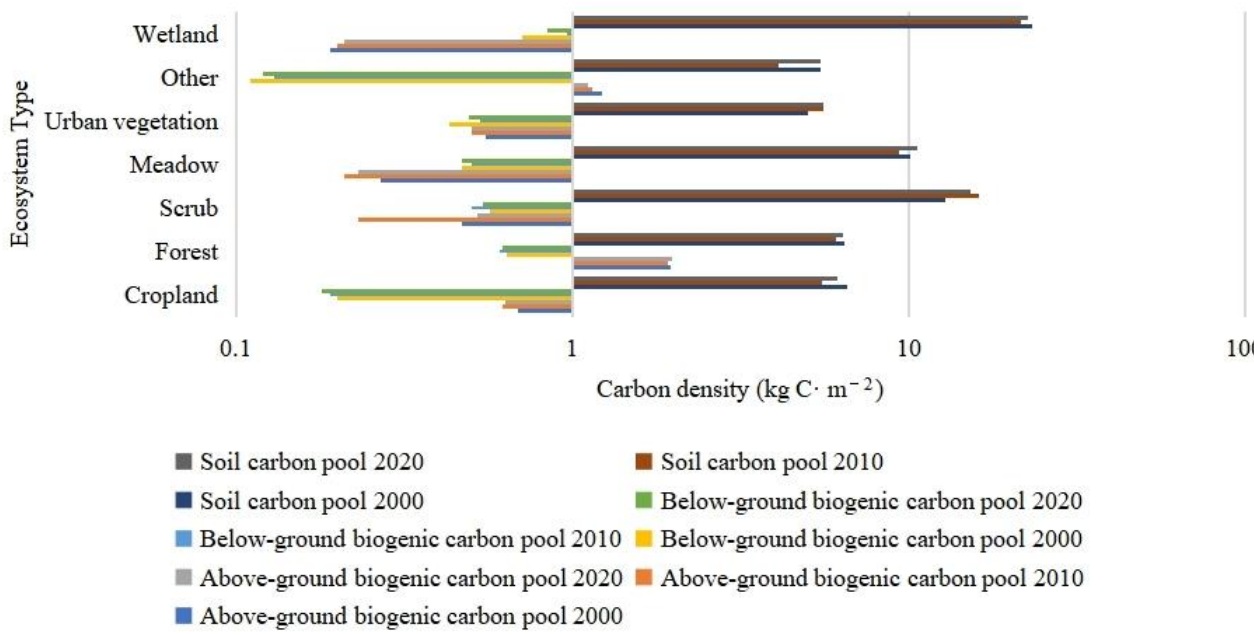

Figure 5. Change in carbon intensity in the Yellow River Basin, 2000–2020.

4.3. Analysis of Impact Factors

The average degree of influence of each factor on the spatial distribution of total carbon storage in the Yellow River basin was altitude > temperature > precipitation > GDP > landscape type > population > NPP > slope direction, among which altitude and temperature affected the distribution of carbon storage to a greater extent (Figure 6).

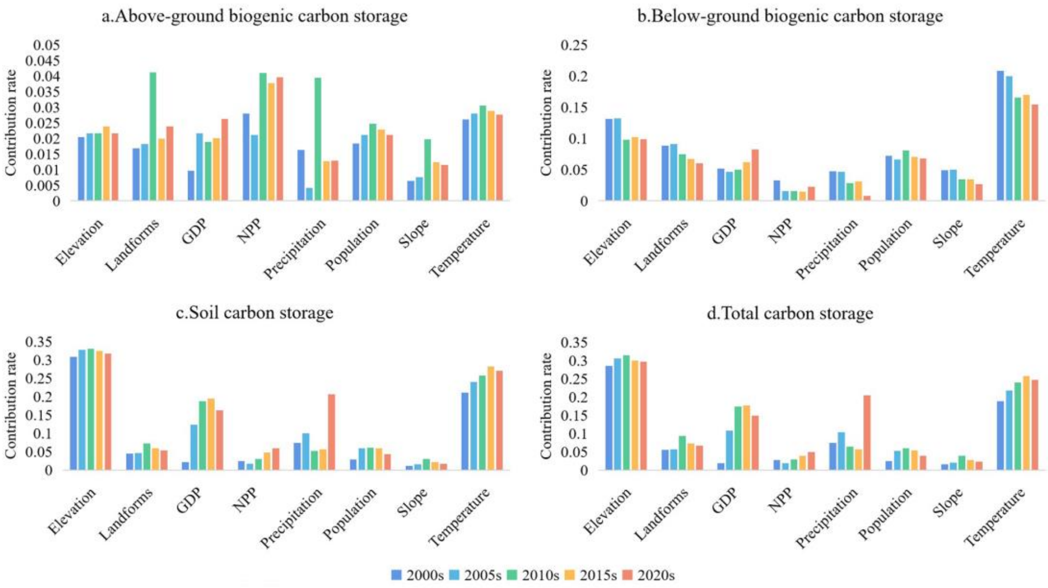

Figure 6. Factor detection results of carbon storage. Diagrams of the (**a**) total carbon storage; (**b**) above-ground biogenic carbon storage; (**c**) below-ground biogenic carbon storage; (**d**) soil carbon storage.

The overall distribution range of each factor in the high carbon storage area remained stable over 20 years, and the above-ground biogenic carbon pool differed more compared to the below-ground biogenic carbon pool, soil carbon pool, and total carbon pool (Table 4). The high-value areas of total carbon storage in the Yellow River Basin were mainly within the climate range of -5~0 °C, precipitation > 400 mm, elevation > 3500 m, slope > 25°, NPP 3000~4000 kg·m^{-2}, population 0~100 persons·km^{-2}, GDP 0~1 million yuan·km^{-2}, and middle-rolling hill.

Table 4. Distribution range of each factor in the high-value area of carbon storage in the study area.

Factor	Total Carbon Pool	Above-Ground Biogenic Carbon Pool	Below-Ground Biogenic Carbon Pool	Soil Carbon Pool
Elevation	5	2–3	5	5
Landforms	5	5	5	5
GDP	1	4–5	1	1
NPP	4	5	2–4	4–5
Precipitation	3–5	4–5	2–5	3–4
Population	1	5	1	1
Slope	4–5	5	5	3–4
Temperature	2	5	1–2	2

4.4. Future Carbon Storage Prediction

The change in carbon storage in the Yellow River Basin from 2030 to 2050 depends on the transfer probability and transfer matrix of land use types under four different scenarios;

the ecological conservation scenario has the best carbon sequestration effect, and the carbon storage is generally increasing and evenly distributed (Figure 7). The carbon storage under the arable land protection scenario decreases by 7.98×10^7~1.33×10^8 t compared to 2020, the carbon storage under the ecological protection scenario develops from a decrease of 3.03×10^7 t to an increase of 1.63×10^8 t compared to 2020, and the carbon storage under the urban development restriction scenario decreases by 6.99×10^7~6.83×10^7 t compared to 2020. The southeastern part of the basin has a large change in carbon storage due to rapid socioeconomic development and frequent human activities, whereas the western and northern parts of the basin have the largest changes due to the large carbon storage bases.

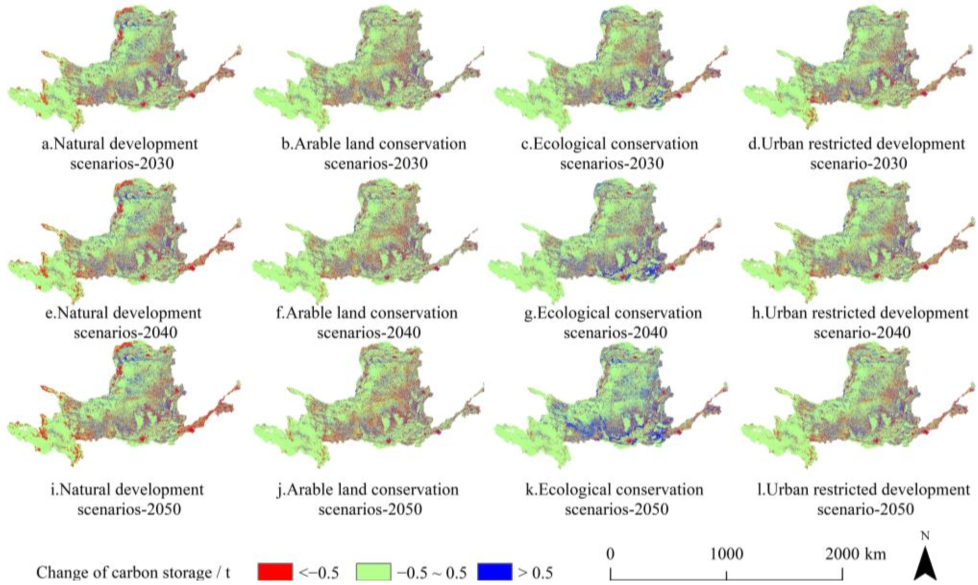

Figure 7. Changes in carbon storage in the Yellow River Basin under different scenarios. Diagrams of the (**a**) natural development scenario-30; (**b**) arable land conservation scenario-2030; (**c**) ecological conservation scenario-2030; (**d**) urban restricted development scenario-2030; (**e**) natural development scenario-40; (**f**) arable land conservation scenario-2040; (**g**) ecological conservation scenario-2040; (**h**) urban restricted development scenario-2040; (**i**) natural development scenario-50; (**j**) arable land conservation scenario-2050; (**k**) ecological conservation scenario-2050; (**l**) urban restricted development scenario-2050.

5. Discussion

5.1. Comparison of Carbon Storage in the Yellow River Basin with the Average in China

The total carbon storage of terrestrial ecosystems in the Yellow River Basin accounts for 8.81% of the carbon storage of terrestrial ecosystems in China (99.13×10^9 t) [33], of which the average aboveground biological carbon density is about 0.56 kg C·m^{-2}, which is lower than the average in China (1.08 kg C·m^{-2}); the average belowground biological carbon density is about 0.45 kg C·m^{-2}, which is lower than the average in China (0.50 kg C·m^{-2}); the average soil carbon density is about 7.93 kg C·m^{-2}, which is also lower than the average in China (9.13 kg C·m^{-2}). The average subsurface biogenic carbon density is about 0.45 kg C·m^{-2}, which is lower than the Chinese average (0.50 kg C·m^{-2}); the average soil carbon density is about 7.93 kg C·m^{-2}, which is also lower than the Chinese average (9.13 kg C·m^{-2}). This indicates that although the Yellow River Basin has implemented ecological restoration measures such as returning farmland to forest and grass, and the vegetation cover has increased significantly and increased carbon sequestration [34,35]; the carbon density level of the whole ecosystem is still lower than the average level in China. Therefore, more efforts are still needed to protect and develop the ecological environment of the Yellow River Basin.

5.2. Comparison of the Results of This Study with Other Results

The total carbon storage of the Yellow River Basin ecosystem estimated by the geographically weighted regression model in this study is higher than that estimated by the InVEST model (3.96×10^9 t) [16], and this difference is mainly due to the different methods of carbon storage estimation. It shows that the geographical weighted regression model can find and calculate the high value area of the ecosystem in the basin to a large extent. Also, compared with the average carbon density of ecosystems estimated in this study, the carbon density estimates of typical vegetation in the Yellow River Basin [13] and ecosystems in the western region [28] based on a large number of sample points were higher than those in this study, which may have been because most previous studies estimated carbon density based on typical vegetation or a single region [36]. In addition, different sampling times may also lead to differences in the estimation results [37]. For example, with the implementation of a series of ecological restoration measures in the Yellow River basin, the vegetation cover such as grassland increased, the carbon sequestration capacity improved, and the carbon density increased [28].

5.3. Changes in Carbon Storage in the Yellow River Basin, 2000–2020

The total carbon storage in the Yellow River Basin showed a trend in decreasing and then increasing in the past 20 years, which was consistent with the results of previous studies [29]. The Yellow River Basin started to carry out ecological projects vigorously in the 21st century, and, although the ecological land area continued to expand [17,22,25,35], the vegetation cover of the new ecological land was low, and the carbon density did not increase significantly (Figure 5), so the total carbon storage in the Yellow River Basin was decreasing from 2000 to 2010. From 2010 to 2020, the results of multi-year afforestation and ecological restoration began to show, the vegetation cover of the watershed increased significantly [38,39], the carbon density of ecosystems such as forests, grasslands, and thickets became larger, and the total carbon storage increased, especially the above-ground biological carbon storage in the key ecological restoration areas such as the eastern and western parts of the high plains of Inner Mongolia [40], the plains of northern China [41], the highland hills of the Gandong plateau in northern Shanxi and central Jin [10,42], and the Guanzhong basin in southern Jin [43].

5.4. Impact of Climate Factors on Carbon Storage

At the scale of the Yellow River Basin, both temperature and precipitation showed a gradual decrease from southeast to northwest, which was similar to the spatial distribution pattern of biological carbon storage [44]. The results of this study showed that precipitation and temperature had a positive effect on carbon density in the Yellow River Basin region, which was the same as previous findings [45]. Meanwhile, compared to the study of vegetation carbon storage in grassland ecosystems [46], which considered the influence of precipitation to be more significant, the results of this study showed that temperature had a greater influence on regional carbon storage. This may have been because this study estimated a variety of ecosystems and included soil carbon pools, and soil carbon storage accounted for a large proportion of the total carbon storage. When the temperature increased, the zooplankton and sediment increased, microbial activity increased, and the decomposition rate of organic matter accelerated accordingly [47,48], which increased the soil carbon storage and made the results of this study show a greater influence of temperature factor.

5.5. Land Use Change and Impact on Carbon Storage under Different Development Scenarios

The results of this study indicate that high socioeconomic activities and the expansion of non-ecological land will lead to a continuous decline in carbon storage and gradual ecological degradation, which is consistent with the results of previous studies [49–51]. In-depth analysis reveals four scenarios in which the expansion of construction land is more driven by economic development; changes in the agricultural land area are more influenced by population growth, more stable climatic conditions promote the growth of forest area, and forests tend to expand to areas with healthier ecological environment (Figure 8). In the future, we can formulate corresponding ecological protection policies based on ecological protection scenarios, slow down economic growth appropriately, and promote the transformation of economic development from "high speed" to "high quality", which can increase the value of ecosystem services in the study area and provide the development goal of fundamental improvement of ecological environment. This can help to improve the value of ecosystem services in the study area and provide some help to the development goal of fundamental improvement of ecological environment quality.

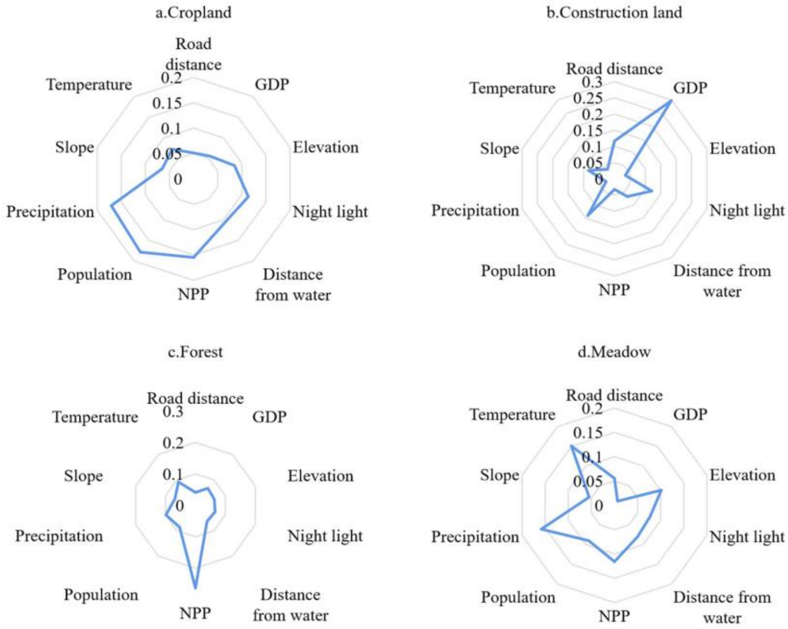

Figure 8. Contribution value analysis of land expansion factor in the study area. Diagrams of the (**a**) cropland; (**b**) construction land; (**c**) forest; (**d**) meadow.

5.6. Research Outlook

In this study, we used a large number of field sample point data, which were extended to the whole watershed by geographically weighted regression analysis to generate spatially continuous facet data. Based on the facet raster data, carbon density and carbon storage in different areas can be estimated more accurately. However, the estimation results are inevitably affected to some extent by the difficulty in obtaining apomictic data. Therefore, to more accurately assess the carbon storage in the Yellow River Basin, future studies should collect more sample point data to improve the accuracy of the results.

6. Conclusions

This paper used the method of geographical weighted regression to estimate carbon stocks in the Yellow River Basin from 2000 to 2020, analyzed the change trend in carbon stocks, discussed the factors affecting the change in carbon stocks, and predicted the carbon stocks from 2030 to 2050. The main conclusions are as follows:

The total carbon storage in the Yellow River Basin is about 8.84×10^9 t, with above-ground biogenic carbon storage, below-ground biogenic carbon storage, and soil carbon storage accounting for 6.39%, 5.07%, and 89.70%, respectively. Temporally, the total carbon storage in the Yellow River Basin decreased and then increased from 2000 to 2020, with a total decrease of 0.67×10^9 t (the average carbon density decreased by 6.80 kg $C{\cdot}m^{-2}$). Spatially, the total carbon storage mainly existed in the western and southern parts of the basin, whereas the carbon storage in the northern part of the east was relatively small. In terms of different ecosystems, the area and carbon density of each ecosystem varied significantly, and forest ecosystems were the main contributor to the increase in carbon storage in the Yellow River Basin.

Precipitation, temperature, and altitude were important factors affecting the spatial pattern of carbon storage in the Yellow River Basin. The range of high-value carbon storage area in the Yellow River Basin was the annual average temperature of −5~0 °C, precipitation in the climate range of >400 mm, altitude >3500 m, slope in the range of topographic factors of >25°, NPP in the range of 3000~4000 kg·m^{-2}, population 0~100 persons·km^{-2}, GDP in the range of 0~1 million yuan·km^{-2}, and the landform of medium undulating mountains.

From the four future development scenarios, the ecological conservation scenario has the best carbon gain effect, followed by the urban restricted development scenario and the natural development scenario, and the arable land conservation scenario is the worst.

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