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The Spatiotemporal Evolution and Prediction of Carbon Storage in the Yellow River Basin Based on the Major Function-Oriented Zone Planning

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Abstract: Land use/cover change is the main reason for the variation of ecosystem carbon storage. The study of the impact of land use on carbon storage has certain reference values for realizing high-quality development in the Yellow River Basin. In this paper, the InVEST model was used to simulate the variation of carbon storage in the Yellow River Basin in 2000, 2005, 2010, 2015, and 2020, and to predict the carbon storage in 2030 in combination with the CA-Markov model, as well as to discuss the impact of land use on carbon storage. The results showed that: (1) The variation trend of carbon storage for different land use types in the Yellow River Basin was different and was mainly manifested as a decrease of cultivated land and unused land, and an increase of forest land, grassland, water, and construction land. The carbon storage in the provincial key development prioritized zone, national development optimized zone, and provincial development optimized zone showed decreasing trends, while the national key development prioritized zone and national major grain producing zone presented a fluctuating downward trend. (2) The ecosystem carbon storage function weakened after 2000, and part of the carbon sink area transformed into a carbon source area. The area with low carbon storage was distributed in the west of the provincial key ecological function zone, and the area with high carbon storage was concentrated in the south and middle of national key ecological function zone and the east of the provincial key ecological function zone. (3) The carbon loss was largest in the urban expansion scenario (UES), followed by the natural development scenario (NDS) and ecological protection scenario (EPS). The carbon storage of different scenarios presented significant positive correlations with land use intensity.

Keywords: carbon storage; carbon emission; InVEST model; major function-oriented zone planning; Yellow River Basin

Citation: Wang, J.; Li, L.; Li, Q.; Wang, S.; Liu, X.; Li, Y. The Spatiotemporal Evolution and Prediction of Carbon Storage in the Yellow River Basin Based on the Major Function-Oriented Zone Planning. *Sustainability* **2022**, *14*, 7963. https://doi.org/10.3390/su14137963

Academic Editors: Federica Raganati and Paola Ammendola

Received: 10 May 2022
Accepted: 27 June 2022
Published: 29 June 2022

1. Introduction

Industrialization and urbanization have brought serious problems such as greenhouse gas emissions, water pollution, and land resource destruction, which have threatened the ecological background [1,2]. In particular, fossil-fuel combustion, deforestation, and irrational land use have made the "greenhouse effect" more and more serious, and carbon emission reduction and carbon neutrality have become international hot topics [3,4]. It has been proven that the increase of CO_2 was related to the ecosystem carbon storage affected by land use [5–7]. Construction land expansion has led to rapid shrinkage of ecological land, part of the "carbon sink area" converted to a "carbon source area", with large amounts of CO_2 emissions. The conversion of forest land and grassland to cultivated land has increased the release of soil carbon. Soil stores three times more carbon than the atmosphere, yet soil carbon is currently threatened by problems such as soil erosion. Many forested areas are still suffering moderate or even intense soil and water loss, which in turn leads to more soil nutrient loss [8]. Studies on upland rice and terraced paddy fields in northern Thailand showed that increasing soil carbon could reduce soil erosion [9]. Furthermore, carbon sequestration plays an important role in adapting to climate extremes and improving agricultural productivity, to ensure food security. Arunrat et al. [10] found that increasing soil organic carbon content by 1 g kg^{-1} could increase rice yields by 302 kg ha^{-1}. Crop yields would increase overall by 32 $\pm$ 11 million tons per year in developing countries as the soil carbon pool in the root zone is increased at the rate of 1 tonC/ha/yr [11]. Ecosystems are the basis of human existence and development, and play an irreplaceable role in maintaining the dynamic balance of life and environment on Earth [12,13]. The process of storing atmospheric CO_2 enhances the soil carbon pool, offsets anthropogenic emissions, and mitigates climate warming. Improving carbon sequestration is of great significance for strengthening ecosystem management and protection, and achieving a carbon peak and carbon neutrality in China.

Methods for assessing regional carbon storage mainly include field investigation, remote sensing retrieval, and model simulation [14,15]. The InVEST model is the most common method for model simulation, with the advantages of simple operation, easy parameter acquisition, and visual representation, and it can accurately reflect carbon storage variations at multiple scales [16,17]. Zarandian et al. [18] assessed the impact of LUCC on carbon storage and sequestration using the InVEST model in the Mazandaran Province of Northern Iran. Lahiji et al. [19] investigated how different land use policies contribute to changes in carbon storage in a mixed agriculture–forest landscape. Tang et al. [20] analyzed the impact of cultivated land expansion on carbon storage in Hubei Province. Combined with the prediction results of land use/land cover, the carbon storage variation under different scenarios could be assessed. Hoque et al. [21] predicted potential variations of the plantation forest using the CA-Markov model under three land management scenarios and estimated the carbon storage from 2018 to 2041. Zhao et al. [22] evaluated carbon storage in the upper reaches of the Heihe River Basin by linking the CA-Markov and InVEST models, which proved applicable for assessing the effect of ecological engineering on carbon storage. The combination of CA-Markov and InVEST models could better reflect the future trends of ecosystem carbon storage and optimize the developmental direction in the basin.

The Yellow River Basin is an important ecological security barrier and the key area for population activities and economic development in China. In order to strengthen the ecological protection and management, and promote the green development of the basin, Major Function-Oriented Zone Planning (MFOZ Planning) was implemented, aiming to form a coordinated territorial-spatial development pattern of population, economy, resources, and environment. Major Function-Oriented Zone Planning (MFOZ Planning) has represented an important attempt in China at spatial planning since the beginning of the new century, and it has also been raised to the national strategic level in the field of land development [23]. In recent years, the strategy of ecological protection and high-quality development in the Yellow River Basin has been put forward in response to the ecological fragility and the weak carrying capacity of the resources and environment [24]. As an important energy base in China, the industrial system of the Yellow River Basin mainly relies on a high coal consumption. Carbon dioxide emissions affect the high-quality development of the Yellow River Basin to a certain extent, which has led to increasing pressure on energy-saving, emission-reduction, and ecological environment protections. Related studies have demonstrated that the carbon storage of terrestrial ecosystems was significant in reducing carbon dioxide concentrations, mitigating the greenhouse effect, and regulating climate change [25–27]. Land use change was a direct factor affecting the carbon storage function of terrestrial ecosystems. Most of the existing studies focused on the impact of land use on carbon storage in counties/cities or natural boundaries within the Yellow River Basin; however, carbon storage in the Yellow River Basin from the perspective of MFOZ has been less analyzed. Thus, this paper analyzed and predicted the impact of land use on ecosystem carbon storage in the Yellow River Basin based on the MFOZ, which was expected to provide a scientific reference for land use planning, optimization of regional ecosystem carbon sequestration, and formulation of reasonable carbon dioxide reduction schemes in the Yellow River Basin. Furthermore, the MFOZ planning strategy can also provide new considerations for countries or regions that face large regional development gaps, a disordered spatial development, and ecological environment degradation.

2. Materials and Methods

2.1. Study Area

The Yellow River Basin originates in the Bayan Har Mountains and spans four geomorphological units, from west to east: Qinghai-Tibet Plateau, the Inner Mongolia Plateau, the Loess Plateau, and the Huang-Huai-Hai Plain; flows through nine provinces and autonomous regions: Qinghai Province, Sichuan Province, Gansu Province, Ningxia Hui Autonomous Region, Inner Mongolia Autonomous Region, Shaanxi Province, Shanxi Province, Henan Province, and Shandong Province; and covers an area of about 2.546 million km^2 (Figure 1). The land types are mainly grassland and unused land. Based on the carrying capacity of resources and environmental and existing development potential, the basin can be divided into a national key development prioritized zone, provincial key development prioritized zone, national development optimized zone, provincial development optimized zone, national major grain producing zone, provincial major grain producing zone, national key ecological function zone, and provincial key ecological function zone, from the perspective of the MFOZ planning implemented in 2010 (Table 1). The Yellow River basin is not only the key region for economic development, but also one of the most important carbon pools in China, and plays a significant role in maintaining the ecosystem carbon balance.

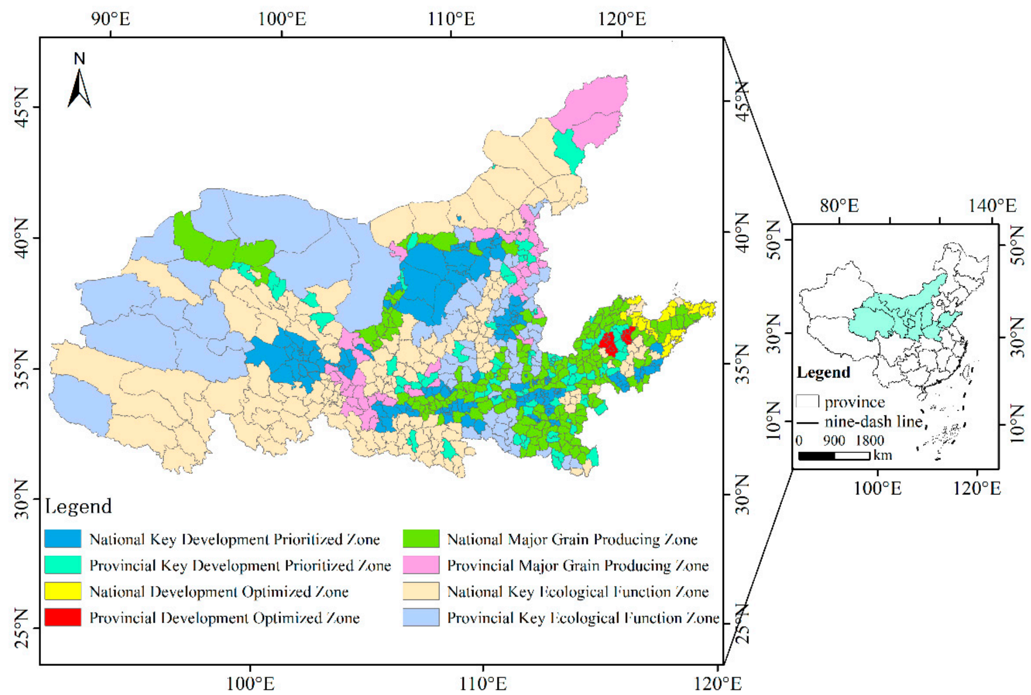

Figure 1. Location of the study area.

Table 1. Introduction of Major Function-Oriented Zones.

Classification	Definition	Number of Counties
National key development prioritized zone	Areas with the best economic foundation and largest development potential; divided by the central government.	167
National development optimized zone	Areas with a high land use density and weak carrying capacity of resources and environment; divided by the central government.	27
National major grain producing zone	Areas significant for food security and basically consisting of traditional farming or pastoral areas, which are highly important for ensuring the grain and meat supply of the country; divided by the central government.	179
National key ecological function zone	Areas consisting of representative natural ecosystems, habitats of rare and endangered wild species, and natural or cultural heritage of special value; divided by the central government.	152
Provincial key development prioritized zone	Areas with the best economic foundation and largest development potential; divided by the provincial governments.	90
Provincial development optimized zone	Areas with a high land use density and weak carrying capacity of resources and environment; divided by the provincial governments.	13
Provincial major grain producing zone	Areas significant for food security, basically consisting of traditional farming or pastoral areas, which are highly important for ensuring the grain and meat supply of the country; divided by the provincial governments.	41
Provincial key ecological function zone	Areas consisting of representative natural ecosystems, habitats of rare and endangered wild species, and natural or cultural heritage of special value; divided by the provincial governments.	67

2.2. Data Sources

The land use data of 2000, 2010, 2015, and 2020 were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/, accessed on 15 December 2021), with the resolution of 1000 m × 1000 m, and were reclassified into cultivated land, forest land, grassland, water, construction land, and unused land. The land use data of 2030 were simulated using the Ca-Markov model based on the data in 2000 and 2015. The carbon emission data were derived from the China Carbon Emission Database and included county-scale CO_2 emission inventories from 1997 to 2017 (CEADs: Carbon Emission Accounts and Datasets, https://www.ceads.net/user/index.php?id=1057&lang=en, accessed on 7 February 2022). The data of the major function-oriented zone came from "the National Major Function-Oriented Zone Planning" issued by the State Council and the provincial Major Function-Oriented Zone Planning.

2.3. InVEST Model

The carbon storage of a terrestrial ecosystem lies in four carbon pools: aboveground biomass, belowground biomass, soil, and dead organic matter [28,29]. Since it was difficult to obtain the carbon density data of dead organic matter, only three carbon reservoirs were considered in this paper. The carbon storage formulas were as follows:

$$C_i = C_{i-above} + C_{i-below} + C_{i-soil} \tag{1}$$

$$C_{tot} = \sum_{i=1}^{n} C_i \times S_i \quad (2)$$

where i is the land use type, $C_{i\text{-}above}$ is the aboveground carbon storage and refers to the biomass of all living vegetation above the soil layer expressed by dry weight, including stems, piles, branches, etc. (t/hm^2); $C_{i\text{-}below}$ is the belowground carbon storage, which encompasses the living root systems of aboveground biomass, usually excluding fine roots that are difficult to distinguish from soil organic components or litter (t/hm^2); $C_{i\text{-}soil}$ is the soil carbon storage, which is the organic component of soil, including fine roots that are difficult to distinguish from underground biomass and represent the largest terrestrial carbon pool (t/hm^2); C_{tot} is the total carbon storage of a terrestrial ecosystem (t); S_i is the area of land use type i (hm^2); and n is the number of land use types, which is six in this study.

The carbon density data were derived from previous research results, rather than actual measurements [26,30–33]. Therefore, it was necessary to correct carbon densities with different climate, soil properties, and land uses (Table 2). Chen et al. [34] showed that belowground carbon allocation (TBCA) was not significantly correlated with average annual temperature, but was significantly positively correlated with average annual precipitation. Alam et al. [35] calculated tree biomass carbon and soil organic carbon (SOC) densities, annual precipitation, and annual precipitation values for 39 map sheet grids of 1.0° latitude × 1.5° longitude, covering the Acacia woodland savannah region of Sudan. The relationship between aboveground biomass carbon density and annual precipitation best fitted an exponential function (R^2 = 0.70, Formula (3)), while SOC density and annual precipitation were linear (R^2 = 0.11, Formula (4)). Giardina et al. [36] made a comprehensive analysis of forest TBCA in a large range and showed that TBCA was linearly correlated with the annual average temperature (Formula (5)); that is, the average annual average temperature of the site at 20 °C was 1.8-times higher than that at 10 °C.

$$C_{SP} = 3.3968 \times P + 3996.1 \quad (3)$$

$$C_{BP} = 6.7981e^{0.00541P} \quad (4)$$

$$C_{BT} = 28 \times T + 398 \quad (5)$$

where C_{SP} is the soil carbon density based on annual precipitation (kg·m^{-2}); C_{BP} and C_{BT} are the biomass carbon density based on annual precipitation and temperature (kg·m^{-2}), respectively; P is the annual precipitation (mm); and T is the annual temperature (°C). The annual temperature and precipitation at a national scale are 7.56 °C and 673.9 mm, respectively, and the annual temperature and precipitation in the Yellow River Basin are 6.86 °C and 362.09 mm. Soil carbon density and biomass carbon density were calculated for the whole country and the Yellow River Basin, then a correction factor was derived according to the following equations. The carbon density for the Yellow River Basin was the product of the national carbon density and the correction factor.

$$K_{BP} = \frac{C'_{BP}}{C''_{BP}} \quad (6)$$

$$K_{BT} = \frac{C'_{BT}}{C''_{BT}} \quad (7)$$

$$K_B = K_{BT} \times K_{BP} \quad (8)$$

$$K_S = \frac{C'_{SP}}{C''_{SP}} \quad (9)$$

where K_{BP} and K_{BT} are the correction coefficients of precipitation factor and temperature factor for biomass carbon density, respectively. C'_{BP} and C''_{BP} are the biomass carbon density of the Yellow River Basin and the national scale obtained from annual precipitation.

C'_{BT} and C''_{BT} are the biomass carbon density of the Yellow River Basin and the national scale based on annual temperature. C'_{SP} and C''_{SP} are the soil carbon density of the Yellow River Basin and the national scale according to the annual temperature. K_B and K_S are the correction coefficient of biomass carbon density and soil carbon density, respectively.

Table 2. Carbon density in the Yellow River Basin (t/hm^2).

Land Use Type	Aboveground Biomass	Belowground Biomass	Soil
Cultivated land	1.02	14.44	69.75
Forest land	7.58	20.76	90.12
Grassland	6.71	15.48	77.23
Water	0	0	11.63
Construction land	0.45	0	64.85
Unused land	0.23	0	26.11

2.4. Composite Index of Land Use Intensity

The land use intensity of different land types was classified by referring to the research of Lu et al. [37] and Liu et al. [38] (Table 3), and the land use intensity formula proposed by Zhuang and Liu [39] was as follows:

$$L_a = 100 \times \sum_{i=1}^{4} A_i \times C_i = 100 \times \sum_{i=1}^{4} A_i \times \frac{S_i}{S} \tag{10}$$

where L_a is the land use index; A_i is the graded land use intensity index of level i; S_i is the land use area corresponding to land use intensity of level i; $C_i = S_i/S$ is the land use area proportion corresponding to land use intensity of level i; S is the total area.

Table 3. Land use intensity division.

Land Use Type	Cultivated Land	Forest Land	Grassland	Water	Construction Land	Unused Land
Land use intensity grade *	3	2	2	2	4	1

* 1 represents low land use degree; 2 represents relatively low land use degree; 3 represents relatively high land use degree; 4 represents high land use degree.

3. Results

3.1. Land Use Characteristics of the Yellow River Basin

Grassland and unused land were the main land use types in the Yellow River Basin, with the area of 103.20 × 10^4 km^2 and 69.82 × 10^4 km^2 in 2020, respectively, and accounted for 40.50% and 27.41% of the total area. Forest land, water, and construction land increased by 0.21%, 0.37%, and 1.04%, respectively, compared with 2000. Among which, the expansion of construction land was the most obvious, with the rate of 0.13 × 10^4 km^2; cultivated land and unused land decreased by 2.03 × 10^4 km^2 and 2.84 × 10^4 km^2, respectively. The variation in area of land use type in the Yellow River Basin from 2000 to 2020 was 71.78 × 10^4 km^2 (Table 4). Grassland was the main contributor, which was mainly converted to unused land, accounting for 37.51% of the transferred area. The transfer out area of cultivated land was about 1.13-times the transfer in area, and mainly turned to grassland (8.47 × 10^4 km^2). Construction land mainly came from cultivated land (4.80 × 10^4 km^2), grassland (0.96 × 10^4 km^2), and unused land (0.28 × 10^4 km^2), accounting for 74.80%, 15.01%, and 4.34% of the transferred area, respectively. The conversion area from other land types to cultivated land accounted for about 36.25% of the total transferred area in the national major grain producing zone. Under the background of ecological environment protection advocated by the state, the national and provincial key ecological function zones were the key areas for ecological protection, and grassland was the main transfer out type. It was concluded that the variation trend of land use in the Yellow River Basin from 2000 to

2020 indicated that part of the grassland was converted to unused land, and construction land expansion occupied a large amount of cultivated land and grassland.

Table 4. Land use type transfer matrix of the Yellow River Basin from 2000 to 2020 (10^4 km^2).

Land Use Type		2020						
		Cultivated Land	Forest Land	Grassland	Water	Construction Land	Unused Land	Total
2000	Cultivated land	31.17	2.45	8.47	0.81	4.80	0.41	48.11
	Forest land	2.18	12.52	5.34	0.13	0.23	0.32	20.72
	Grassland	8.37	5.66	76.13	1.30	0.96	9.78	102.20
	Water	0.66	0.10	1.04	2.55	0.14	0.65	5.14
	Construction land	3.03	0.09	0.39	0.21	1.76	0.05	5.53
	Unused land	0.69	0.41	11.72	1.08	0.28	58.49	72.67
	Total	46.10	21.23	103.09	6.08	8.17	69.70	254.40

3.2. Temporal and Spatial Pattern of Carbon Storage

The carbon storage of the Yellow River Basin in 2000, 2005, 2010, 2015, and 2020 were 19,073.23 $\times$ 10^6 t, 19,055.56 $\times$ 10^6 t, 19,064.93 $\times$ 10^6 t, 19,061.71 $\times$ 10^6 t, and 19,162.20 $\times$ 10^6 t, respectively. From the perspective of major function-oriented zones, the carbon storage in the provincial key development prioritized zone, national, and provincial development optimized zone indicated a descending trend. Although the forest land in provincial key development prioritized zones increased, the decrease in the rate of grassland was higher than that of forest land, resulting in the loss of carbon storage (Figure 2b). The carbon storage of grassland and construction land in the national development optimized zone changed significantly, and decreasing by about 12.46 $\times$ 10^6 t and increasing by 7.99 $\times$ 10^6 t, respectively, followed by the carbon storage of cultivated land, which decreased by 7.31 $\times$ 10^6 t (Figure 2c). The carbon storage in the national key development prioritized zone and national major grain producing zone showed a fluctuating downward trend (Figure 2e). The grassland of the national key development prioritized zone decreased by 1333 km^2 from 2000 to 2005, leading to a decrease of 8.53 $\times$ 10^6 t in carbon storage, and then basically stabilizing between 2133 $\times$ 10^6 t and 2135 $\times$ 10^6 t during 2005–2020 (Figure 2a). The carbon storage of the provincial key ecological function zone increased before 2015, and reached a minimum of 4021.52 $\times$ 10^6 t, with the decrease of grassland and the increase of construction land, in 2020 (Figure 2h). The national key ecological function zone was the largest in the Yellow River Basin, and its carbon storage variation was deeply influenced by land use types. Although cultivated land and construction land decreased, forest land and grassland increased during 2015–2020, resulting in a carbon storage increase of 147.25 $\times$ 10^6 t (Figure 2g).

The distribution pattern of carbon storage in the Yellow River Basin was lower in the west and northwest, and higher in the central and northeast over the past 20 years (Figure 3). The low carbon storage area was mainly distributed at high altitude (west of the provincial key ecological function zone), where the native vegetation was destroyed, the desertification degree was high, and carbon storage capacity was weak. The high carbon storage area was mainly concentrated in the forest land and grassland in the center of the basin (south and middle of the national key ecological function zone and east of provincial key ecological function zone). A sub-high carbon storage area appeared in the national major grain producing zone of the eastern Yellow River Basin, which was dominated by cultivated land, and the carbon storage per unit area was close to the medium level of 8522.01 t/km^2.

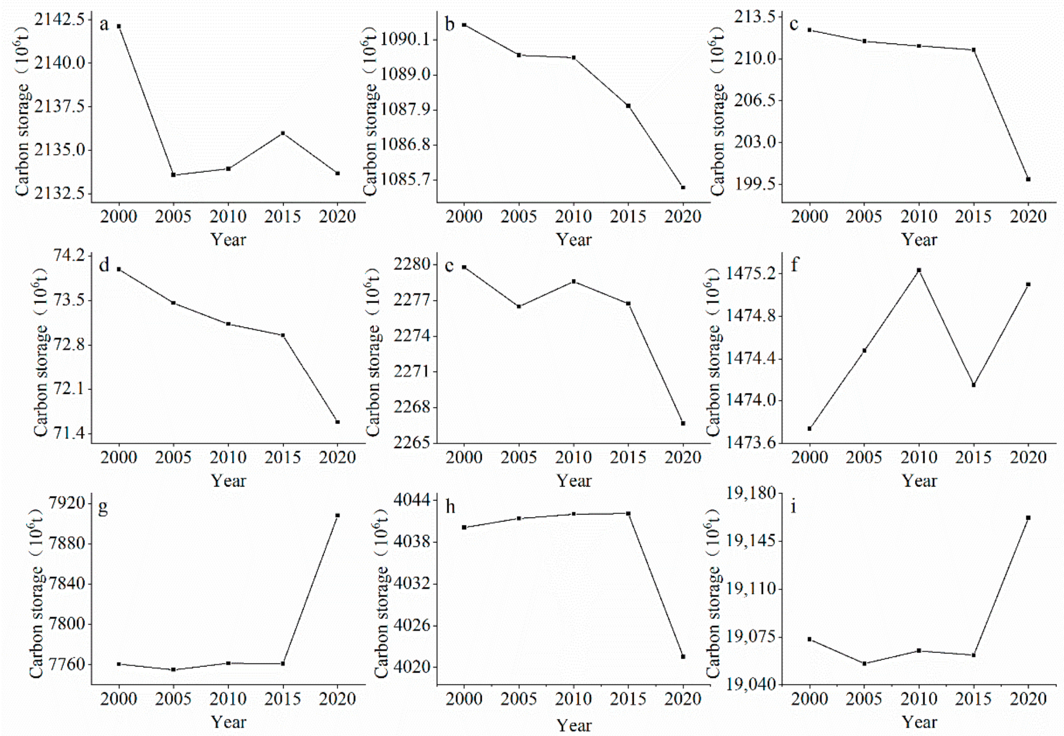

Figure 2. Annual variation of carbon storage in different major functional zones of the Yellow River Basin (**a**–**h**) are the carbon storage in national key development prioritized zone, provincial key development prioritized zone, national development optimized zone, provincial development optimized zone, national major grain producing zone, provincial major grain producing zone, national key ecological function zone and provincial key ecological function zone, respectively; (**i**) is the total carbon storage.

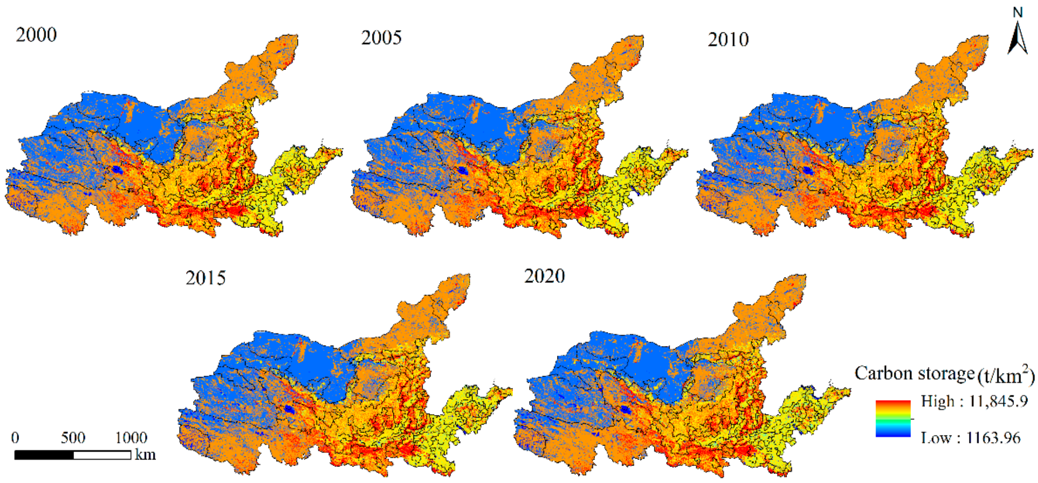

Figure 3. Distribution of carbon storage in the Yellow River Basin from 2000 to 2020.

Based on the carbon storage variation per unit grid, the spatial evolution of carbon storage in the study area were obtained, and was divided into a "carbon sink zone", "balance zone", and "carbon source zone" (Figure 4). Carbon storage variation was mainly concentrated in the central basin during 2000–2005 (the northern part of national key development prioritized zone and the central of the national key ecological function zone), where the carbon source zone was larger than the carbon sink zone, and carbon storage was impaired. The balance zone accounted for more than 99.70% from 2005 to 2010, and carbon sources and carbon sink zones were dispersed. The carbon sink zone was larger than the carbon source zone, indicating the accumulation of carbon storage. From 2010 to

2015, the carbon source and carbon sink zones in northern Golmud city of the provincial key ecological function zone presented a zonal distribution, while being scattered in the national key development prioritized zone and national major grain producing zone. The carbon sink zone was 6778 km^2, which was significantly smaller than the carbon source zone of 11,042 km^2, indicating impaired carbon storage. From 2015 to 2020, the Alxa League of provincial key ecological function zones was dominated by carbon balance, while the carbon source zone alternated with carbon sink zone in other regions. Overall, the ecosystem was affected and threatened by degradation due to the weakened carbon storage and the transformation from a carbon sink zone to carbon source zone during 2000–2020.

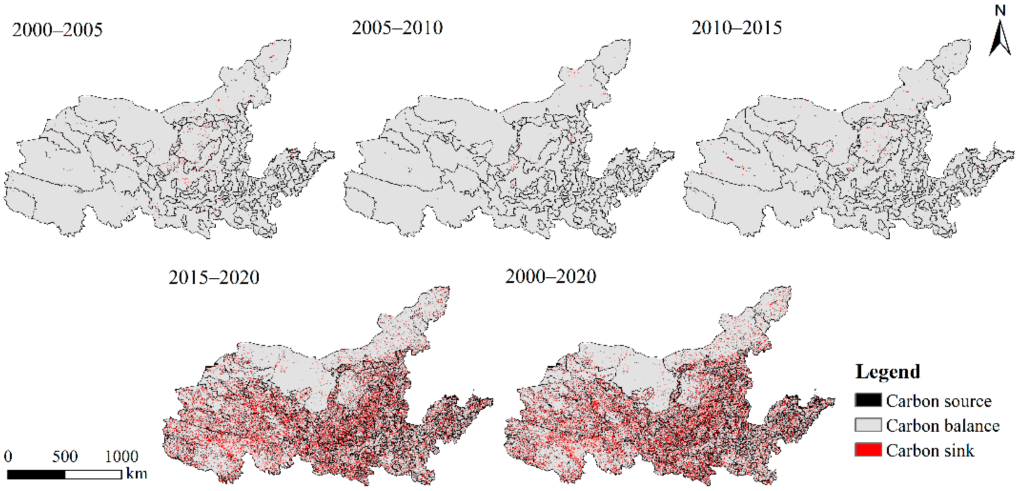

Figure 4. Spatial distribution of carbon sources, carbon balance, and carbon sink zones during 2000–2020.

3.3. Prediction of Carbon Storage under Different Scenarios

In the IDRISI software, the land use data in 2000 and 2015 were considered as the start and end years, respectively. The forecast time and the tolerance were set to 15 years and 0.15, respectively, from which the transition probability matrix could be obtained. The atlas of transfer probability and suitability could be re-adjusted according to existing land use status and relevant policies, to simulate three land use scenarios in 2030 [40]: a natural development scenario (NDS), urban expansion scenario (UES), and ecological protection scenario (EPS) (Figure 5).

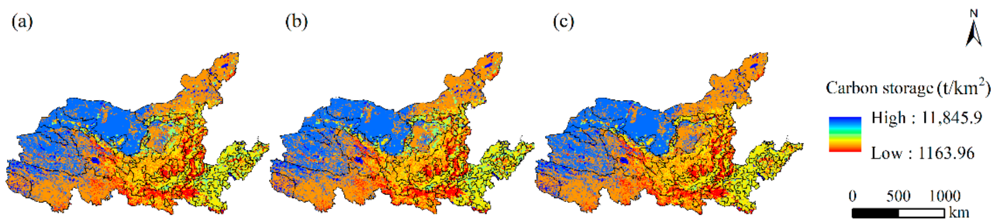

Figure 5. Spatial distribution of carbon storage in the Yellow River Basin under the natural development scenario (**a**), urban expansion scenario (**b**), and ecological protection scenario (**c**).

Compared with 2020, the carbon storage in the three scenarios decreased by 372.46×10^6 t, 423.74×10^6 t, and 178.61×10^6 t, respectively. As shown in Figure 6, the carbon storage varied with different land types. The carbon storage of cultivated land and unused land decreased, while that of forest land, grassland, water, and construction land increased from 2000 to 2020. The carbon storage in construction land and water increased at a constant rate before 2015 and accelerated after 2015. The forest land carbon storage increased at a rate of 3.12×10^6 t per year during 2000–2020. In the NDS, the carbon storage of forest land, water, and construction land increased, while the grassland decreased in 2030, leading to carbon loss in the Yellow River Basin. The carbon storage of construction land increased by 515.35 × 10^6 t, which partially compensated the carbon loss. The significant reduction in carbon storage under the UES was attributed to the expansion of construction land, which occupied large amounts of cultivated land, grassland, and unused land. The reduction of cultivated land and grassland caused a carbon loss of 1084.90 × 10^6 t. Construction land expanded exponentially during 2020–2030, while carbon storage only increased by 641.02 × 10^6 t, due to its smaller carbon density. Under the EPS, the transfer probability of ecological land to construction land was controlled with the guidance of ecological protection, and the carbon storage of cultivated land, forest land, and grassland, respectively, increased by 245.31 × 10^6 t, 84.76 × 10^6 t, and 324.25 × 10^6 t compared with the NDS. The construction land was controlled under this scenario, and the carbon storage reduced by 469.16 × 10^6 t. To sum up, the carbon loss under the EPS was the smallest, indicating that the implementation of ecological engineering was conducive to a carbon storage increase in the basin and the realization of a regional carbon balance.

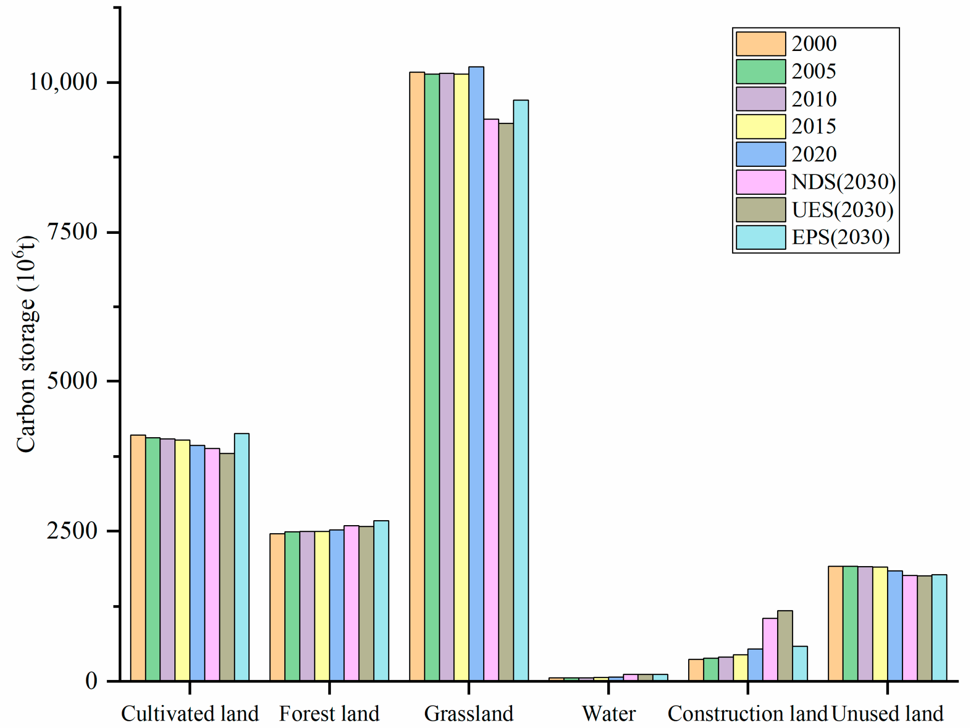

Figure 6. Carbon storage variation of different land use types.

The variation trend of carbon storage in each major function-oriented zone was different under the three scenarios (Table 5). Under the NDS, carbon storage increased only in provincial key ecological function zones, due to the expansion of forest land, water, and construction land (a8). The variation of carbon storage in each major function zone of the UES was similar to that of the NDS. Among them, unused land in the provincial development optimized zone decreased from 31 km^2 to 0 km^2 during 2020–2030, with the carbon loss of 81,649.85 t (b4). In addition, the reduction of cultivated land and grassland also caused the loss of some carbon storage. As the key area for ecological protection, the national key ecological function zone accounted for 36.49% of the Yellow River Basin, and the carbon loss was serious due to grassland reduction (b7). Under the EPS, the carbon storage of the national development optimized zone (c3), national major grain producing zone (c5), and provincial key ecological function zone (c8), respectively, increased by 0.34 × 10^6 t, 6.87 × 10^6 t, and 44.18 × 10^6 t compared with 2020. While, other zones decreased, with the largest descending rate of 2.32% in the national key ecological function zone (c7), followed by the provincial major grain producing zone (c6).

Table 5. Carbon storage variation for land use types in the major function-oriented zones of the Yellow River Basin under different scenarios (10^6 t).

Scenarios	Land Use	National Key Development Prioritized Zone [1]	Provincial Key Development Prioritized Zone [2]	National Development Optimized Zone [3]	Provincial Development Optimized Zone [4]	National Major Grain Producing Zone [5]	Provincial Major Grain Producing Zone [6]	National Key Ecological Function Zone [7]	Provincial Key Ecological Function Zone [8]
NDS [a]	Cultivated land	425.89	470.73	111.37	23.27	1222.24	313.41	925.44	393.60
	Forest land	331.00	128.11	12.73	18.47	286.46	179.38	1011.18	622.61
	Grassland	988.88	267.67	7.02	4.30	323.74	863.56	5149.13	1778.16
	Water	14.57	6.32	2.15	0.39	13.38	9.03	40.46	28.67
	Construction land	245.14	159.03	58.26	21.65	271.31	54.21	135.71	105.74
	Unused land	67.86	19.34	0.86	0.00	119.51	16.87	428.03	1112.90
UES [b]	Cultivated land	411.86	451.88	105.11	21.29	1186.86	309.98	919.58	391.84
	Forest land	328.23	127.47	12.36	18.22	283.99	178.89	1010.38	619.76
	Grassland	963.96	263.35	6.57	4.13	314.84	856.89	5133.47	1767.20
	Water	14.49	6.30	2.13	0.38	13.39	9.05	40.55	28.67
	Construction land	275.72	177.08	63.64	23.46	307.07	61.84	152.13	115.76
	Unused land	67.21	19.17	0.79	0.00	118.80	16.51	426.59	1109.61
EPS [c]	Cultivated land	482.21	516.90	130.04	28.57	1302.11	324.91	942.91	403.61
	Forest land	349.89	137.82	18.89	22.77	301.35	183.03	1024.57	636.39
	Grassland	1090.79	296.22	10.30	4.96	359.87	892.43	5232.66	1819.48
	Water	15.11	6.62	2.23	0.41	13.58	8.86	39.60	28.56
	Construction land	107.78	96.39	37.96	14.64	177.16	23.17	59.46	65.33
	Unused land	73.44	19.94	0.86	0.00	119.46	17.77	430.25	1112.34

[a] repesents NDS, [b] repesents UES, [c] repesents EPS; [1–8] repesents national key development prioritized zone, provincial key development prioritized zone, national development optimized zone, provincial development optimized zone, national major grain pro-ducing zone, provincial major grain producing zone, national key ecological function zone, and provincial key ecological function zone, respectively.

3.4. Effect of Land Use on Carbon Storage

3.4.1. Carbon Storage Variation Caused by Land Use Type Transfer

Carbon storage variation was obtained from the carbon density of each land type and land use transfer matrix from 2020 to 2030 under the different scenarios (Figure 7). Under the NDS, the conversion area from grassland to other land types was 30.70×10^4 km^2, which was the main cause of carbon storage change, with the carbon loss of about 1111.15×10^6 t; of which, the conversion of grassland to unused land decreased the vegetation cover and reduced the carbon storage in soil, aboveground and belowground, leading to a carbon loss of about 773.88×10^6 t. The conversion of grassland to cultivated land, water, and construction land was 8.47×10^4 km^2, 2.39×10^4 km^2, and 3.45×10^4 km^2, which was also not conducive to the increase of carbon storage. The cultivated land transfer was less than that of grassland, and the conversion of cultivated land to water, construction land, and unused land caused a carbon loss of 210.74×10^6 t.

The carbon loss under UES was 44.75×10^6 t more than that under NDS in 2030. The carbon loss caused by the conversion of cultivated land, forest land, and grassland to other land types were 69.12×10^6 t, 256.43×10^6 t, and 1128.39×10^6 t, respectively. In this scenario, the area of construction land increased exponentially, with cropland, grassland, and unused land being the main types of transfer. The expansion of construction land occupied 7.14×10^4 km^2 of cultivated land in the past 10 years, and the carbon storage was reduced by 142.33×10^6 t. Coupled with the construction of some infrastructure types occupying grassland and reducing the area of ecological land, this led to a reduction of 139.07×10^6 t in carbon storage. Owing to the low soil carbon density, the conversion of construction land to other land types only increased the carbon storage to a certain extent (66.87×10^6 t) and was not enough to balance the carbon loss; therefore, urban expansion was not conducive to carbon sequestration.

The transformation among cultivated land, grassland, forest land, and unused land under the EPS from 2020 to 2030 caused carbon storage changes. The carbon loss of forest land and grassland roll-out was 1258.34×10^6 t. The aboveground biomass of forest land plays an important role in ecosystem carbon pool construction, and its carbon sequestration capacity far exceeds other vegetation types, so the conversion of forest land to any other land type will reduce the carbon storage. The grassland ecosystem fixed CO_2 through photosynthesis, which was mainly stored in plants (10.6%) and soil (89.4%), with a high carbon density. Apart from the conversion from grassland to forest land, which could increase some carbon storage, other conversions only led to a carbon loss.

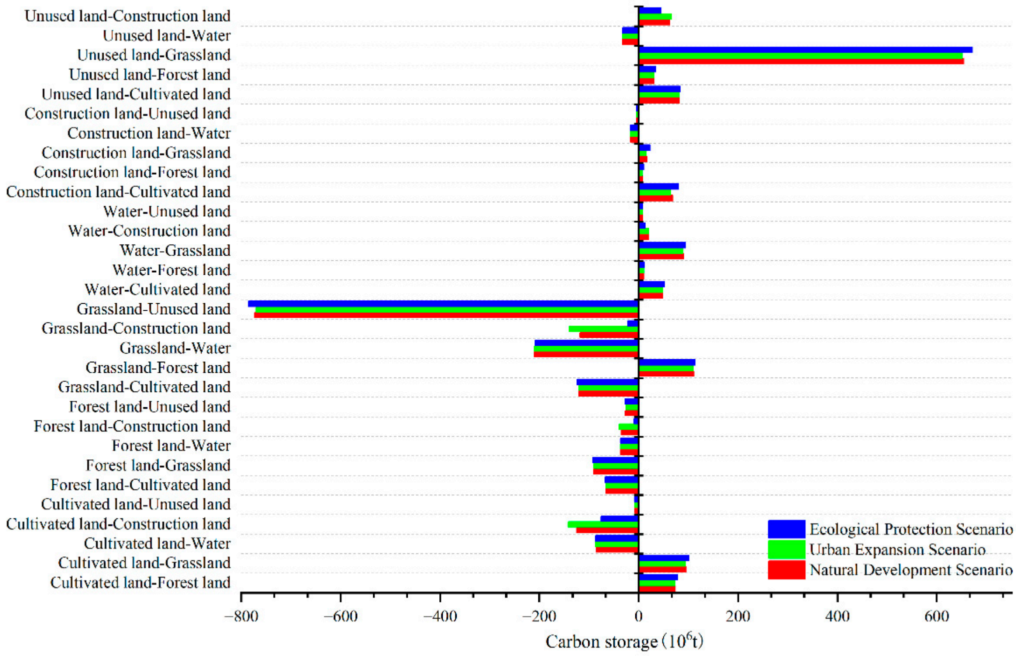

Figure 7. Impact of land type transformation on carbon storage from 2020 to 2030.

3.4.2. Effect of Land Use Intensity on Carbon Storage

Land use intensity can reflect surface cover change and the disturbance from human activities on a landscape. Studying the impact of land use intensity on carbon storage can provide a theoretical basis for ecological sustainable development and environment change. In view of the large range and high calculation level, a 50 km × 50 km fishing net was created, then the Yellow River Basin was divided into 1168 units. A comprehensive index of land use intensity was calculated for each grid, and inverse distance interpolation was performed to divide the study area into five intensity zones (Figure 8): a low intensity zone (<1.3), relatively low intensity zone (1.3–1.8), medium intensity zone (1.8–2.3), relatively high intensity zone (2.3–2.8), and high intensity zone (>2.8).

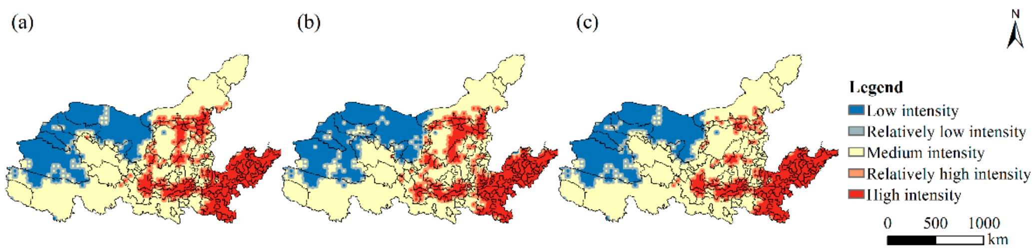

Figure 8. Land use intensity of the Yellow River Basin under the natural development scenario (**a**), urban expansion scenario (**b**), and ecological protection scenario (**c**).

The land use intensity in most of the provincial key ecological function zones of the west and northwest Yellow River Basin was below 1.8, which was the consequence of the high terrain and low land use intensity, with less effects from human activities. The land use intensity in most of national and provincial development optimized zone, provincial key development prioritized zone, and national major grain producing was greater than 2.8. The medium land use intensity was mainly distributed in the national key development prioritized zone, provincial major grain producing zone, and national key ecological function zone of the middle reaches. The results indicated that the lowest land use intensity in the basin was 2.35 under the EPS and the highest was 2.38 under the NDS. Compared with the NDS, the land use intensity of the national key development prioritized zone, national and provincial major grain producing zones, and provincial key ecological function zone under the UES increased, especially the growth rate of 3.22% in the national key development prioritized zone.

The carbon storage of each fishing net was calculated, and its correlation with land use intensity was analyzed; the correlation coefficients were 0.629, 0.647, and 0.671 for the NDS, UES, and EPS, respectively, showing an extremely significant positive correlation. The land use intensity distribution was obviously divided into three parts: east, middle, and west. The ecological environment in the western part was relatively poor, which imposed great restrictions on human activities, and the land use intensity was relatively low. In addition, unused land was the main land use type, its aboveground and belowground carbon storage were small. Therefore, the land use intensity was positively correlated with carbon storage. The east part has a developed economy, superior natural conditions, and a high land use intensity, which was mainly manifested by the expansion of construction land and reclamation of cultivated land, leading to carbon storage increases to a certain extent.

4. Discussion

4.1. Exploring the Relationship between Ecosystem Carbon Storage and Carbon Emissions

The carbon storage in terrestrial ecosystems is more than that of the atmosphere, has a significant impact on global climate change driven by carbon dioxide, and is mainly affected by land use change. As the carrier of human activities, land use not only provides necessary living conditions, but is also accompanied by greenhouse gases emissions (carbon dioxide), which have direct or indirect impacts on carbon emissions. Based on the available carbon emission data (the carbon emission data in 2020 was estimated using GDP), the carbon emissions of each major function-oriented zone were calculated separately based on each county, and the carbon offset (the proportion of fixed CO_2 by terrestrial ecosystems to regional energy CO_2 emissions) was analyzed (Table 6). The results showed that the proportion of each zone decreased by different degrees; in particular, the national key ecological function zone decreased from 113.07 in 2000 to 25.30 in 2020, indicating that the growth rate of carbon sequestration was far slower than the increase rate of carbon emissions. The scale of industry in part of the Inner Mongolia Autonomous Region has expanded since 2000, and this was accompanied by a rapid increase in carbon emissions and a significant weakening of carbon offsets. The carbon offsets proportion in the provincial optimization development zone was less than 1 after 2005, indicating that carbon storage was not sufficient to offset CO_2 emissions, and this would be detrimental to the achievement of carbon reduction targets. The trend of carbon storage and carbon emissions is consistent with the previous research of other scholars. Zhang et al. [41] and Zhou et al. [42] found that carbon emissions increased by different degrees in all provinces, and Dai [43] revealed that the increase of carbon emissions in Inner Mongolia was significant, which is consistent with the findings of this paper. Yang et al. [44] showed that carbon storage would decrease in 2030 under the natural development scenario and the ecological conservation scenario, and a decreasing trends was also presented in carbon storage for the three scenarios of 2030. However, the control range of ecological land and carbon emissions still needs to be further explored for carbon neutrality, due to the different statistical methods used for carbon storage and carbon emissions.

Table 6. Carbon offset rates in major oriented function zones of the Yellow River Basin.

	National Key Development Prioritized Zone	Provincial Key Development Prioritized Zone	National Development Optimized Zone	Provincial Development Optimized Zone	National Major Grain Producing Zone	Provincial Major Grain Producing Zone	National Key Ecological Function Zone	Provincial Key Ecological Function Zone
2000	10.20	8.37	5.03	3.30	10.93	61.96	113.07	73.08
2005	5.66	4.41	1.69	1.15	5.71	33.88	55.25	42.52
2010	3.54	2.96	1.17	0.84	3.87	19.33	33.71	25.80
2015	3.07	2.73	1.16	0.87	3.44	15.79	28.35	22.00
2020	2.69	2.44	0.99	0.77	2.98	14.03	25.30	19.44

4.2. Recommendations for Optimization of Carbon Storage Function

It has been found that the Yellow River Basin has suffered from a fragile habitat in recent years. On the one hand, vegetation coverage under the background of global climate change has affected habitats. On the other hand, intensified human activities have brought adverse effects on the ecological environment, such as the increase of carbon dioxide. Some scholars found that vegetation plays a crucial role in regulating climate and greenhouse gases, by capturing and sequestering carbon dioxide through photosynthesis [45–47]. Therefore, land cover changes directly affect the carbon sequestration of terrestrial ecosystems. Quantitatively assessing the impact of land use changes on carbon storage could provide a reference for carbon reduction research.

In this paper, carbon density was obtained by referring to previous studies and was modified according to temperature and precipitation, which is more accurate than current national carbon density. The results showed that the carbon storage fluctuated over the last 20 years, GGP could improve the ecosystem carbon storage, while construction land expansion led to carbon storage reduction. The declining rate of carbon storage in the EPS was smaller than that in the NDS in 2030, indicating that ecological measures were conducive to carbon sequestration and carbon balance in the Yellow River Basin. Xu et al. [48] also concluded that the implementation of ecological projects, such as GGP, could increase carbon storage. Carbon storage reduction due to construction land expansion was consistent with the results of Li et al. [49] and Liu et al. [28].

In consideration of the carbon storage variation under the three scenarios in 2030, the following aspects should be taken into consideration: First, emission reduction plans should be tailored to local conditions and highlight local characteristics. Development optimized zones (economically developed areas) should focus on science and technology innovation, and industries with high carbon emissions should be converted and upgraded to industries that consume less energy and emit less carbon. Provincial key ecological function zones (coal-dominated areas) should reduce the consumption of traditional energy from coal and promote the clean use of coal and conversion technology. Second, a low carbon land use structure should be sought in the future. Since the dominate land use type was grassland in the national key ecological function zone of the Yellow River Basin, the descending rate of carbon storage should be slowed in the future by returning cultivated land to grassland, developing unused land, and restoring ecologies. Ecological protection should be strengthened and the proportion of cultivated land should be controlled to prevent carbon storage decline in the national major grain producing zones with high carbon storage, so as to realize a harmonious development of ecology and economy. However, the model lacks the corresponding measured data to validate the correction results. The accuracy of ecosystem carbon storage assessment could be further improved by combining the measured data and strengthening the carbon density monitoring of various land use types in future.

4.3. Application of MFOZ Planning

Urbanization and industrialization lead to disorder spatial development and the deterioration of the ecological environment in China. In order to regulate spatial development and build a sustainable development pattern, the state has implemented the strategy of

MFOZ planning. MFOZ planning was a long-term national land development master plan, promulgated and implemented on the basis of natural environmental elements, social and economic development level, ecosystem characteristics, and a spatial differentiation of human activities. In response to the contradiction between the environment and development, different space planning strategies have also been proposed abroad. In order to reduce spatial differences and maintain urban functions, Germany divided land space into four categories: dense areas, rural areas, residential areas and transportation corridors, and central area systems [50]. The fifth spatial plan of the Netherlands divided the Netherlands into a base layer, network layer, and application layer to address issues of water resources, transportation, and regional spatial differences [51]. In France, the entire country was divided into four types: urban areas, mixed urban and rural areas, rural areas, and mountainous and coastal areas [52]. MFOZ planning emphasized multiple spatial divisions and multi-level functions. In the past ten years, MFOZ planning has achieved remarkable results. The two indicators of forest land retention and forest coverage have been basically achieved, and the urban space has great potential in 2020 [53]. Lang [54] found that the efficiency of agricultural security increased significantly from 2006 to 2017 in urbanized areas and major agricultural production areas, which has an obvious and positive guiding effect on the development of urbanized areas and the improvement of the agricultural comprehensive utilization efficiency in the major grain producing zone. In addition, MFOZ can improve the efficiency of resource allocation, reversing the trend of ecological environment deterioration at the source. In a more complex international context, MFOZ will provide a reference for countries or regions facing similar problems.

5. Conclusions

This study analyzed and predicted the carbon storage in the Yellow River Basin from the perspective of different land use types and MFOZ, and revealed the response of carbon storage to land use.

1. The carbon storage variation trend of each land use type in the Yellow River Basin from 2000 to 2020 was different, which was mainly manifested as a decrease of cultivated land and unused land, and an increase of forest land, grassland, water, and construction land. The carbon storage in the provincial key development prioritized zone, national development optimized zone, and provincial development optimized zones showed decreasing trends, while the national key development prioritized zone and national major grain producing zone presented a fluctuating decreasing trend.
2. From 2000 to 2020, the ecosystem carbon storage was weakened, and part of the carbon sink area was transformed into a carbon source area. The low carbon storage area was distributed in the west of the provincial key ecological function zone, and the high carbon storage area was concentrated in the south and middle of the national key ecological function zone and the east of the provincial key ecological function zone.
3. The carbon loss was the largest in urban expansion scenario (UES), followed by the natural development scenario (NDS) and ecological protection scenario (EPS). The correlation coefficients between carbon storage and land use intensity under the NDS, UES, and EPS were 0.629, 0.647, and 0.671, respectively, showing significant positive correlations.

Author Contributions: Conceptualization, J.W. and S.W.; Data curation, L.L., X.L. and Y.L.; Formal analysis, J.W., L.L., S.W. and X.L.; Investigation, J.W. and Q.L.; Methodology, L.L. and S.W.; Project administration, Q.L.; Resources, S.W.; Software, L.L., Q.L. and Y.L.; Supervision, Q.L. and S.W.; Validation, Q.L.; Visualization, S.W.; Writing—original draft, J.W. and L.L.; Writing—review & editing, J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (2020YFF0305905), the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (2019QZKK0201), Key Research and Development Project of Hebei Academy of Sciences, (22107), Science and Technology Project of Hebei Academy of Sciences (22103), the Basic Research

Program of Shanxi Province (20210302123248), the Philosophy and Social Science Foundation of Shanxi Province (2020YY069).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable. No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We would like to extend special thanks to the editors and reviewers for their insightful advice and comments on the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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