

Article

Analysis of Changes in Vegetation Carbon Storage and Net Primary Productivity as Influenced by Land-Cover Change in Inner Mongolia, China

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Abstract: Exploring the influence of vegetation carbon stocks over land-cover change and the relationship between land-cover change and net primary production (NPP) is of great practical importance for achieving China's carbon neutrality target. Therefore, this paper analyses the spatio-temporal distribution of land-cover change and NPP change in Inner Mongolia from 2000 to 2020 and explores the vegetation carbon stock change caused by land-cover change, the relationship between land cover and NPP, and the relationship between land-cover change and NPP change. The results show that the main land-cover change in Inner Mongolia during 2000–2020 was the conversion from other land-cover types to grassland, with the conversion of bare land to grassland from 2000 to 2010 covering an area of 20,634.87 km². During the period of 2000–2020, the high values of NPP were mainly located in northeastern Inner Mongolia, and the low values were mainly distributed in southwestern Inner Mongolia. The total carbon storage changes in vegetation affected by land-cover change during 2000–2010 and 2010–2020 were 10,736,986.11 t and 3,894,272.41 t. The mean values of NPP for different land covers were, in descending order, forest > cultivated land > wetland > grassland > artificial surfaces > shrubland > water bodies > bare land. Between 2000 and 2010, the change in land-cover type to water bodies was the main cause of the decrease in NPP, and the increase in NPP was mainly due to the conversion of other land-cover types to cultivated land, forest, and grassland. The implementation of appropriate conservation and management measures (e.g., the construction of forest and grass ecological protection), planting, and the protection of high-vegetation carbon storage plants and other means can improve the level of vegetation carbon sequestration and protect the ecological environment of Inner Mongolia.

Keywords: spatial and temporal changes; transfer matrix; spatial association; net primary production



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1. Introduction

Vegetation net primary production (NPP) is the net amount of carbon sequestered by green plants through photosynthesis [1]. It is an important indicator of terrestrial ecosystem productivity, offsetting anthropogenic carbon emissions and maintaining carbon balance at the land surface [2,3]. Improving vegetation carbon storage is important for achieving the goal of sustainable ecosystem development [4]. Land-cover change is considered one of the main drivers of NPP change [5,6]. An in-depth assessment of the relationship between land-cover change and NPP response and of the impact of land-cover change on vegetation carbon storage is critical for achieving carbon balance in terrestrial systems owing to the vital atmospheric feedback from land systems [7].

Terrestrial ecosystems have a strong carbon sequestration capacity; the amount of carbon sequestered by vegetation varies from region to region [8,9]. Many researchers have conducted studies on this subject. For example, DeFries et al. (1999) estimated the impact of human-induced land-cover change on atmospheric carbon emissions and net primary

production using a global terrestrial carbon cycle model, a satellite map of vegetation, and a global map of natural vegetation [10]. Achard et al. (2004) used the results of deforestation surveys in the humid tropics and published deforestation data in the dry tropics, applied to reference data on biomass, to develop new estimates of net carbon emissions [11]. Houghton et al. (2012) summarised 13 estimates of net carbon emissions from land use and land-cover change, including deforestation, agricultural land area change, and forest management [12]. Yang et al. (2014) explored the impact of land use and land-cover change driven by ecological restoration programmes in Xinjiang from 2001 to 2009 [13]. Lai et al. (2016) explored vegetation and soil carbon stock changes in China between 1990 and 2010 due to a combination of land-use category conversion and management [14]. Li et al. (2017) used satellite and inventory-based biomass observations to constrain historical cumulative land use and land-cover change emissions from nine DGVMs to model the new relationship between vegetation biomass and historical cumulative land use and land-cover change emissions [15]. Peng et al. (2017) quantified the global NPP response to drought and land-cover change from 2000 to 2014 [16]. Chuai et al. (2019) studied the relationship between “physical-social” integrated carbon balance and land-cover change in Nanjing City over the period of 2000–2015 [17]. Wu et al. (2019) assessed land-cover change in Kunshan City between 2006 and 2016, predicted future land cover in 2030 under three models, and quantified the spatial and temporal responses of crop production, carbon storage, habitat quality, flood regulation, and nitrogen and phosphorus retention to land-cover change [18]. Yang et al. (2020) used Hubei Province as an example and proposed a hierarchical framework integrating system dynamics, land-use modelling, and carbon stock assessment models to explore carbon storage under different scenarios between 2010–2015 and 2015–2030 [19]. Hao et al. (2021) explored the downward response between NPP and climatic factors from 2002 to 2019 [20]. Although the above studies have explored the effects of land-cover change on carbon storage or NPP, the analysis of different land-cover types and the extent to which their change affects carbon storage or NPP is not comprehensive enough. Relatively few studies have been conducted on the same study area combining both NPP and carbon storage under different land-cover types. It is worth noting that carbon storage and NPP are important for the realisation of dual-carbon schemes. Therefore, it is necessary to explore the relationship between the response of land-cover change to NPP and carbon storage under the combined influence of NPP and carbon storage and to further develop guidelines for scientific and regional land planning.

Inner Mongolia is an important energy resource base in China, with a vast territory, well-developed stratigraphy, frequent magmatic activity, good mineralization conditions, and abundant mineral resources [1]. In 2020, Inner Mongolia’s carbon emissions will reach 630 million tons, the fourth highest in China, and its carbon emissions per unit of GDP and per capita carbon emissions will be nearly four times the national average. Inner Mongolia’s carbon emissions are large, its energy supply is still in the growth phase, and it is difficult to decarbonise the thermal power sector, which makes it difficult and challenging to achieve the goal of carbon peaking and carbon neutrality. Therefore, exploring vegetation carbon storage in response to land-cover change and the potential relationship between land-cover change and NPP is scientifically relevant for accomplishing the dual carbon goal in Inner Mongolia.

This paper explores vegetation carbon storage as influenced by land-cover change and the relationship between land-cover change and NPP from 2000 to 2020 in Inner Mongolia. First, GlobeLand30 land-cover data and NPP data were used to determine land-cover change and NPP change. Second, the amount of change in vegetation carbon storage affected by land-cover change was calculated based on the land-cover change transfer matrix. Then, spatial correlation analysis was used to explore the relationships and impacts between land cover and NPP. Finally, the impacts and changes between different land-cover changes and NPP changes were further analysed.

The main innovation and contribution of this paper can be found in its exploration of the vegetation carbon stock response to land-cover change and the relationship between

land-cover change and NPP in Inner Mongolia from a more comprehensive perspective. Specifically, we examine the following factors: (1) The spatial distribution of land-cover changes and NPP changes is analysed from a relatively comprehensive perspective. (2) The amount of vegetation carbon stock change influenced by land-cover change is further investigated from 2000 to 2020. (3) Spatial correlation analysis is conducted on land cover and NPP, and the effects of different land-cover types on NPP values are explored in Inner Mongolia. (4) The link between land-cover change and NPP change is further explored, and the changes in NPP values due to different land-cover changes are assessed. This study is crucial to the achievement of an optimal land spatial pattern in Inner Mongolia.

2. Materials and Methods

2.1. Study Area

Inner Mongolia is located in the north of China between $37^{\circ}24'$ – $53^{\circ}23'$ north latitude and $97^{\circ}12'$ – $126^{\circ}04'$ east longitude [21,22]. As shown in Figure 1, Inner Mongolia borders Heilongjiang, Jilin, Liaoning, and Hebei in the northeast; Shanxi, Shaanxi, and Ningxia in the south; Gansu in the southwest; and Russia and Mongolia in the north. Inner Mongolia straddles northeast, north, and northwest China. Inner Mongolia is an important energy region in China, with high energy consumption and a high proportion of industry; to a certain extent, this increases the difficulty of achieving its carbon neutrality target [5,6]. The terrain of Inner Mongolia extends diagonally from northeast to southwest and is basically a plateau-type landscape area covering plateaus, mountains, hills, plains, deserts, rivers, and lakes, and it possesses rich ecological carbon sink resources [23]. Inner Mongolia has rich ecological carbon sink resources; it has the highest in the country in terms of forest area and the second highest in the country in terms of grassland area [24,25]. Ecological carbon sinks are an effective means of achieving the carbon neutrality target. Therefore, exploring the effects of land-cover change on vegetation carbon storage and the response of land-cover change to NPP offers the possibility of addressing the double-carbon problem.

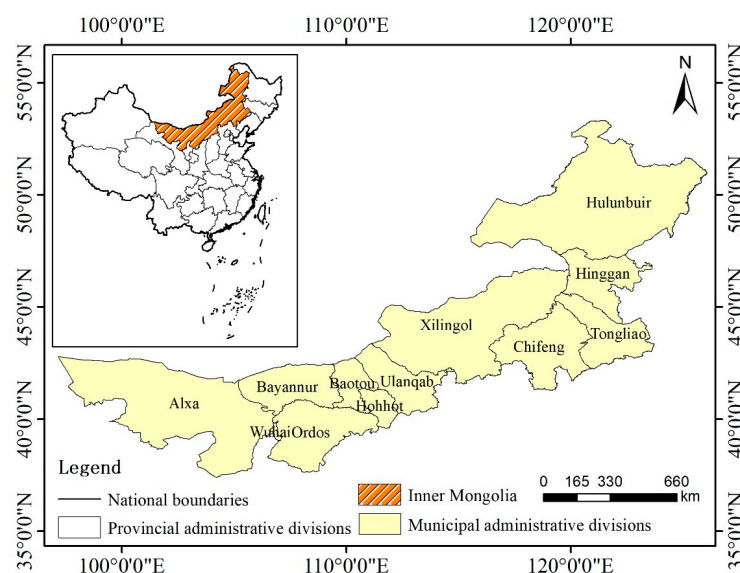


Figure 1. Location of Inner Mongolia.

2.2. Data

Data used included GlobeLand30 land-cover maps and NPP data [26]. GlobeLand30 data are part of a global geographic information public product, available through the GlobeLand30 website (<http://globeland30.org/>, accessed on 11 December 2022). NPP reflects the efficiency with which plants fix and transform photosynthetic products and also determines the amount of material and energy available to heterotrophic organisms, including various animals and people [24]. NPP data were obtained through the Google Earth Engine

platform [27–29] (<https://code.earthengine.google.com/>, accessed on 13 December 2022) to obtain MOD17A3H 500 m resolution data.

The release of the GlobeLand30 global land-cover data for 2020 provides a useful basis for understanding land-cover change in recent years [30,31]. GlobeLand30 land-cover data are available for 10 land-cover types [32]. The overall accuracy of the GlobeLand30 land-cover data for 2010 and 2020 is 83.50% and 85.72%, respectively, with kappa coefficients of 0.78 and 0.82 [33]. GlobeLand30 global land-cover data have a relatively high accuracy and can be used in relatively large-scale studies [34–36].

2.3. Methods

2.3.1. Land-Cover Change Rate and Change Transfer Matrix

The land-cover change rate is used to evaluate the change in each land-cover type over the years [37]. The calculation equation is as follows.

$$LCR = \frac{A_b - A_a}{A_a} \times 100\% \quad (1)$$

where A_a is the area of a particular land-cover type in year a , and A_b is the area of a particular land-cover type in year b .

The land-cover change transfer matrix [38,39] is a quantitative relationship based on changes in land-cover types over time in the same area, which provides a quantitative visualisation of conversion among land-cover types. In this study, the GlobeLand30 land-cover change transfer matrix was acquired using ArcGIS 10.2 software.

2.3.2. Land-Cover-Change-Influenced Vegetation Carbon Storage

We analysed land-cover change on vegetation carbon storage changes in Inner Mongolia using land-cover change and vegetation carbon storage density corresponding to land-cover types [40]. It is worth noting that the changes in soil organic carbon caused by land-cover-type changes were not considered in this study due to the long time period over which soil organic carbon changes occur [17]. The specific equation is as follows:

$$\Delta C_{ij} = (V_i - V_j) \times A_{ij} \quad (2)$$

where ΔC_{ij} represents vegetation carbon stock change due to conversion from land-cover-types i to j ; V_i is the density of vegetation carbon for land-cover type i ; V_j is the density of vegetation carbon for land-cover types j ; and A_{ij} is the area converted from land-cover-types i to j .

2.3.3. Spatial Correlation Analysis

Spatial correlation analysis was carried out between NPP and land cover to calculate correlation coefficients and clarify their association. The Pearson correlation coefficient was used to measure whether the two datasets lie on top of a line and to measure the linear relationship between the fixed distance variables [41–43]. Sig is an abbreviation for statistical significance [44]. The value of sig is the statistical p -value, and the test of significance is based on the p -value. If the p -value is $0.01 < p < 0.05$, the difference is significant, and if $p < 0.01$, the difference is highly significant [45]:

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (3)$$

where X and Y denote samples for comparison; $\bar{X}$ and $\bar{Y}$ are the mean of the comparison samples.

3. Results

As shown in Figure 2, firstly, land-cover change and NPP change in Inner Mongolia, including the change amount, change rate, land-cover change transfer matrix, and spatial distribution, were obtained using GlobeLand30 land-cover data and NPP data from 2000 to 2020. Secondly, the changes in vegetation carbon storage affected by land-cover change were calculated by combining the vegetation carbon density of each land-cover type. Then, the correlation and influence between land-cover data and NPP data were analysed using the spatial correlation method. Finally, the changes in NPP values with different land-cover changes were explored through land-cover changes and NPP changes.

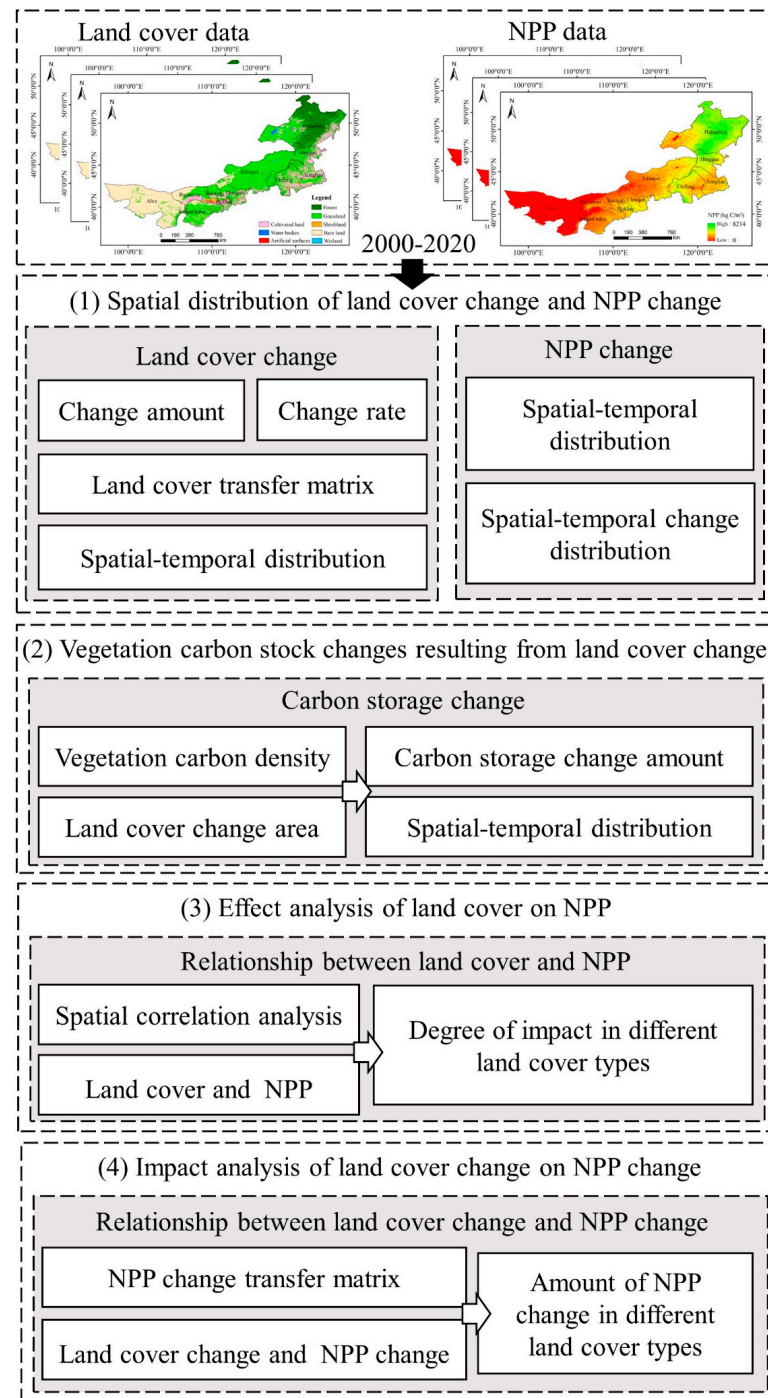


Figure 2. Flowchart of this study.

3.1. Spatial Distribution of Land-Cover Change and NPP Change

As shown in Figure 3, the southwestern part of Inner Mongolia is mainly bare land, the central part is mainly grassland, and the northeastern part is mainly forested, with a more dispersed distribution of cultivated land and less artificial surface region. There is one more obvious lake in the northeastern region. In particular, the central part of Inner Mongolia showed a marked conversion of grassland to shrubland in 2010.

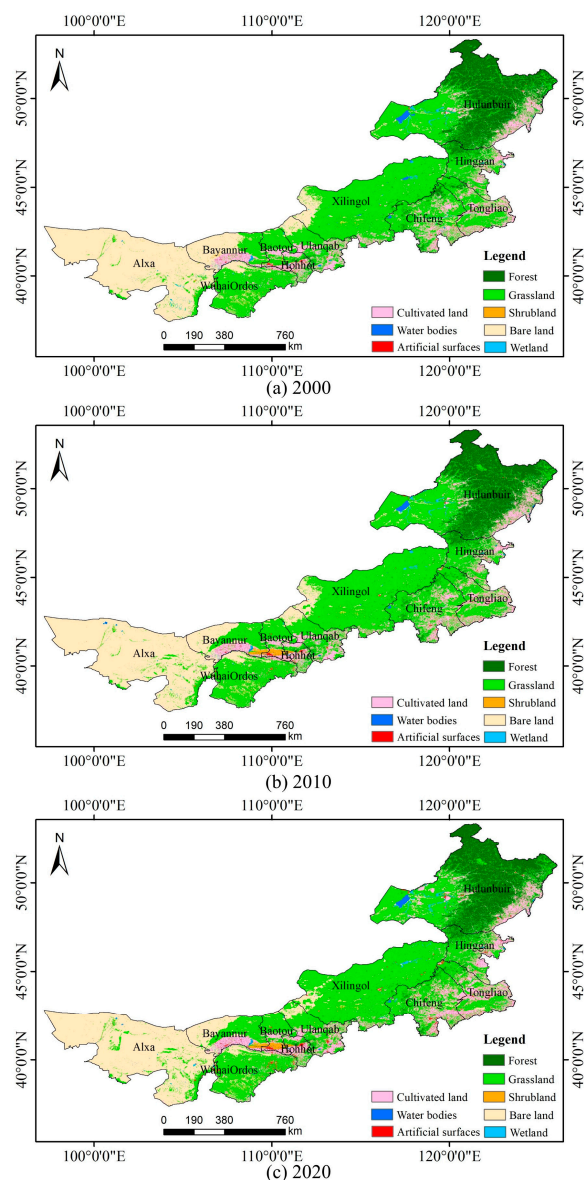


Figure 3. Spatial distribution of land-cover in Inner Mongolia, 2000–2020.

As shown in Table 1, Inner Mongolia has the largest grassland area, accounting for approximately 46–47% of the overall area, followed by bare land. As shown in Figure 4, between 2000 and 2010, the largest increase in grassland area was 14,884.64 km²; shrubland showed an increase of 3769.61 km², a change of 65.10%; wetlands and water bodies showed a decrease of 22.26% and 18.22%, respectively; and artificial surfaces increased by 1298.63 km², a change of 17.07%. The reduction in cultivated land was 5185.56 km². From 2010 to 2020, grassland decreased by 9797.81 km², and shrubland decreased by 699.42 km². Bare land still showed a decreasing trend, decreasing by 12,316.37 km², and water bodies trended upward, with a change rate of 14.00%. The artificial surface area increased

by 6005.93 km², or 67.42%. Cultivated land increased by 11.03%, with an area change of 15,221.71 km².

Table 1. Land-cover change in Inner Mongolia, 2000–2020.

	2000		2010		2020		2000–2010		2010–2020	
	Area/km ²	Proportion/%	Area/km ²	Proportion/%	Area/km ²	Proportion/%	Amount of Change/km ²	Rate of Change/%	Amount of Change/km ²	Rate of Change/%
Cultivated land	143,241.55	12.36	138,056.00	11.92	153,277.71	13.23	−5185.56	−3.62	15,221.71	11.03
Forest	132,292.75	11.42	132,616.90	11.45	133,672.85	11.54	324.15	0.25	1055.95	0.80
Grassland	534,473.80	46.13	549,358.45	47.42	539,560.64	46.57	14,884.64	2.78	−9797.81	−1.78
Shrubland	5790.57	0.5	9560.18	0.82	8860.76	0.76	3769.61	65.10	−699.42	−7.32
Wetland	7678.73	0.66	5969.67	0.51	5747.86	0.50	−1709.06	−22.26	−221.81	−3.72
Water bodies	6566.03	0.57	5369.56	0.46	6121.38	0.53	−1196.47	−18.22	751.82	14.00
Artificial surfaces	7609.68	0.66	8908.31	0.77	14,914.24	1.29	1298.63	17.07	6005.93	67.42
Bare land	320,912.36	27.7	308,726.42	26.65	296,410.05	25.58	−12,185.94	−3.80	−12,316.37	−3.99

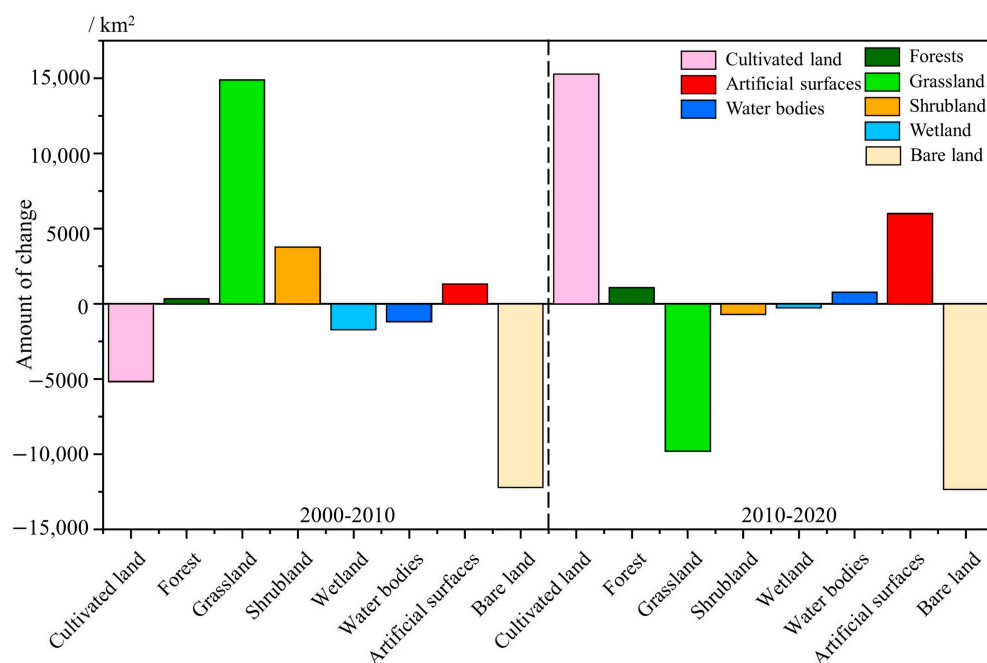


Figure 4. Amount of land-cover change in Inner Mongolia, 2000–2020.

Figure 5 shows the land-cover changes in Inner Mongolia from 2000 to 2020. From 2000–2010, conversions from other land-cover types to grassland, shrubland, and forest were the main land-cover changes in Inner Mongolia, while the conversion from grassland to shrubland was mainly concentrated in Bayannur City, Baotou City, and Hohhot City. The conversion of bare land to grassland occurred mainly in Bayannur municipality and the Alxa League region. Grassland-to-forest and forest-to-grassland conversions occurred mainly in Hulunbeier City.

As shown in Table 2, the area of land-cover types converted to grassland in Inner Mongolia was higher than those converted to other types. The areas of cultivated land, forest, and bare land converted to grassland were 11,003.96 km², 14,326.38 km², and 20,634.87 km², respectively. From 2010 to 2020, conversions of other land-cover types to grassland, cultivated land, artificial surface, and wetlands were the main land-cover changes in Inner Mongolia. The conversion of bare land to grassland mainly took place in Xilingrad League, Ulanqab City, and Alxa League. Grassland conversion to cultivated land mostly happened in Hulunbeier City, Chifeng City, and Tongliao City. The expansion of artificial surfaces took place mainly in Baotou City, Ordos City, Hohhot City, and Ulanqab City. Changes in wetlands and water bodies occurred mainly in the northeastern part of

Xilingrad League and the western part of Hulunbeier City. The area converted from other types to grassland remained the largest, with an area of 48,575.22 km², followed by the conversion of other types to bare land, with an area of 12,693.50 km².

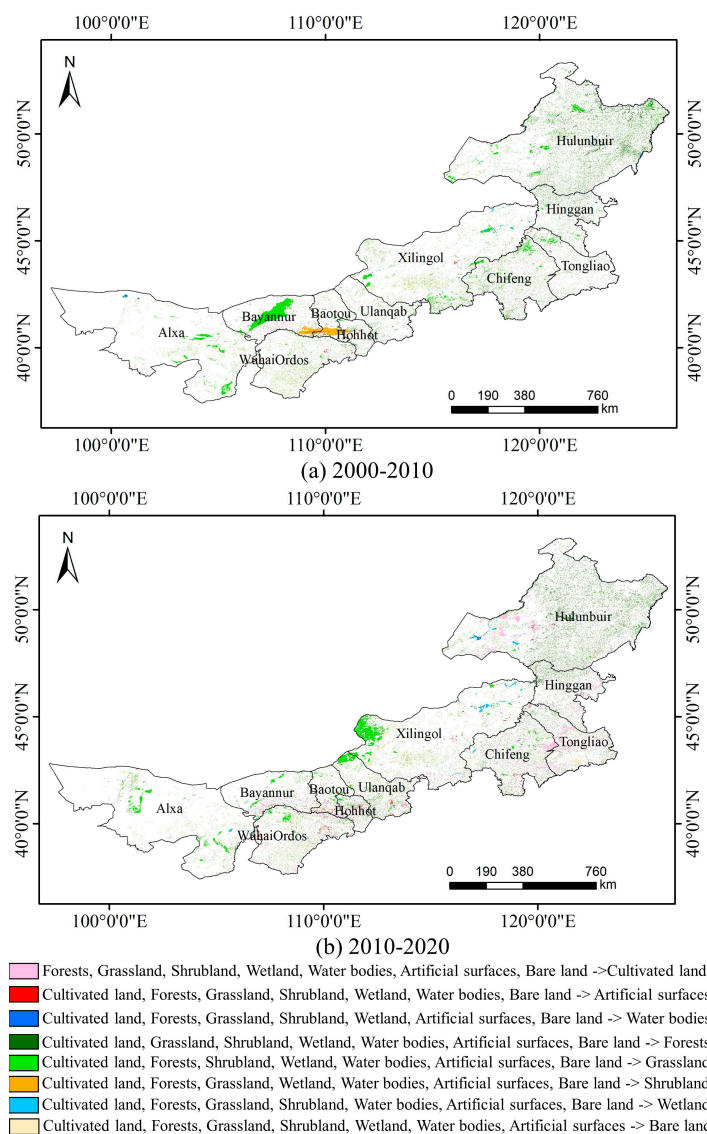


Figure 5. Land-cover change in Inner Mongolia, 2000–2020.

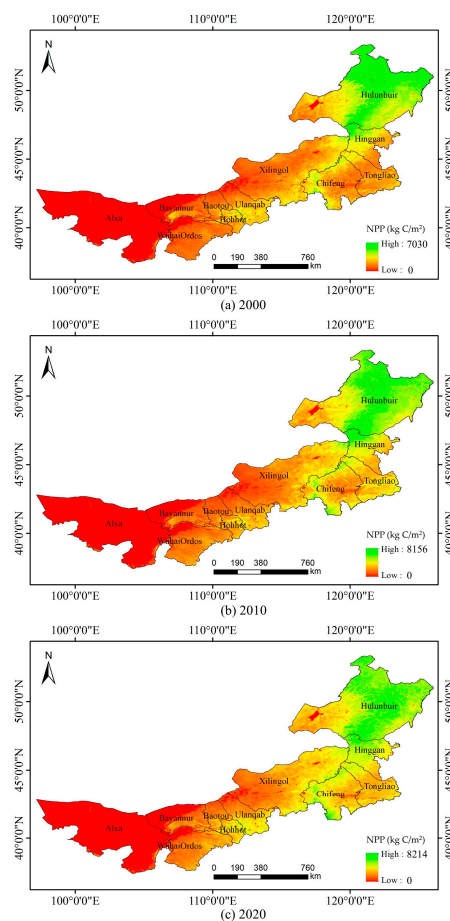
As shown in Figure 6, the areas with high NPP values in Inner Mongolia from 2000 to 2020 were mainly located in the northeastern region, e.g., Hulunbeier City, Xinggan League, and the border of Chifeng City and Xilingrad League. The areas with low NPP values were mainly concentrated in the southwestern region, e.g., Alxa League, Bayannur City, Wuhai City, and Ordos City. The distribution of NPP data in Inner Mongolia from 2000 to 2020 is in line with the change in surface vegetation from forest–grassland–desert and grassland–desert from the east to the west.

As shown in Figure 7, between 2000 and 2010, there was an increasing trend in NPP values in Hulunbeier City, Xinggan League, Tongliao City, Chifeng City, and the northeastern part of Xilingrad League, as well as the southern part of Ordos City. Decreases in NPP were evident in the southern part of Xilingrad League, the central part of Ulanqab City, and the southern part of Baotou City. Between 2010 and 2020, the NPP values in the southeastern regions of Hulunbeier City and Tongliao City showed a significant decrease. Chifeng City, the eastern part of Xinggan League, the southern part of Ulanqab City, the southern part of Baotou City, and Hohhot City showed a significant increase.

Table 2. Land-cover transfer matrix for 2000–2020.

Area/km ²	Cultivated Land	Forest	Grassland	Shrubland	Wetland	Water Bodies	Artificial Surfaces	Bare Land	Total 2010
Cultivated land	129,877.15	276.69	6548.15	45.77	378.77	302.54	529.87	97.05	138,055.99
Forest	734.85	117,518.53	13,733.21	377.98	120.50	117.79	12.20	1.83	132,616.90
Grassland	11,003.96	14,326.38	496,955.99	3066.67	1825.68	1140.21	404.68	20,634.87	549,358.44
Shrubland	164.33	109.00	6907.41	1979.53	76.32	31.79	7.07	284.72	9560.18
Wetland	92.24	17.44	586.74	6.03	4544.21	661.80	6.30	54.90	5969.67
Water bodies	224.83	35.55	416.99	6.52	452.78	3967.38	8.94	256.56	5369.56
Artificial surfaces	1036.06	6.12	1135.36	5.83	11.59	11.28	6608.29	93.78	8908.31
Bare land	108.13	3.04	8189.95	302.23	268.87	333.23	32.33	299,488.63	308,726.42
Total 2000	143,241.55	132,292.75	534,473.80	5790.57	7678.73	6566.03	7609.68	320,912.36	1,158,565.47

Area /km ²	Cultivated Land	Forest	Grassland	Shrubland	Wetland	Water Bodies	Artificial Surfaces	Bare Land	Total 2020
Cultivated land	122,910.99	664.64	26,585.36	527.99	226.19	252.16	1078.72	1031.66	153,277.71
Forest	492.21	120,958.79	11,843.62	292.67	6.10	61.65	15.59	2.22	133,672.85
Grassland	10,551.24	10,456.65	490,985.41	2538.29	1282.79	404.28	434.60	22,907.37	539,560.63
Shrubland	118.38	302.67	2518.19	5709.26	4.65	5.10	22.19	180.33	8860.76
Wetland	93.91	23.80	1644.15	26.62	3534.89	297.28	1.94	125.27	5747.86
Water bodies	338.93	91.44	778.65	27.80	505.39	3998.32	12.69	368.17	6121.38
Artificial surfaces	3352.07	96.84	3532.10	139.78	63.37	19.13	7316.09	394.85	14,914.24
Bare land	198.27	22.08	11,470.95	297.78	346.29	331.64	26.49	283,716.55	296,410.05
Total 2010	138,056.00	132,616.90	549,358.45	9560.18	5969.67	5369.56	8908.31	308,726.42	1,158,565.48

**Figure 6.** Spatial distribution of annual NPP data in Inner Mongolia.

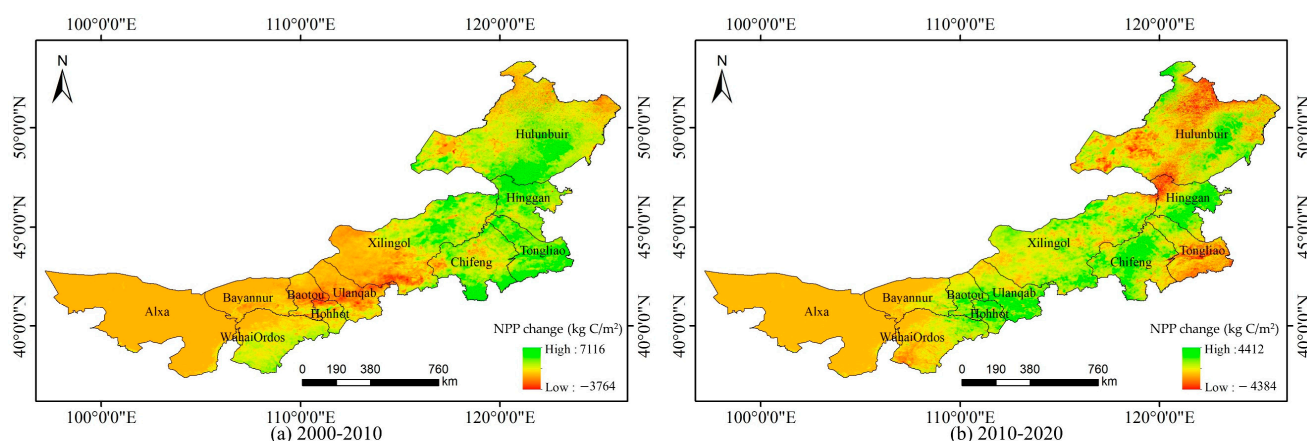


Figure 7. Change in annual NPP data for Inner Mongolia.

3.2. Vegetation Carbon Stock Changes Resulting from Land-Cover Change

The density of vegetation carbon storage for different land-cover types [7,46] is shown in Table 3. As shown in Table 4, according to the change in land cover from 2000 to 2020, the changes in vegetation carbon storage affected by land-cover change in Inner Mongolia from 2000 to 2010 and from 2010 to 2020 were 10,736,986.11 t and 3,894,272.41 t, respectively. The reductions in carbon storage of vegetation from 2000–2010 were 2,211,796.64 t, 38,494,983.06 t, and 8,240,144.44 t for the conversion of cultivated land, forest, and shrubland to grassland, respectively. From 2010 to 2020, the carbon storage of vegetation from other land-cover types converted to grassland and artificial surfaces decreased by 35,555,321.59 t and 2,223,251.93 t, respectively. The increase in the carbon storage of vegetation affected by land-cover change from 2000 to 2020 was mainly due to the conversion of other land-cover types to forest, cultivated land, and shrubland.

Table 3. Carbon density of vegetation in different land-cover types.

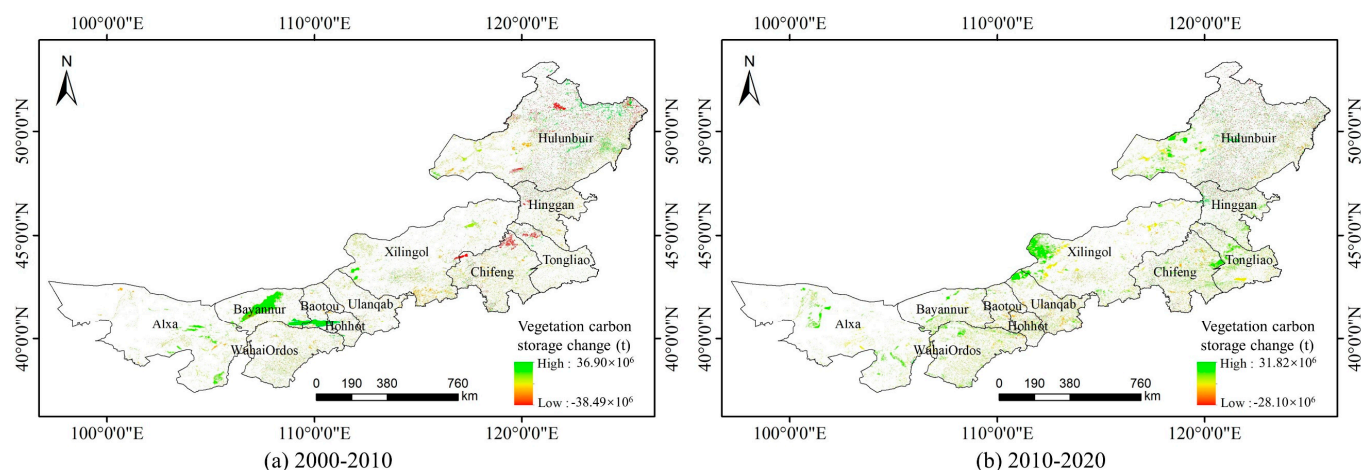
Land-Cover Type	Vegetation Carbon Density (t C/ha)		
	X	X _{min}	X _{max}
Cultivated land	3.25	1.29	5.70
Forest	28.11	12.06	50.18
Grassland	1.24	0.00	2.30
Shrubland	28.11	12.06	50.18
Wetland	0.67	0.00	1.80
Water bodies	-	-	-
Artificial surfaces	-	-	-
Bare land	0.67	0.00	1.80

Figure 8 shows the spatial distribution of changes in vegetation carbon storage affected by land-cover change in Inner Mongolia from 2000 to 2020. From 2000 to 2010, the increase in vegetation carbon storage affected by land-cover change was mainly concentrated in the central and western parts of Inner Mongolia, i.e., the southeastern part of Alxa League, the central part of Bayannur City, the southern part of Baotou City, and the western part of Hohhot City, with some increase in the northeastern part of Inner Mongolia. The areas where vegetation carbon storage decreased were mainly located in the northern part of Chifeng City, the northwestern part of Tongliao City, the eastern part of Xilingrad League, and the northern part of Hulunbeier City. From 2010 to 2020, the increase in vegetation carbon storage mainly occurred in the western and southern parts of Alxa League, the central part of Bayannur City, the northern part of Ordos City, the northern part of Ulanqab City, the western part of Xilingrad League, the border between Tongliao City and Chifeng City, and the western part of Hulunbeier City. The regional distribution of the reduction in vegetation carbon storage was more dispersed.

Table 4. Carbon storage change transfer matrix, 2000–2020.

Carbon Storage/t	Cultivated Land	Forest	Grassland	Shrubland	Wetland	Water Bodies	Artificial Surfaces	Bare Land	Total 2010
Cultivated land	0.00	−687,848.36	1,316,177.21	−113,787.45	97,723.92	98,324.75	172,208.21	25,039.98	907,838.26
Forest	1,826,843.81	0.00	36,901,146.82	0.00	330,649.80	331,110.78	34,300.38	5033.04	39,429,084.65
Grassland	−2,211,796.64	−38,494,983.06	0.00	−8,240,144.44	104,063.85	141,386.04	50,180.38	1,176,187.68	−47,475,106.20
Shrubland	408531.34	0.00	18560220.34	0.00	209429.49	89,368.72	19,864.77	781,267.84	20,068,682.50
Wetland	−23,797.71	−47,865.79	−33,444.06	−16,548.79	0.00	44,340.76	422.10	0.00	−76,893.49
Water bodies	−73,069.43	−99,925.99	−51,707.18	−18,336.72	−30,336.09	0.00	0.00	−17,189.84	−290,565.24
Artificial surfaces	−336,718.40	−17,210.91	−140,784.74	−16,386.16	−776.30	0.00	0.00	−6283.20	−518,159.71
Bare land	−27,898.60	−8337.37	−466,827.33	−829,323.78	0.00	22,326.50	2165.92	0.00	−1,307,894.67
Total 2000	−437,905.62	−39,356,171.47	56,084,781.06	−9,234,527.34	710,754.68	726,857.55	279,141.76	1,964,055.50	10,736,986.11

Carbon Storage/t	Cultivated Land	Forest	Grassland	Shrubland	Wetland	Water Bodies	Artificial Surfaces	Bare Land	Total 2020
Cultivated land	0.00	−1,652,293.05	5,343,656.84	−1,312,595.32	58,357.67	81,953.24	350,583.19	266,167.61	3,135,830.16
Forest	1,223,636.30	0.00	31,823,814.73	0.00	16,731.54	173,290.56	43,825.46	6097.44	33,287,396.03
Grassland	−2,120,799.06	−28,097,011.30	0.00	−6,820,372.60	73,119.28	50,131.05	53,890.86	1,305,720.18	−35,555,321.59
Shrubland	294,285.22	0.00	6,766,388.89	0.00	12,753.01	14,331.88	62,382.27	494,816.46	7,644,957.75
Wetland	−24,229.61	−65,303.63	−93,716.79	−73,048.30	0.00	19,917.51	129.89	0.00	−236,250.93
Water bodies	−110,152.28	−257,025.19	−96,553.20	−78,133.43	−33,860.80	0.00	0.00	−24,667.46	−600,392.37
Artificial surfaces	−1,089,421.81	−272,222.30	−437,980.56	−392,926.36	−4245.90	0.00	0.00	−26,455.00	−2,223,251.93
Bare land	−51,153.89	−60,584.23	−653,844.20	−817,106.67	0.00	22,219.77	1774.51	0.00	−1,558,694.72
Total 2010	−1,877,835.13	−30,404,439.70	42,651,765.71	−9,494,182.68	122,854.79	361,844.01	512,586.17	2,021,679.23	3,894,272.41

**Figure 8.** Spatial distribution of vegetation carbon storage changes in Inner Mongolia.

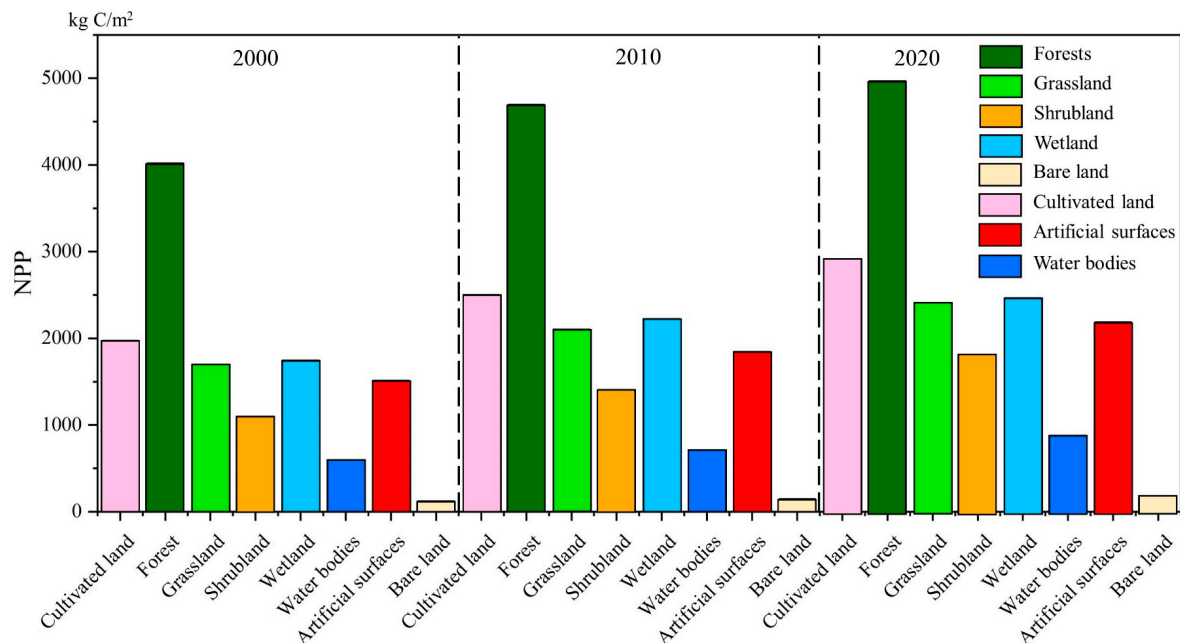
3.3. Effect Analysis of Land Cover on NPP

Table 5 shows the spatial correlation analysis between land-cover and NPP data from 2000 to 2020. The GlobeLand30 land-cover-type values are specified as follows: cultivated land is 10, forest is 20, grassland is 30, shrubland is 40, wetland is 50, water bodies are 60, artificial surface is 80, and bare land is 90. It can be clearly seen that there is a significant negative correlation between the spatial distribution of land-cover type values and the spatial distribution of NPP values. Combined with the Pearson correlation coefficient, it can be observed that land-cover types with smaller values, such as cultivated land, forest, and grassland, have larger NPP values. Land-cover types with larger values, such as water bodies, artificial surfaces, and bare ground, have smaller NPP values.

As shown in Figure 9, different land-cover types had different effects on the value of NPP from 2000 to 2020, with the mean values of NPP for different land-cover types in descending order being forest > cultivated land > wetland > grassland > artificial surfaces > shrubland > water bodies > bare land. From 2000 to 2020, the mean values of NPP for different land-cover types showed an increasing trend.

Table 5. Spatial correlation analysis of NPP and land-cover.

Year	Pearson Correlation Coefficient	<i>p</i>	Sig
2000	−0.75	<i>p</i> < 0.05	0.000
2010	−0.77	<i>p</i> < 0.05	0.000
2020	−0.80	<i>p</i> < 0.05	0.000

**Figure 9.** Impact of land-cover on NPP from 2000 to 2020.

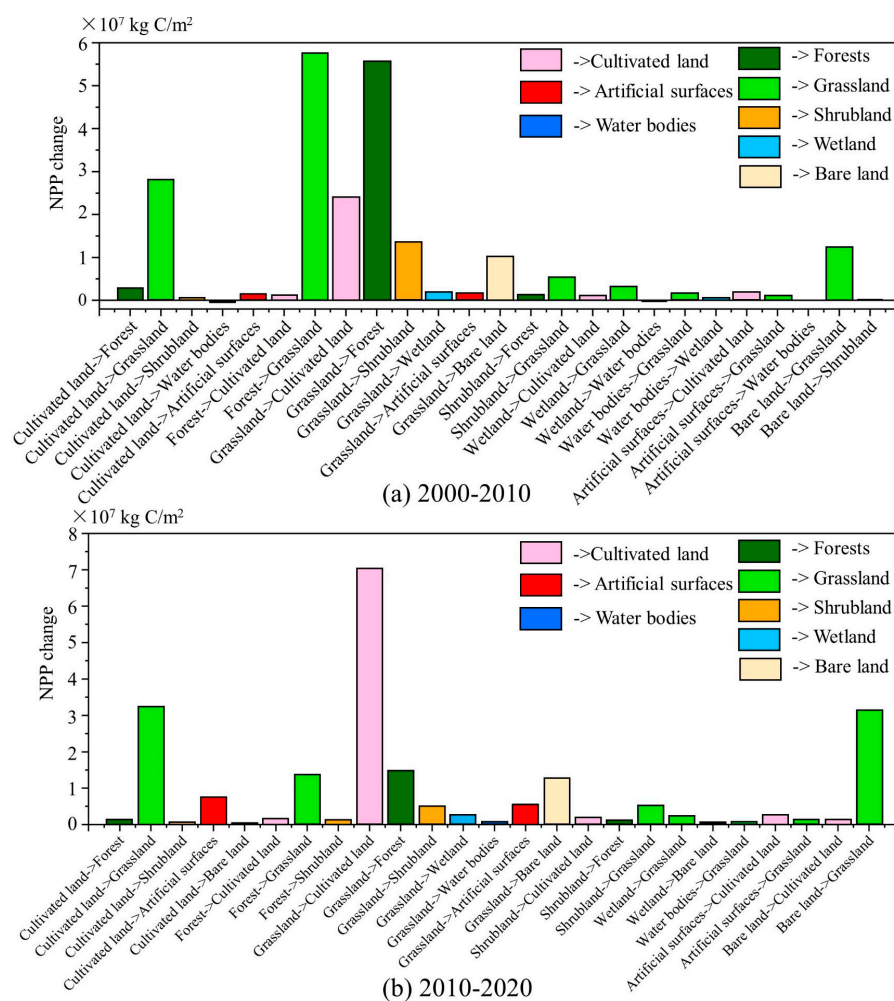
3.4. Impact Analysis of Land-Cover Change on NPP Change

The changes in total NPP for land-cover change from 2000 to 2020 are shown in Table 6. The total NPP change is a better reflection of the increase or decrease in NPP due to land-cover change than the average NPP change. The NPP values in the land-cover-unchanged areas of Inner Mongolia from 2000 to 2020 all showed an increasing trend. As shown in Figure 10, between 2000 and 2010, the main cause of the decrease in NPP was the conversion of land-cover types to water bodies, where the conversion of cultivated land to water bodies led to a decrease in NPP of 534,539 kg C/m², the conversion of wetlands to water bodies led to a decrease in NPP of 292,667 kg C/m², and the conversion of artificial surfaces to water bodies led to a decrease in NPP of 32,119 kg C/m². Excluding areas with a constant land-cover type, the main causes of the increase in NPP between 2000 and 2020 were the conversion of other land-cover types to cultivated land, forest, and grassland. Between 2000 and 2010, the change from other land-cover types to cultivated land resulted in an increase in NPP of 28,785,156 kg C/m², and the conversion of grassland to cultivated land accounted for 83.03%. Other land-cover types converted to forest caused an increase in NPP of 60,048,533 kg C/m², and the conversion of grassland to forest accounted for 92.42%. The transformation of other land-cover types to grassland resulted in an increase in NPP distribution of 108,968,184 kg C/m²; the conversion of forest to grassland accounted for 52.56%. The increase in NPP due to the conversion of grassland to cultivated land accounted for 89.52% of the increase in NPP due to the conversion of other land-cover types to cultivated land between 2010 and 2020. Grassland conversion to forest contributed to 85.89% of the increase in NPP due to the conversion of other land-cover types to forest.

Table 6. Change values of total NPP for land-cover change in Inner Mongolia, 2000–2020.

kg C/m ²	Cultivated Land	Forest	Grassland	Shrubland	Wetland	Water Bodies	Artificial Surfaces	Bare Land	Total 2010
Cultivated land	406,114,329	1,169,605	23,914,517	143,274	964,289	509,333	1,911,831	172,307	434,899,485
Forest	2,878,620	467,431,458	55,495,608	979,299	235,248	403,390	49,211	7157	527,479,991
Grassland	28,058,357	57,275,312	1,302,144,881	5,370,034	3,128,824	1,620,546	1,175,172	12,339,939	1,411,113,065
Shrubland	365,988	387,244	13,613,528	3,468,966	86,489	54,602	17,502	220,171	18,214,490
Wetland	104,954	59,769	1,646,985	5964	9,550,637	531,213	16,452	25,024	11,940,998
Water bodies	−534,539	110,800	280,942	9063	−292,667	1,840,279	−32,119	11,426	1,393,185
Artificial surfaces	1,394,838	14,315	1,565,948	16,298	4974	6742	15,694,092	38,496	18,735,703
Bare land	148,686	6273	10,125,997	85,771	221,618	132,021	17,878	36,197,546	46,935,790
Total 2010	438,531,233	526,454,776	1,408,788,406	10,078,669	13,899,412	5,098,126	18,850,019	49,012,066	2,470,712,707

kg C/m ²	Cultivated Land	Forest	Grassland	Shrubland	Wetland	Water Bodies	Artificial Surfaces	Bare Land	Total 2020
Cultivated land	318,640,138	1,464,411	70,352,941	1,858,616	374,149	344,429	2,744,625	1,448,455	397,227,764
Forest	1,207,830	196,967,659	14,434,310	1,083,187	11,653	53,311	10,230	4195	213,772,375
Grassland	32,309,689	13,627,000	1,041,160,803	5,153,926	2,350,488	701,075	1,064,254	31,281,484	1,127,648,719
Shrubland	388,134	1,167,602	4,830,593	14,919,439	8505	9066	57,268	112,354	21,492,961
Wetland	114,366	65,991	2,461,719	25,332	4,617,929	273,750	2418	106,043	7,667,548
Water bodies	73,701	28,032	522,954	80	222,464	1,435,713	13,398	107,950	2,404,292
Artificial surfaces	7,448,703	122,335	5,605,565	271,748	48,506	17,615	12,581,532	294,047	26,390,051
Bare land	366,421	27,949	12,459,579	285,775	487,245	144,129	22,242	43,531,236	57,324,576
Total 2020	360,548,982	213,470,979	1,151,828,464	23,598,103	8,120,939	2,979,088	16,495,967	76,885,764	1,853,928,286

**Figure 10.** Impact of land-cover changes on NPP changes from 2000 to 2020.

4. Discussion

4.1. Analysis of This Study

Agreeing with the results of Li et al. (2018) [47], the main change that occurred in Inner Mongolia from 2000 to 2020 was the conversion of grassland, which was mainly due to the increase in sown pastures. The conversion of forest, cultivated land, and shrubland to grassland was the main reason for the decrease in carbon storage in Inner Mongolia's vegetation between 2000 and 2010. This was followed by the conversion of cultivated land, forest, grassland, and shrubland to bare land. During 2010–2020, the conversion of cultivated land, forest, and shrubland to grassland and the conversion of cultivated land, grassland, forest, and shrubland to artificial surfaces were the main reasons for the reduction in vegetation carbon storage in Inner Mongolia [47,48]. Economic and population growth in Inner Mongolia are the main influences leading to increased urbanisation [49,50]. The increase in forest and shrubland due to the implementation and enactment of relevant ecological protection policies is the main reason to maintain positive vegetation carbon stocks in Inner Mongolia.

The correlation between the spatial distribution of land-cover types and the spatial distribution of NPP in this study illustrates the relatively high NPP of forests, cultivated land, wetland, and grassland, which is consistent with the findings of [20,51]. This is due to the fact that vegetation is one of the most important components of terrestrial ecosystems and plays an important role in global climate change processes and carbon balance, with the ability to indicate changes in the atmospheric, water, and soil components of the natural environment [52]. The conversion of cultivated land, wetland, and artificial surfaces to water bodies was the main reason for the decrease in NPP. Other land-cover types being converted to cultivated land, forest, and grassland are the main reasons for the increase in NPP. In addition, the mean values of NPP for each land-cover type exhibited an increasing trend from 2000 to 2020, which is related to the ecological protection policy in Inner Mongolia.

4.2. Recommendations of This Study

Combined with the above findings, the following measures can improve the carbon sequestration capacity of the vegetation in Inner Mongolia to a certain extent. Specifically, the continued implementation of desert management measures and instruments [49], such as the forest and grass ecological protection construction promoted by Alxa League, has contributed to the continuous increase in grassland area. Forests, shrublands, and other crops with high vegetation carbon storage density can be reasonably planted in Inner Mongolia, and existing crops with high vegetation carbon storage density can be protected [12,53]. On this basis, land-cover types with low vegetation carbon storage density, such as wetlands, croplands, and grasslands, should also be protected and managed accordingly [54].

The next most important recommendation for Inner Mongolia is to optimize thermal power and industrial restructuring strategies to respond positively to the slowdown and cessation of the construction of high-energy-consuming and high-polluting projects [55]. We recommend accelerating the implementation and popularisation of clean and renewable energy sources, reducing the total energy consumption in all sectors as far as possible, developing green and low-carbon industry codes, and strengthening the implementation in all sectors and localities [56–58].

4.3. Limitations of This Study

In this study, the NPP data were MODIS MOD17A3H 500 m resolution data. The GlobeLand30 data were 30 m resolution data. The difference in spatial resolution between the two datasets was large, and although the results obtained are generally consistent with other studies, there was insufficient spatial refinement for the NPP data and insufficient temporal scale for the GlobeLand30 data. Therefore, further studies need to further investigate relevant data with higher spatial resolutions and higher temporal resolutions to obtain finer results.

In addition, besides the effects of land-cover change, some studies have shown that the effects of natural factors such as climatic factors also respond to NPP [59,60]. However, this study did not consider the influence of climatic factors on NPP. Therefore, further studies need to consider the extent and proportion of the effect of land-cover change on NPP, as well as the extent and proportion of the effect of climatic factors on NPP [51].

5. Conclusions

This paper made use of GlobeLand30 land-cover data to analyse changes in vegetation carbon storage in Inner Mongolia as influenced by land-cover change from 2000 to 2020 and the relationship between land-cover change and NPP. Specific conclusions are presented below.

- (1) During the period of 2000–2020, the conversion of land cover in Inner Mongolia mainly occurred regarding other land-cover types into grassland, of which the conversion of bare land to grassland was 20,634.87 km² from 2000 to 2010. A more pronounced conversion of grassland to shrubland also occurred from 2010 to 2020.
- (2) The high values of NPP were mainly concentrated in the northeastern regions of Inner Mongolia, e.g., Hulunbeier City, Xinggan League, and the border of Chifeng City and Xilingrad League, while the low values were mainly distributed in the southwestern regions of Inner Mongolia, e.g., Alxa League, Bayannur City, Wuhai City, and Ordos City.
- (3) The changes in total carbon storage in vegetation affected by land-cover change from 2000 to 2010 and 2010 to 2020 were 10,736,986.11 t and 3,894,272.41 t, respectively. Of these, the conversion of cultivated land, forest, and shrubland to grassland and the expansion of artificial surfaces were responsible for the decrease in vegetation carbon storage.
- (4) The spatial distribution of land-cover types was significantly correlated with the spatial distribution of NPP, and the mean values of NPP for land cover from 2000 to 2020 were in the following order: forest > cultivated land > wetland > grassland > artificial surfaces > shrubland > water bodies > bare land.
- (5) From 2000 to 2020, NPP in areas of Inner Mongolia where land cover did not change all exhibited an increasing trend. The change from land-cover types to water bodies was the main cause of the decrease in NPP. Without including areas with unchanged land-cover types, the main reason for the increase in NPP between 2000 and 2020 was due to other land-cover types converting to cultivated land, forests, and grassland.
- (6) Improving the carbon sequestration capacity of Inner Mongolia's vegetation can achieve the double-carbon target as soon as possible and protect Inner Mongolia's ecological environment. For example, the implementation of appropriate conservation policies (e.g., forest and grass ecological protection construction), the rational planting of high vegetation carbon storage plants, the protection of land-cover types with low vegetation carbon storage, etc.

This study provides a more comprehensive analysis of vegetation carbon storage influenced by land-cover change and the potential relationship between land-cover change and NPP in Inner Mongolia, which can provide some referential basis for local governments to coordinate land spatial planning.

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