land

MDPI

Article

Tracking Land-use Trajectory and Other Potential Drivers to Uncover the Dynamics of Carbon Stocks of Terrestrial Ecosystem in the Songnen Plain

Lei Chang, Han Luo, Huijia Liu, Wenxin Xu, Lixin Zhang and Yuefen Li *

College of Earth Sciences, Jilin University, Changchun 130061, China; changlei21@mails.jlu.edu.cn (L.C.); luohan23@mails.jlu.edu.cn (H.L.); liuhuijia@jlu.edu.cn (H.L.); wxxu23@mails.jlu.edu.cn (W.X.); lixinz23@mails.jlu.edu.cn (L.Z.)

* Correspondence: yfli@jlu.edu.cn; Tel.: +86-137-5600-9975

Abstract: Land-use change is an important factor affecting terrestrial carbon balance, and it is crucial to explore the response of terrestrial carbon stocks to land-use change, especially in the Songnen Plain, which faces a fierce conflict between the rapid growth of production activities and ecosystem degradation. In this study, we measured soil organic carbon and vegetation biocarbon stocks in the Songnen Plain based on IPCC-recommended methodologies, and explored the characteristics of carbon stock changes in land-use trajectories, land-use drivers, and specific land-use change scenarios (cropland cultivation, returning cropland to forests, the expansion of land for construction, deforestation, greening, and land degradation). The results showed that soil organic carbon stock in the Songnen Plain decreased by 1.63×10^5 t, and vegetation biocarbon stock increased by 2.10×10^7 t from 2005 to 2020. Human factors and natural factors jointly contributed to the land-use change, but the extent of the role of human factors was greater than that of natural factors. The increase in land-use trajectory led to the decrease in soil organic carbon stock and the increase in vegetation biocarbon stock. There was no difference in the effects of human-induced and natural-induced land-use changes on vegetation biocarbon stocks, but the effects on soil organic carbon stocks were diametrically opposite, increasing by 43.27 t/km^2 and decreasing by 182.02 t/km^2, respectively. The reclamation of arable land, returning cropland to forests, and greening led to a net increase in terrestrial carbon stocks (+813,291.84 t), whereas land degradation, deforestation, and land-use expansion led to a decrease in terrestrial carbon stocks (−460,710.2 t). The results of this study can provide a reference for the adjustment of land-use structure and the increase in terrestrial carbon stock in the Songnen Plain.

Keywords: land cover change; conversion pattern; soil organic carbon; vegetation biocarbon

Citation: Chang, L.; Luo, H.; Liu, H.; Xu, W.; Zhang, L.; Li, Y. Tracking Land-use Trajectory and Other Potential Drivers to Uncover the Dynamics of Carbon Stocks of Terrestrial Ecosystem in the Songnen Plain. *Land* **2024**, *13*, 618. https://doi.org/10.3390/land13050618

Academic Editor: Nir Krakauer

Received: 15 March 2024
Revised: 29 April 2024
Accepted: 1 May 2024
Published: 3 May 2024

1. Introduction

In recent decades, the massive burning of fossil fuels has exacerbated the increase in atmospheric CO_2 concentration, which not only increases surface temperature and triggers global warming, but also hinders the normal growth of crops and gradually poses a threat to human survival [1,2]. As the world's largest carbon reservoir, terrestrial ecosystems are an important part of the global carbon cycle, absorbing about 31% of anthropogenic CO_2 emissions annually [3], which has a significant inhibitory effect on controlling atmospheric CO_2 concentrations [4]. However, land-use change affects the carbon stock of terrestrial ecosystems by altering the soil structure and surface vegetation succession [5,6], and causes carbon emissions to a certain extent. It can be seen that land-use change is not only a hotspot of concern for environmental change, but also a key point for studying carbon stock changes in terrestrial ecosystems [7]. It has been pointed out that the terrestrial carbon emissions due to land-use change were $9 \pm 7 \times 10^7$ tC globally in 2020 [8], and this carbon emission is considered to be the second largest anthropogenic source of CO_2

into the atmosphere after the emission from fossil fuel combustion [9]. Therefore, the accurate quantification of the impacts of land-use change on terrestrial carbon stocks is key to achieving carbon neutrality goals and an effective way of mitigating global climate change [10,11].

Terrestrial ecosystems are mainly involved in the carbon balance process through soil organic carbon pools and vegetation biocarbon pools, both of which have relatively stable carbon stocks and play a significant role in comprehensive carbon sequestration and offsetting carbon emissions, and are important sources of carbon sinks [12–16]. It was found that the average carbon stock of terrestrial ecosystems in China was $9.92 \pm 0.87 \times 10^9$ tC, of which soil carbon stock was $8.46 \pm 0.81 \times 10^9$ tC and vegetation biocarbon stock was $1.46 \pm 0.32 \times 10^9$ tC [17], and soil carbon stock was about 4.29–8.15 times that of vegetation biocarbon stock. However, terrestrial carbon stocks are not spatially homogeneously distributed. For example, terrestrial and soil carbon stocks are significantly higher in northeastern China and the Tibetan Plateau and vegetation biocarbon density is higher in eastern China than in western China [18]. Land-use change is the main reason for this phenomenon [19–21]. On the one hand, differences in land-use patterns directly affect changes in terrestrial carbon stocks, with increases in carbon emissions caused by urban sprawl areas leading to reductions in terrestrial carbon stocks, while on the contrary, the protection of forests and wetlands contributes to increases in terrestrial carbon stocks [22,23]. On the other hand, the interconversion of land-use modes back affects the terrestrial carbon balance, which in turn affects the change in terrestrial carbon stock [7,24–26]. For example, in agricultural production areas, grassland reclamation creates a large amount of carbon emissions for cropland, leading to a decrease in terrestrial carbon stocks [27]. On the contrary, returning farmland to forests effectively restores surface vegetation communities and improves the carbon sequestration capacity and the potential of terrestrial ecosystems [28,29]. In addition, it is often difficult to restore terrestrial carbon stocks to their initial levels when land is converted from non-construction land to construction land [30].

The above studies show that land-use change leads to significant spatial heterogeneity in terrestrial carbon stocks, and it is necessary to study the response of terrestrial carbon stocks to land-use change in specific regions. Meanwhile, land-use change is usually categorized into two types: natural-induced and human-induced driven [31]. Although current studies have explored the response of their carbon stocks to land-use change at regional, national, and global scales [32–35], they have not differentiated the difference in the response of terrestrial carbon stocks to naturally induced and human-induced land-use change. Therefore, distinguishing and clarifying the magnitude of this difference is of great theoretical importance. In addition, we hypothesize that there is also a significant difference in the impact of land-use change processes (land-use trajectories) on terrestrial carbon stocks.

The Songnen Plain is an important grain production base in China, which is crucial for national and regional food security [36]. At the same time, the Songnen Plain is adjacent to the northeast China Protective Forest Region and possesses a large forest reserve, which plays an important ecological role in absorbing atmospheric CO_2 and is an important component of terrestrial carbon stocks [37,38]. In recent years, many irrational production activities have taken place in the Songnen Plain in order to meet the needs of social development and national food production requirements. This has resulted in frequent land-use change activities, leading to the continuous deterioration of the regional ecological environment. Eventually, it affects the change in terrestrial carbon stocks. Therefore, it is of great practical significance for the Songnen Plain, where the relationship between production activities and ecosystems is becoming increasingly contradictory, to investigate the impact of land-use change on terrestrial carbon stocks in the Songnen Plain.

Therefore, this paper selected the Songnen Plain in China as the study area to investigate the relationship between land-use and carbon stock. The IPCC-based terrestrial carbon stock measurement method was used to calculate the soil organic carbon stock and vegetation biocarbon stock to analyze the differences in the impacts of naturally induced and human-induced land-use changes on carbon stock, and to verify whether land-use trajectories affect carbon stock changes. Finally, this paper quantifies carbon stock changes in the Songnen Plain under six land-use scenarios: returning farmland to the forest, reclaiming cropland, deforestation, land degradation, the expansion of construction land, and greening. This work is of great practical significance for optimizing the land-use structure, alleviating ecological pressure, and increasing terrestrial carbon stocks.

2. Materials and Methods

2.1. Study Area

The Songnen Plain is located in the central region of northeastern China, mainly situated in the Heilongjiang and Jilin Provinces. The overall terrain is low and open, and it is a place where swampy wetlands develop [39]. The Songnen Plain selected in this study is located between N 43°59′21′′–N 48°55′34′′ and E 121°38′09′′–E 128°32′44′′, with a total area of 1.8×10^5 km^2 (Figure 1). The region has a temperate continental monsoon climate with very pronounced changes in the seasons. The average annual temperature is about 4 °C, and the annual rainfall is about 270–500 mm, with the highest rainfall from June to mid-September, accounting for about 65% of the annual precipitation. The uneven distribution of rainfall between regions and the large variations between months and years results in drought being the main climatic feature of the region. Therefore, the Songnen Plain, as an important commodity grain base in China, is more sensitive to climate change [40].

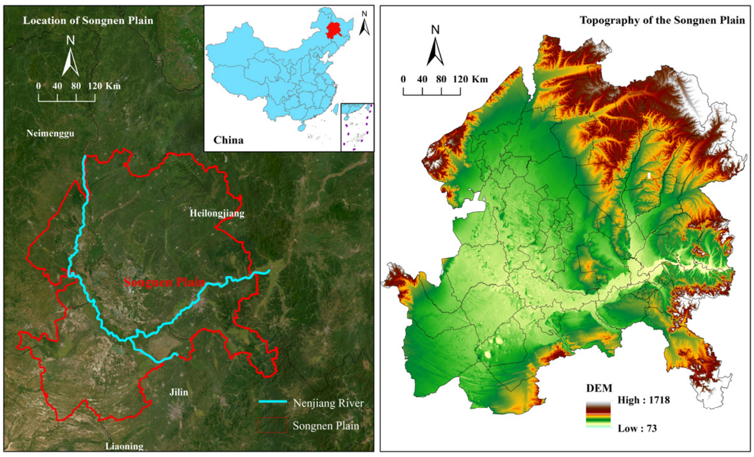

Figure 1. Location of the Songnen Plain.

2.2. Data Sources

Land-use cover change data (2005, 2010, 2015, and 2020) were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/ (accessed on 25 March 2023). Soil data were obtained from the National Science and Technology Resources Shared Service Platform-National Earth System Science Data Center-Soil Subcenter (http://soil.geodata.cn (accessed on 18 February 2023). Soil organic carbon data were obtained from the Global Soil Organic Carbon Map of the Food and Agriculture Organization of the United Nations Soil Database (https://www.fao.org/home/en/ (accessed on 18 February 2023). Net primary productivity (NPP) data (2005, 2010, 2015 and 2020) were obtained from the MODIS satellite-based MOD17A3HGF product released by the National Aeronautics and Space Administration (NASA) (https://lpdaac.usgs.gov/products/mod17a3hgfv061/ (accessed on 20 March 2023).

2.3. Research Methods

2.3.1. Classification of Land-use Types

Based on the land-use cover data obtained, this study divides land-use types into eight main categories: cropland, woodland, grassland, wetland, water, construction land, underutilized land, and saline-alkali land (Table 1). It should be noted that, limited to the soil organic carbon and NPP data obtained, this study does not include watersheds in the scope of the study.

Table 1. Land-use type.

First-Type	Sub-Type
1. Cropland	paddy fields drylands
2. Woodland	forested land shrubland open woodland other woodland
3. Grassland	high-cover grassland medium-cover grassland low-cover grassland
4. Wetland	——
5. Construction land	urban land rural settlements other construction land
6. Underutilized land	sandy land bare land bare rocky gravel land
7. Saline-alkali land	——
8. Water	——

2.3.2. Land-use Trajectory

Trajectory analysis is an analytical method used to describe the dynamic change in land-use over time. In this study, ArcGIS 10.3 software is used to obtain land-use trajectory data by raster algebra calculation on land-use raster data, and the specific formulas are as follows:

$$Y_i = C_{1i} \times 10^{n-1} + C_{2i} \times 10^{n-2} + \ldots\ldots + C_{ni} \times 10^{n-n}$$

where Y_i represents the land-use trajectory of the ith plot, C_{1i}, C_{2i}, and C_{ni} represent the land-use types of the ith plot at different times, and 1, 2, and n represent the land-use types (cropland, woodland, grassland, wetland, construction land, underutilized land, saline-alkali land, and water). For example, "2136" indicates that land-use change has gone through the process of "woodland—cropland—grassland—underutilized land".

Based on the number of changes in land-use type during the study period, we defined land-use trajectories as zero-step, one-step, two-step, and three-step. Where zero-step indicates no change in the land-use type; one-step indicates only one change in land-use type, for example, "3111", "1222"; two-step indicates two changes in land-use type, for example. "1311", "2311"; three-step indicates three changes in land-use type, for example, "4313", "2341".

In addition, based on the results of land trajectory analysis, this paper categorizes the transformation between lands into two types: human-induced and natural-induced (Table 2). The human-induced type indicates that the land is directly interfered with by human factors, and the natural land-use type is transformed into the human-induced land-use type (cropland, construction land, etc.); whereas the naturally induced type indicates that the land is transformed by the climatic factors and the indirect intervention of human beings, which is usually manifested in the salinization of the land, the degradation of the vegetation cover, etc., and the naturally induced type usually transforms more slowly.

Table 2. Type of land-use change.

Human-Induced Types	Naturally Induced Types
Cropland → Woodland, Construction land, Grassland	Cropland → Wetland, Water, Underutilized land, Saline-alkali land
Woodland → Cropland, Construction land	Woodland → Grassland, Wetland, Water, Underutilized land, Saline-alkali land
Grassland → Cropland, Woodland, Construction land	Grassland → Wetland, Water, Underutilized land, Saline-alkali land
Water → Cropland, Woodland, Construction land	Water → Grassland, Underutilized land, Saline-alkali land, Wetland
Wetland → Cropland, Woodland, Construction land	Wetland→ Grassland, Underutilized land, Saline-alkali land, Water
Construction land → Cropland, Woodland, Grassland, Wetland, Water, Underutilized land, Saline-alkali land	— —
Underutilized land → Cropland, Woodland, Construction land	Underutilized land → Grassland, Wetland, Water, Saline-alkali land
Saline-alkali land → Cropland, Woodland, Construction land	Saline-alkali land → Grassland, Wetland, Water, Underutilized land

2.3.3. Vegetation Biocarbon Measurement

In this study, the NPP data (with a resolution of 500 m), provided by the U.S. MODIS satellite, were used as the basis for quantifying the vegetation biocarbon stock, and are combined with the method recommended by the IPCC and the research method used by Song et al. [41,42] to calculate the vegetation biocarbon stock of The Songnen Plain from 2005 to 2020.

2.3.4. Soil Organic Carbon Measurement

In this paper, the organic carbon density of 31 soil types in the study area was calculated using the global soil organic carbon map and soil type data, and we referred to the results of previous studies [43,44]. The obtained carbon density data were superimposed with the land-use data at the corresponding time points to obtain the average organic carbon density of each soil type under different land-use cover conditions, which served as the basis for calculating the soil organic carbon stock. By synthesizing the research methods of IPCC and methods used by previous researchers [25,41,45], the soil organic carbon stock in the Songnen Plain from 2005 to 2020 was calculated. The soil organic carbon stock in watersheds was not considered in this study due to the limitation of soil organic carbon map data.

3. Results

3.1. Land-use Change

Differences in land-use types are the fundamental factors affecting soil organic carbon stocks and vegetation biocarbon stocks. Land-use types in the Songnen Plain changed dramatically from 2005 to 2020, with a total of 9787.95 km^2 of eight land-use types changing, accounting for 5.44% of the total land area in the study area (Table 3). During the 15-year period, land-use types in the Songnen Plain experienced a net increase in the areas of water, cropland, woodland, and construction land areas, which increased by a net amount of 110.71 km^2 (+2.39%), 879.50 km^2 (+0.85%), 379.72 km^2 (+1.84%), and 536.63 km^2 (+7.93%), respectively. On the contrary, the areas of grassland, wetland, underutilized land and saline-alkali land decreased by 719.04 km^2 (−4.46%), 465.92 km^2 (−24.89%), 210.03 km^2 (−1.36%) and 511.56 km^2 (−4.44%), respectively.

Table 3. Land-use transfer matrix for the Songnen Plain, 2005–2020 (unit:10^2 km^2).

		2020							
		Water	**Crop**	**Wood**	**Grass**	**Wet**	**Construction**	**Underutilized**	**Saline**
2005	Water	41.72	0.55	0.28	0.35	0.41	0.04	1.87	1.16
	Crop	1.43	1005.72	7.54	5.90	1.09	5.69	1.06	2.13
	Wood	0.36	5.17	198.34	1.29	0.14	0.27	0.38	0.19
	Grass	0.46	14.34	1.46	137.73	0.06	0.84	1.75	4.48
	Wet	0.83	0.57	0.72	0.32	12.06	0.04	4.15	0.03
	Construction	0.08	2.29	0.13	0.17	0.01	64.83	0.04	0.16
	Underutilized	1.11	6.10	0.37	2.96	0.24	0.17	141.45	1.72
	Saline-alkali	1.48	4.62	1.08	5.22	0.05	1.20	1.34	100.17

Combined with the spatial distribution (Figure 2), in 2020, cropland was the most dominant land-use type, concentrated in the northern part of the Songnen Plain, accounting for 57.74% of the total land area. Woodland, on the other hand, is concentrated in the northeastern region, and grassland and wetland are distributed in the central region. The southern part of the Songnen Plain is the main gathering area of saline-alkali land, and also the main area of land-use change. Land-use changes in this region mainly show three characteristics: cropland reclamation, afforestation, and construction land expansion. The main sources of cropland reclamation are grassland and underutilized land, with an area of 1433.68 km^2 and 609.52 km^2, respectively. While afforestation is caused by the policy of "returning cropland to forests", which has transformed about 754.10 km^2 of cropland into woodland, cropland and saline-alkali land are the sources of land for construction land expansion, with an area of 569.18 km^2 and 119.80 km^2, respectively. Overall, the land-use characteristics of the Songnen Plain are characterized by a simple and stable structure in the north, and a complex and active change in structure in the south.

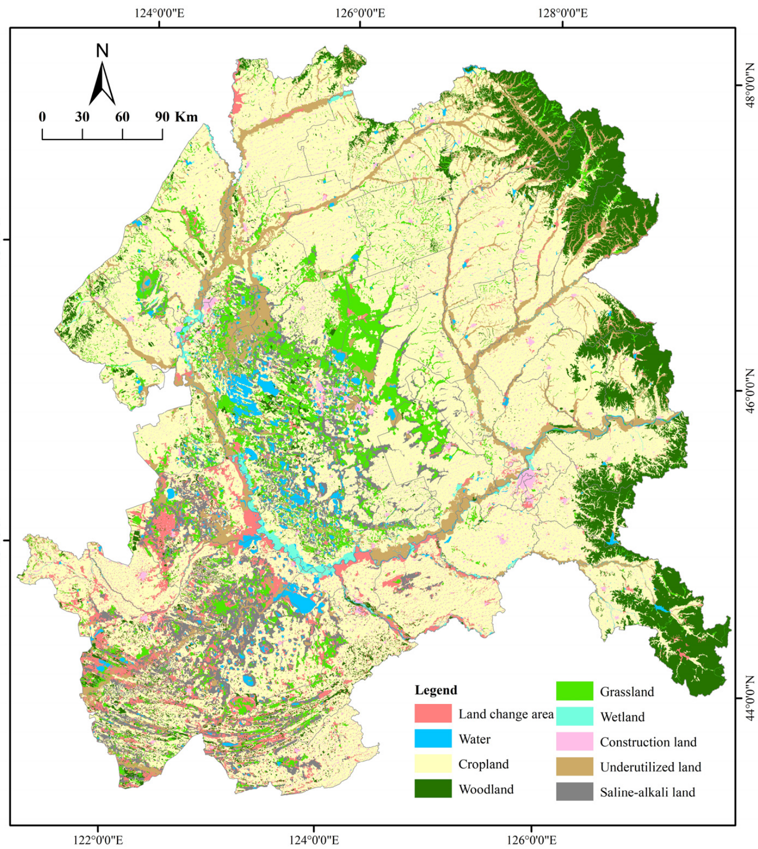

Figure 2. Land-use change in the Songnen Plain, 2005–2020.

3.2. Carbon Stock Changes

From 2005 to 2020, terrestrial carbon stocks in the Songnen Plain showed an overall increase, with a net increase of 2.09×10^7 t (Figure 3). Among them, vegetation biocarbon is the main contributor to the increase in terrestrial carbon stock, with a contribution value of 2.10×10^7 t. On the contrary, soil organic carbon has an inverse effect on the increase in terrestrial carbon stock, with a decrease of 1.63×10^5 t. However, in combination with the base of carbon stock, in 2020, soil organic carbon stock was still the main component of terrestrial carbon stock in the Songnen Plain, with a carbon density much higher than that of vegetation biocarbon, accounting for 78.08% (8.02×10^8 t) of total carbon stock, while the vegetation biocarbon stock was only 2.25×10^8 t. The results show that, although the base of vegetation biocarbon stock is small, the change is more active, and the net increase in carbon stock is much larger than that of soil organic carbon.

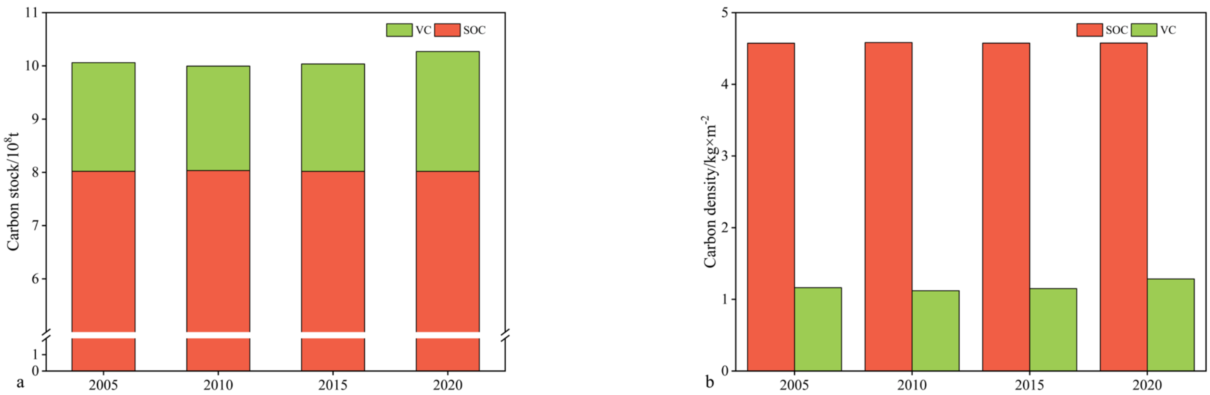

Figure 3. Changes in carbon stocks in the Songnen Plain, 2005–2020. (**a**) changes in soil organic carbon and vegetation biocarbon stocks; (**b**) changes in soil organic carbon and vegetation biocarbon density.

In terms of spatial distribution, during the study period, the high-value areas of terrestrial carbon stocks were mainly concentrated in the northern part of the Songnen Plain, while the low-value areas were mainly concentrated in the vicinity of the Nenjiang River Basin (Figure 4). Overall, the terrestrial carbon stock shows a gradual decrease from north to south. The range of low-value areas of the terrestrial carbon stock shows an increasing trend in the period 2005–2010, indicating that the total amount of the terrestrial carbon stock decreased in this period. On the contrary, the range of high terrestrial carbon stock areas expands during the period 2010–2020, especially in the northern part of the Songnen Plain, where the expansion trend is particularly significant. This is consistent with the results of increasing the terrestrial carbon stocks, shown in Figure 3.

There was significant spatial variability in terrestrial carbon stock changes in the Songnen Plain from 2005 to 2020, with the increase in carbon stocks concentrated in the northeastern and central regions (zones I, III and IV) and the decrease in the southeastern regions (zones II and V) (Figure 5). The change in vegetation biocarbon stock was much larger than that of soil organic carbon stock, and zone V was the only zone with a decrease in vegetation biocarbon stock, with a decrease of 46.14 t, while zone I was the zone with the largest increase in vegetation biocarbon stock, with an increase of 114.06 t. The increase in soil organic carbon stock occurred only in zones III and V, with an increase of 5.42 t and 2.82 t, respectively. Area III is also the only area where both soil organic carbon and vegetation biocarbon stocks increased. Overall, the spatial change in carbon stock in the Songnen Plain is characterized by the "increase in the north and decrease in the south", with the increase in vegetation biocarbon stock as the main feature.

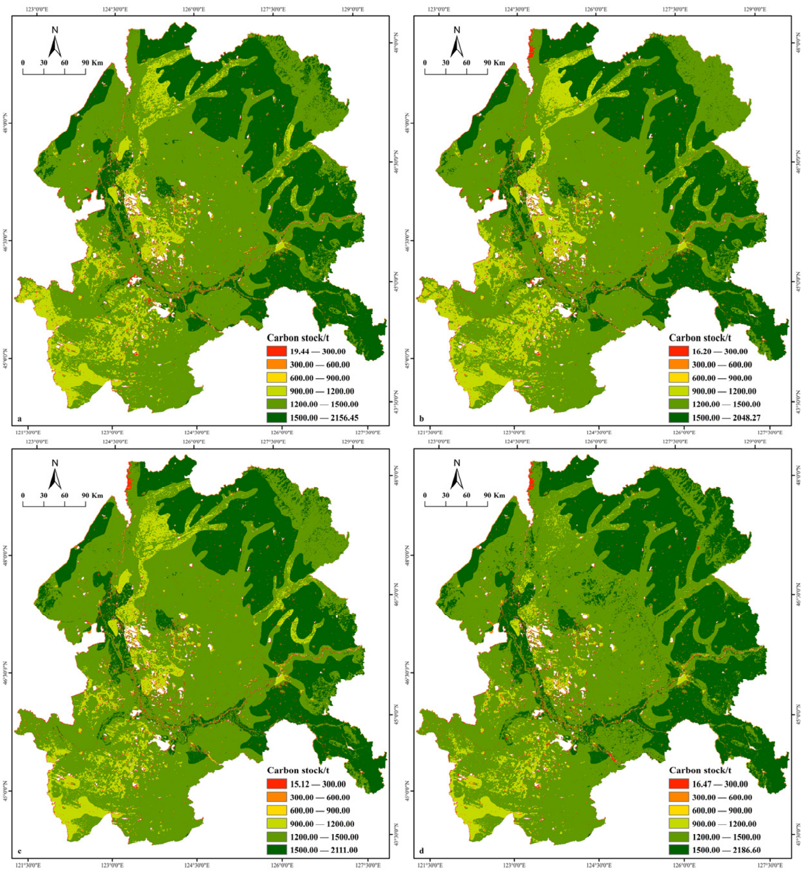

Figure 4. Spatial distribution of the terrestrial carbon stocks in the Songnen Plain. (**a**–**d**) represent the terrestrial carbon stocks in 2005, 2010, 2015, and 2020.

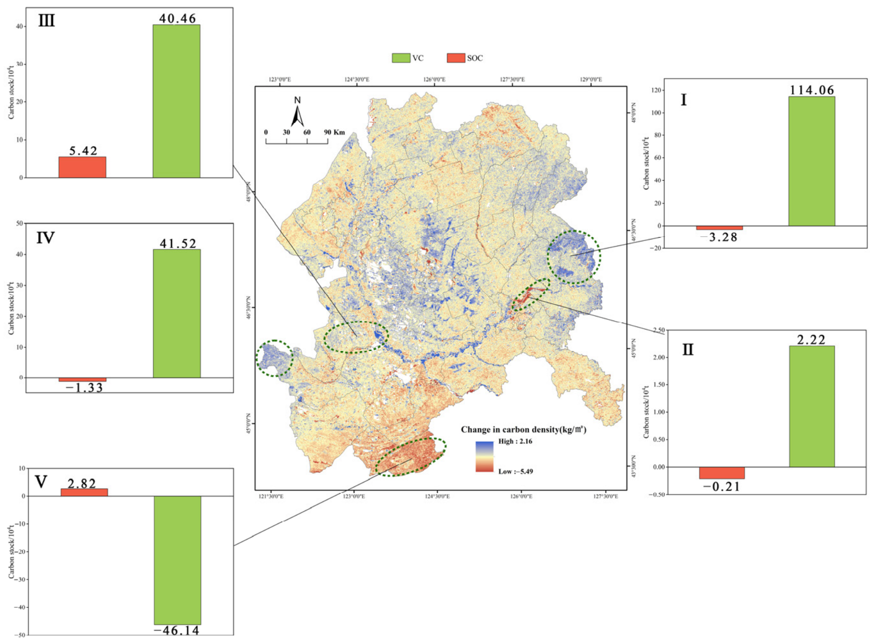

Figure 5. Spatial changes in carbon stocks, 2005–2020.

3.3. Land-use Trajectory Analysis

In the past 15 years, the land with no change in utilization accounted for 94.38% of the total area of the Songnen Plain, mainly concentrated in the northern part of the Songnen Plain (Figure 6a). The land with one-step, two-step, and three-step utilization changes accounted for 5.28%, 0.33%, and 0.01% of the total area, respectively (Table 4), concentrated in the southern part of the Songnen Plain. Compared to 2005, there existed 97.42% of cropland, 96.10% of woodland, 95.63% of construction land, 91.42% of underutilized land, 89.63% of water, 86.91% of saline-alkali land, 85.25% of grassland, and 64.38% of wetland for the occurrence of the change in utilization. Among them, the probability of a one-step change in wetland is much higher than that of other land, while the probability of two-step and three-step changes in grassland is the highest, which indicates that the stability of cropland, woodland, and construction land is higher, while the stability of wetland and grassland is poorer.

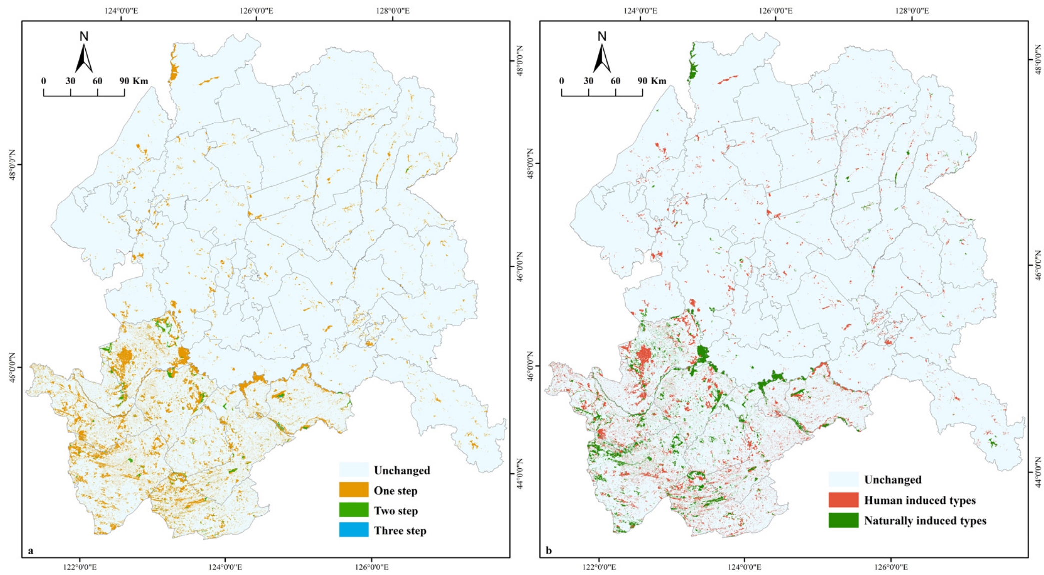

Figure 6. Land-use trajectory in the Songnen Plain, 2005–2020. (**a**) spatial distribution of land-use trajectories; (**b**) spatial distribution of the different land-use change factors.

Table 4. Percentage of the trajectory steps for different land-use types (%).

Step	Crop	Wood	Grass	Wet	Construction	Underutilized	Saline	Water	Total
0	97.42	96.10	85.25	64.38	95.63	91.42	86.91	89.63	94.38
1	2.40	3.74	13.75	34.70	4.20	7.82	12.67	9.66	5.28
2	0.18	0.15	0.96	0.91	0.17	0.76	0.41	0.71	0.33
3	0.00	0.01	0.04	0.01	0.00	0.00	0.01	0.00	0.01

One-step changes mainly include "3111" (10.55%, grassland reclaimed as cropland), "1333" (5.83%, cropland converted to grassland), "1222" (4.75%, cropland converted to woodland), "3777" (4.63%, grassland degraded to saline-alkali land), and "4666" (4.29%, degradation of wetland to underutilized land). The two-step changes include "1611" (11.96%, cropland converted to underutilized land and then converted to cropland), "1311 (6.83%, cropland converted to grassland and then converted to cropland)", and "3211" (6.00%, grassland to woodland to cropland). The three-step changes exist between individual lands and are small in size. The above trajectories show that one-step and two-step changes mainly occurred between 2005 and 2015, and that cropland and grassland participated in most of the trajectory change processes, which is consistent with the characteristics of the Songnen Plain as a farming region.

Combined with the land-use change factors (Figure 6b, Table 5), in the area where land-use change occurred, the area of change due to human-induced effects was 5982.21 km^2, and the area of change due to natural-induced effects was 3805.74 km^2. Cropland was the land with the largest area change in the human-induced type (1912.83 km^2), and saline land was the land with the largest area change in the natural-induced type (809.15 km^2), and grassland had a larger area for both types of change. This shows that both human factors and natural factors have a significant influence on land-use change, but human factors play a slightly larger role than natural factors, which may be related to the long-term agricultural and animal husbandry production activities in the Songnen Plain.

Table 5. Different land-use change factors (unit: km^2).

Type	Crop	Wood	Grass	Wet	Construction	Underutilized	Saline	Water	Total
Human-induced	1912.83	543.73	1663.58	133.01	288.34	664.08	689.98	86.66	5982.21
Naturally induced	570.68	235.69	675.85	532.58	0.00	603.80	809.15	378.00	3805.74

3.4. Land-Use Change and Carbon Stock

As can be seen from Table 6, there is a significant difference in the influence of land-use trajectory on the change in terrestrial carbon stock, which is manifested in the negative correlation between the number of steps of land-use transformation and soil organic carbon stock. The reduction in soil organic carbon stock per unit area in the region with 3 steps of land-use transformation (−835.47 t/km^2) was 32.76 and 8.58 times of that with 1 step (−25.50 t/km^2) and 2 steps (−97.37 t/km^2) of transformation, respectively. On the contrary, the vegetation biocarbon stock was positively correlated with the number of steps of land-use pattern transformation, and the increase per unit area was 1 step (81.20 t/km^2), 2 steps (62.33 t/km^2), and 3 steps (191.52 t/km^2), respectively. The difference between human-induced and natural-induced land-use changes on carbon stock is mainly reflected in soil organic carbon, with the human-induced type contributing to the increase in soil organic carbon stock (43.27 t/km^2), while the natural-induced type leads to a large amount of soil organic carbon loss (−182.02 t/km^2).

Table 6. Carbon stock changes in different land-change patterns.

Type		Area/km^2	SOC Change/t	VC Change/t	SOC Change/t × km^{-2}	VC Change/t × km^{-2}
Trajectory	One step	9500.01	−242,244.88	771,364.13	−25.50	81.20
	Two step	593.16	−57,753.90	36,970.29	−97.37	62.33
	Three step	7.24	−6050.78	1387.05	−835.47	191.52
Contributing	Human	5982.21	258,845.75	470,743.92	43.27	78.69
	Naturally	3805.74	−692,736.23	321,908.78	−182.02	84.59

Because the area of the 3-step transformation region in the land-use trajectory is small, in terms of spatial distribution, 1-step transformation mainly occurs in the region of carbon stock increase, and 2-step transformation dominates in the region of carbon stock decrease (Figures 6 and 7). In the human-induced type, carbon stock mainly increases, while in the natural-induced type, carbon stock increases and decreases are interspersed, and the area of carbon stock decreases is large and dispersed.

Based on the results of the land-use trajectory analysis, this study classified the land-use changes in the Songnen Plain into six main types, including cropland reclamation, returning cropland to forests, land degradation, deforestation, the expansion of construction land, and greening (Table 7). Among them, except for deforestation and greening, which are naturally induced, all other land-use changes are human-induced, and these land-use activities affect the changes in the terrestrial carbon stocks by changing the soil structure and above-ground vegetation composition.

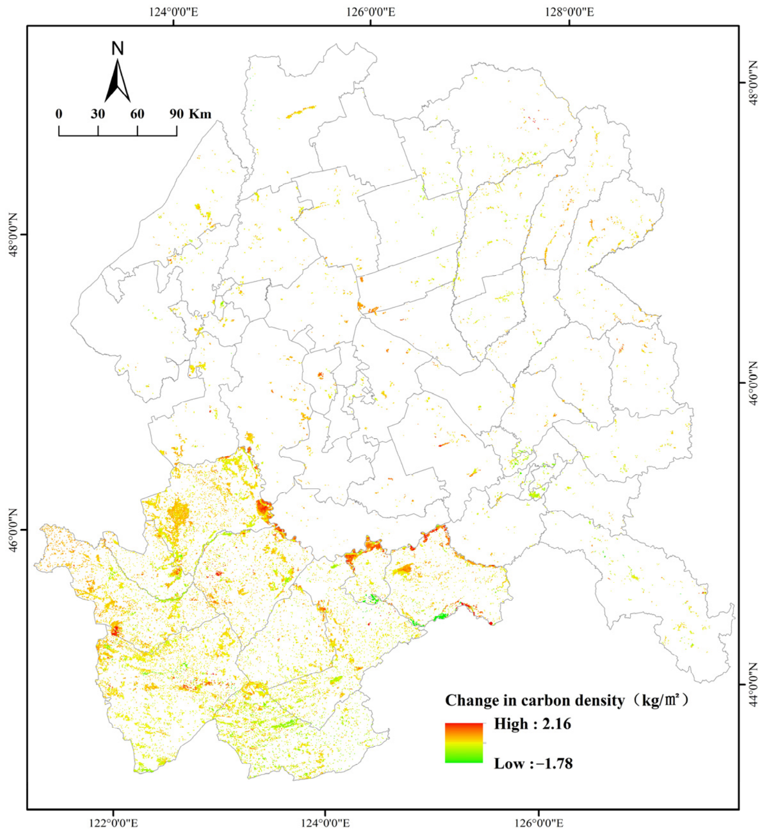

Figure 7. Changes in carbon intensity in the land-use change regions, 2005–2020.

Table 7. Type of land-use change.

Type	Land-use Before	Land-use After
Cultivation	Any land-use (except woodland)	Cropland
Grain for green	Cropland	Woodland, Grassland
Degradation	Cropland, Grassland, Wetland	Underutilized land, Saline-alkali land
Deforestation	Woodland	Any land-use
Expansion of construction	Any land-use (except woodland)	Construction land
Reforest	Underutilized land, Saline-alkali land	Grassland, Woodland

In the past 15 years, the activities of cultivating cropland, returning cropland to forests, and greening have brought a net increase in terrestrial carbon stocks in the Songnen Plain, in increments of 421,259.38 t, 261,988.7 t, and 1,300,043.76 t, respectively (Table 8). Compared to returning cropland to forest, the increase in soil organic carbon stock and vegetation biocarbon stock in reclaimed cropland was larger, but its increase per unit area was smaller than that of returning cropland to forest, which indicated that forest and grassland had a higher carbon sequestration efficiency. In terms of greening activities, the human-induced type brought about significantly greater carbon sequestration per unit area of vegetation (+155.46 t/km^2) than the naturally induced type (+109.63 t/km^2), which may be related to anthropogenic intervention and maintenance activities. On the contrary, land degradation, deforestation, and construction land expansion activities led to the reduction in terrestrial carbon stocks in the Songnen Plain, which decreased by 284,689.39 t, 83,849.45 t, and 92,171.36 t, respectively. The land degradation activities resulted in the substantial reduction in above-ground vegetation, and the rate of reduction in vegetation biocarbon stocks was much larger than that of soil organic carbon. In terms of deforestation, the human-induced type is mainly dominated by soil organic carbon stock, while the natural-induced type is dominated by the reduction in vegetation biocarbon stock, and the difference in the degree of destruction and the way of utilizing the land after destruction are the main factors for this difference.

Table 8. Carbon stock changes due to land-use.

Type		Area/km^2	SOC Change/t	VC Change/t	SOC Change/t × km^{-2}	VC Change/t × km^{-2}
Cultivation	Human-induced	2791.51	203,624.45	217,634.93	72.94	77.96
Grain for green	Human-induced	1343.65	132,719.94	129,268.76	98.78	96.21
Degradation	Naturally induced	1360.34	−73,997.69	−210,691.7	−54.40	−154.88
Deforestation	Human-induced	543.73	−44,532.51	−5635.38	−81.90	−10.36
	Naturally induced	199.54	−9378.25	−24,303.31	−47.00	−121.80
Expansion of construction	Human-induced	794.26	−41,825.73	−50,345.63	−52.66	−63.39
Reforest	Human-induced	145.38	2157.37	22,600.06	14.84	155.46
	Naturally induced	817.76	15,634.78	89,651.55	19.12	109.63

In terms of spatial distribution (Figure 8), deforestation and greening activities are concentrated in the southern part of the Songnen Plain, while land degradation, the return of cropland to forest, and the expansion of construction land are concentrated in the central part. The cultivation of cropland is the most widely distributed land-use activity, which is also in line with the actual situation of agricultural production in the Songnen Plain, and is distributed throughout the study area. On the whole, the activities causing the reduction in terrestrial carbon stocks are mostly concentrated in the southern part of the Songnen Plain, which indicates that the human interference activities in the southern part are more intense and the ecological environment is not in a good condition.

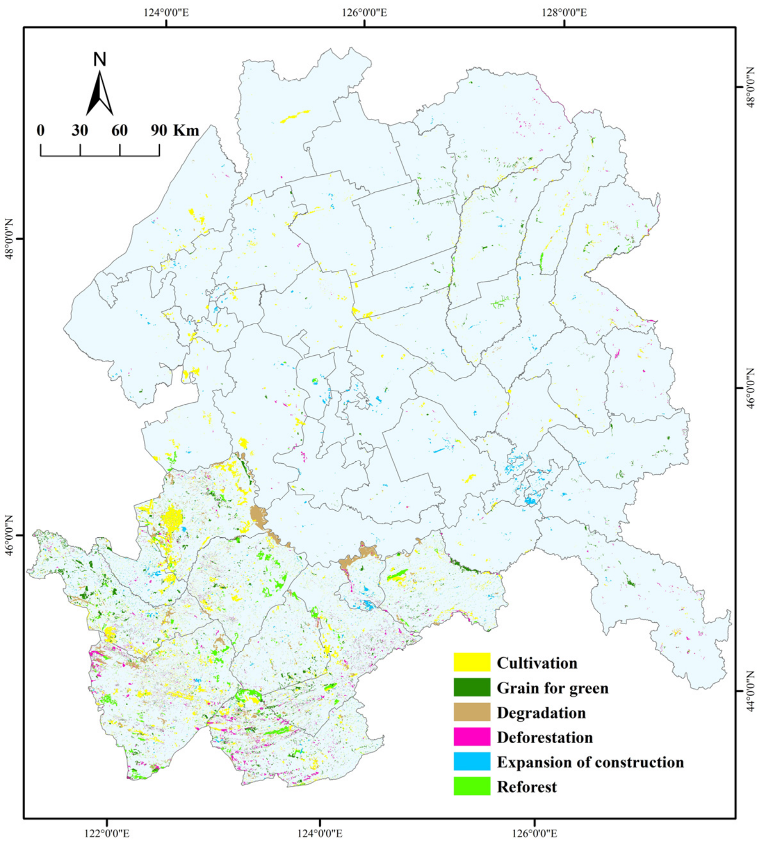

Figure 8. Spatial distribution of cultivation, grain for green, degradation, deforestation, the expansion of construction, and reforestation in the Songnen Plain, 2005–2010.

4. Discussion

4.1. Scientific Validity of Measurements

The carbon densities measured in this study were analyzed by fitting with the results of others. As can be seen from Figure 9, in the same area, the ranges of soil organic carbon density and vegetation biocarbon density measured in this paper were 1.15–7.57 kg/m^2 and 0.07–2.38 kg/m^2, respectively, while the ranges of carbon density in others' studies were 0.92–10.12 kg/m^2 and 0.01–2.40 kg/m^2, respectively. The carbon density ranges measured in this study were all within the range of the results of others' studies, and the correlation coefficients (R^2) were 0.72 (soil organic carbon) and 0.70 (vegetation biocarbon), so the fitting effect was satisfactory and the results of the carbon stock estimation were reasonable.

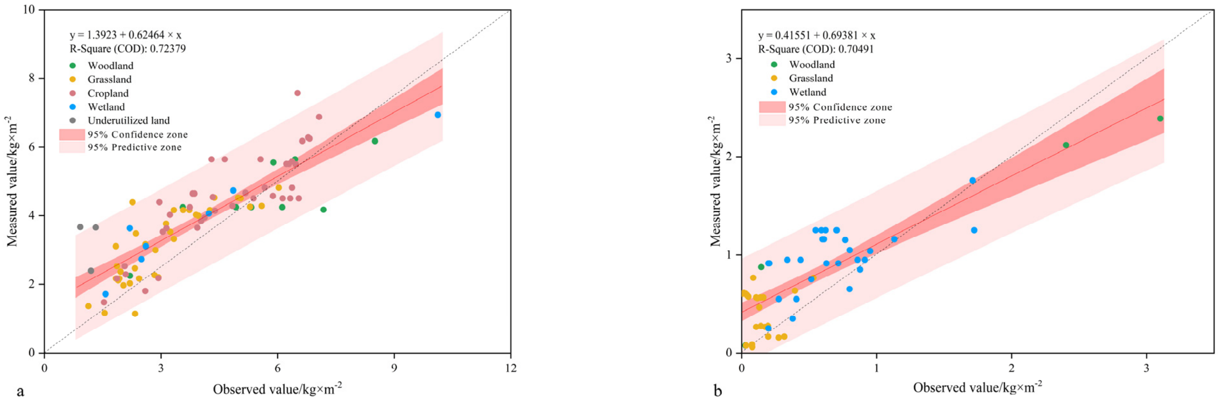

Figure 9. Comparison of the measured and observed soil organic carbon density (**a**) and vegetation biocarbon density (**b**) in the Songnen Plain.

The results of this study showed that the overall soil organic carbon stock in the Songnen Plain showed a decreasing trend in the past 15 years, with an overall decrease of 1.63 × 10^5 t, but it still accounted for more than two-thirds of the terrestrial carbon stock in the Songnen Plain, which is consistent with the results of previous studies [39,46]. The range of vegetation biocarbon stock was 1.96 × 10^8 to 2.25 × 10^8 t, with an increase of 2.08 × 10^7 t in stock, which measured similarly to the results of previous studies [17,24]. It is worth noting that the overall vegetation biocarbon density was significantly lower than the soil organic carbon density, reflecting that the soil carbon pool in the Songnen Plain possessed a higher carbon density, corroborating Li et al. (2007) and Yang et al. (2007), who measured that Northeast China possessed a higher soil organic carbon density [47,48].

4.2. Analysis of Land-use Change

Since 2005, the land-use structure of the Songnen Plain has changed dramatically, mainly characterized by the expansion of cropland, woodland, and construction land and the degradation of grassland and wetland. As an important agricultural production area in China, the Songnen Plain is an indispensable part of ensuring national food security [36]. This strategic importance has forced the implementation of a series of policies to control and ensure the stable growth of food production, and one of the effective ways is to expand the area of cropland by reclaiming it [49–51]. In this regional context, the Songnen Plain's cropland area increased by nearly 900 km^2, mainly from the transfer of grassland and underutilized land. In addition, the Songnen Plain is located at the edge of the protective forests in northeastern China, with high forest cover, which has an important function of windbreak and sand fixation. Especially after the Chinese government put forward the target of "returning cropland to forests" and the forest coverage rate, a large amount of marginal cropland in the Songnen Plain was transformed into forested grassland, which then promoted the increase in forested area and woodland cover year by year [52,53]. The expansion of construction land, on the other hand, stems from the continued urbanization process in China. The Songnen Plain is a typical primary industry-dominated area, but with the development of socio-economic and new industries, the demand for construction land continues to increase, and the urban construction land boundary continues to expand outward.

Despite the fact that returning cropland to forest also includes returning cropland to grass, the area of grassland in the Songnen Plain still showed a decreasing trend during the study period (a decrease of 719.07 km^2), which is consistent with the findings of Zhang et al. [54]. In the past 15 years, land-use changes related to the agricultural sector (reclamation of grassland into cropland), as well as the rapid development of animal husbandry, and the ensuing grazing pressure, have been the main causes of the large-scale degradation of grassland [44,55]. And, the reduction in wetland area is mainly related to natural factors, which can change the composition of surface vegetation and its succession through changes in climatic conditions such as precipitation and temperature, and then change its original land-use structure. In 2005–2010, floods and droughts occurred frequently in the Songnen Plain, especially in 2007, when a large-scale drought occurred, leading to the curtailment of vegetation growth, coupled with the fact that ecological protection was not properly emphasized in that period [39,56,57]. As a result, the wetland ecological environment continued to deteriorate, and the surface vegetation and water resources were continuously depleted, which in turn led to extensive wetland degradation.

Generally speaking, human factors and natural factors play a joint role in land-use change in the Songnen Plain. The land-use change caused by natural factors is usually slow and occurs mainly through changing the surface vegetation to change the land-use mode, which can be summarized as quantitative change causing qualitative change, while the human factor is more rapid and usually can change the land-use structure in a short period of time to satisfy the needs of production activities, which is also the reason why the land-use change caused by human factors in the Songnen Plain is dominant.

4.3. Impact of Land-use Change on Terrestrial Carbon Stocks

Land-use change is one of the important factors affecting terrestrial carbon stocks, and is also regarded as the most uncertain component of the global carbon cycle [58,59]. Land-use change has a significant impact on soil organic carbon and vegetation biocarbon stocks in the Songnen Plain, and the impacts of different land-use transitions on terrestrial carbon stocks vary significantly depending on the area of land-use change, as well as carbon density.

We found a significant negative correlation between land-use trajectories and soil organic carbon stocks, as evidenced by the fact that an increase in the number of land-use change steps resulted in an exponential loss of soil organic carbon stocks. This may be due to the fact that frequent land-use activities increase the intensity of soil activities, resulting in a large amount of carbon originally stored in the soil being released into the atmosphere [60]. On the contrary, vegetation biocarbon stock was positively correlated with the land-use trajectory, and although there was no significant difference between the 1-step transformation and the 2-step transformation, the 3-step transformation led to a significant increase in vegetation biocarbon stock. This may be related to the implementation of ecological conservation measures in the study area in recent years, which can significantly change the land-use trajectory, but this needs to go through a long-term transformation process [61,62], so there is a significant difference between the 1-step and 2-step transformations and the 3-step transformation. The difference between human-induced and naturally induced impacts on terrestrial carbon stocks is mainly reflected in soil organic carbon (SOC), with human-induced impacts leading to an increase in SOC, while natural-induced impacts led to a large decrease in SOC. We believe that the main reason for this is that human-induced land-use change does not leave the soil exposed for a long period of time due to anthropogenic interventions, whereas naturally induced land-use change lacks anthropogenic interventions and is prone to form a vicious cycle under natural conditions, leading to increased soil exposure and a subsequent loss of a large amount of soil organic carbon.

Reclaimed cropland is the main contributor to the increase in soil organic carbon and vegetation biocarbon stocks in the Songnen Plain. On the one hand, the increase in the reclaimed area is the direct cause of the increase in terrestrial carbon stock; on the other hand, the reclaimed cropland is mainly converted from saline-alkali and low-cover grassland, and the structure and density of the ground surface vegetation are effectively improved after the cultivation operation, which then promotes the increase in soil organic carbon and vegetation biocarbon stock [27]. This feature is similar to the findings of Pan et al. (2010) and Zhang et al. (2010) [63,64]. However, the carbon sequestration efficiency of the reclaimed cropland was lower than that of the fallow forests, which mainly stemmed from the differences in land-use intensity and protection degree. Over the past 15 years, the importance of ecological restoration has been gradually emphasized by the Chinese government [61,62], and a large amount of marginal cropland has been transformed into woodland and grassland and protected by the ecological protection red line, a measure that has effectively increased terrestrial carbon stocks [37,38,65]. In addition, the rising CO_2 concentration in the atmosphere further increases the carbon flux between vegetation and the atmosphere, thus increasing the vegetation biocarbon stock [66]. Greening (afforestation) shows the difference between human factors and natural factors in terms of vegetation biocarbon; greening brought about by human factors can rapidly form woodlands or grasslands with good vegetation conditions in a short period of time, while natural factors usually require a long-term vegetation succession process. However, the sequestration efficiency of vegetation biocarbon stocks is higher than that of soil organic carbon for both human and natural factors, suggesting that vegetation will have more carbon sequestration than soil [67].

Land degradation and deforestation have resulted in the loss of soil organic carbon and vegetation biocarbon stocks in the Songnen Plain. In the process of land degradation, the rate of decrease in vegetation biocarbon stock is significantly larger than that of soil organic carbon stock, and grassland and wetland are the main sources of land degradation. Under the action of severe climatic conditions such as drought, high temperature, and so on [39,57], the growth of vegetation on the surface of the grassland and wetland is seriously inhibited, and the vegetation community is rapidly degraded, and vegetation biocarbon stock is the first to be affected. There are significant anthropogenic and natural differences in soil organic carbon stock changes due to deforestation, which is mainly related to the land-use mode after deforestation. Deforestation caused by human factors is usually used in agricultural production activities, and the intensity of soil activities is high, which causes the release of carbon originally stored in the soil, and then causes the decline of soil organic carbon stocks [60,68]. Natural deforestation is part of the succession of vegetation communities. It is dominated by the conversion to grassland and underutilized land. This leads to a significant degradation of the surface vegetation communities and, therefore, a decrease in vegetation biocarbon stocks is predominant.

In addition, climatic factors are one of the most important factors affecting terrestrial carbon stocks [69]. Climate change will adversely affect the environment and soils, for example, an increase in temperature may lead to a loss of soil carbon, while precipitation will increase soil organic carbon [70]. In summary, climatic factors affect terrestrial carbon stocks mainly by limiting human adjustments to land-use patterns and surface vegetation growth. The overall trend of soil organic carbon stocks in the Songnen Plain from 2005 to 2020 was decreasing (by 1.63×105 t). Cropland, as the main land-use type in the Songnen Plain, continued to expand during the study period. This was mainly due to the increase in temperature during the growing season, which encouraged farmers to reclaim more grasslands and wetlands for agriculture [49,51], resulting in the release of carbon sequestered in the soil. In terms of vegetation biocarbon, the vegetation biocarbon stock decreased drastically from 2005 to 2010, mainly due to the frequent occurrence of floods and droughts in the Songnen Plain during this period, especially the large-scale drought in 2007, which directly led to the curtailment of vegetation growth [39,56,57]. The high level of vegetation degradation has led to a drastic reduction in vegetation biocarbon stocks.

The results of this study show that land-use activities in the Songnen Plain have gradually weakened. Land-use changes related to agriculture and forestry have a positive impact on terrestrial carbon stocks, which is consistent with the findings of Hu et al. [5]. Overall, land-use change brings carbon sinks to the Songnen Plain, and the carbon sink areas in the Songnen Plain are mainly concentrated in the north, while the land-use change in the southern region is more active, and carbon sequestration and carbon emission areas are cross-coexisting. Human-induced land-use change dominates, and compared to natural factors, human-induced factors bring more carbon sinks.

4.4. Comparison of Research Methods

Among the many methods for calculating terrestrial carbon stocks, the Bookkeeping model has been widely used to measure changes in terrestrial carbon stocks. The model can monitor the changing relationship between soil organic carbon pools and vegetation biocarbon pools over long time periods, and has been well-validated at different regional and global scales [71,72]. However, the Bookkeeping model usually assumes that carbon density is an invariant constant, and together with the fact that the applied function is also static in nature, the results of model measurements of terrestrial carbon stocks have some deviations from actual observations [73,74]. The InVEST model can be used to predict carbon sequestration under different scenarios and the response of terrestrial carbon stocks to land-use change [75,76]. However, similar to the accounting model, the InVEST model requires the input of fixed parameters to simulate carbon stocks, and the setting of parameters is subjective and deviates from actual carbon stocks. Dynamic Global Vegetation Models (DGVMs) can be used to estimate carbon at large spatial scales, such as national and global, but the data inputs to the models are usually of a high resolution. and do not accurately represent land-use change, leading to large discrepancies between carbon stock estimates and the actual situation [58]. In addition, process-based ecosystem models can estimate carbon stocks by simulating photosynthesis. However, due to computational constraints, the model is unable to integrate carbon stock estimates with land-use change [77,78]. The carbon stock measurement method based on the IPCC recommendation takes into account the direct carbon stock changes caused by land-use changes [79]. And, compared to other methods, the calculation process of this method is simpler and less demanding on samples [80].

4.5. Uncertainties and Limitations

The estimation results of carbon stocks by different researchers usually have a certain high degree of variability, which is mainly due to the diversity of data sources, and one of the important variabilities is the variability of area. In this study, the results of carbon stock estimation are based on the calculation of average carbon density and area, which leads to the fact that area is the most direct factor affecting the change in carbon stock in this study, and the effect of area on the change in stock is not excluded, which also means that the accuracy of area determines the reasonableness of the carbon stock estimation results. Moreover, the change in terrestrial carbon stock is a dynamic process that changes from moment to moment, and this study only considered the terrestrial carbon stock under a specific time node and its land-use type, which can reflect the trend of the overall carbon stock change in the study area, but it cannot accurately indicate the specific time node of the turn of the carbon stock. In addition, the calculation of vegetation biocarbon in this paper only considered the existing vegetation stock on the ground. The potential carbon stock from vegetation litter and root systems was not considered. This will be investigated in future studies.

5. Conclusions

By measuring soil organic carbon and vegetation biocarbon stocks in the Songnen Plain, we explored land-use trajectories, drivers of land-use change, and the characteristics of changes in terrestrial carbon stocks under actual land-use change scenarios. The results of the study show that over the past 15 years, the Songnen Plain has been characterized by a small decrease in soil organic carbon (1.63 × 10^5 t) and a significant increase in vegetation biocarbon (2.10 × 10^7 t). Land-use activities in the Songnen Plain have gradually weakened, and human factors and natural factors have played a joint role in land-use changes, but the degree of human factors' role is slightly larger than that of natural factors. The land-use trajectory was significantly negatively correlated with soil organic carbon stock and positively correlated with vegetation biocarbon stock. The difference between the effects of human-induced and natural-induced types on carbon stocks centered on soil organic carbon stocks, with the human-induced type leading to an increase in soil organic carbon stocks and the natural-induced type leading to a decrease in soil organic carbon stocks. Activities such as reclaiming cropland land, returning cropland to forests, and greening brought a net increase in terrestrial carbon stocks in the Songnen Plain, while activities such as land degradation, deforestation, and the expansion of construction land led to a decrease in terrestrial carbon stocks. The results of this paper provide a reference for better increasing terrestrial carbon stock and ecological protection in the Songnen Plain.

CRediT author statement

The specific contributions made by each author are as follows:

Author Contributions: Conceptualization, L.C., H.L. (Han Luo), W.X. and L.Z.; methodology, L.C.; Results, L.C.; Supervision, L.C., Y.L. and H.L. (Huijia Liu); Writing and Editing, L.C., L.Z., Y.L. and H.L. (Huijia Liu); Data, H.L. (Han Luo) and W.X. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Grant No. 42177447), the Science and Technology Development Plan Project of Jilin Province (Grant No. 20220508124RC), and the Natural Science Foundation of Jilin Province, China (Grant No. 20210101395JC).

Data Availability Statement: The authors do not have permission to share data.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Quere, C.L.; Moriarty, R.; Andrew, R.; Peters, G.; Ciais, P.; Friedlingstein, P.; Jones, S.; Sitch, S.; Tans, P.; Arneth, A. Global carbon budget 2014. *Earth Syst. Sci. Data.* **2015**, *7*, 47–85. [CrossRef]
2. Farrelly, D.J.; Everard, C.D.; Fagan, C.C.; McDonnell, K.P. Carbon sequestration and the role of biological carbon mitigation: A review. Renew. Sustain. *Energy Rev.* **2013**, *21*, 712–727.
3. Friedlingstein, P.; O'Sullivan, M.; Jones, M.W.; Andrew, R.M.; Hauck, J.; Olsen, A.; Peters, G.P.; Peters, W.; Pongratz, J.; Sitch, S.; et al. Global Carbon Budget 2020. *Earth Syst. Sci. Data.* **2020**, *12*, 3269–3340. [CrossRef]
4. Zhang, C.X.; Xie, G.D.; Zhen, L.; Li, S.M.; Deng, X.Z. Estimates of variation in Chinese terrestrial carbon storage under an environmental conservation policy scenario for 2000–2025. *J. Res. Ecol.* **2021**, *2*, 315–321.
5. Hu, X.Q.; Li, Z.W.; Chen, J.; Nie, X.D.; Liu, J.Y.; Wang, L.X.; Ning, K. Carbon sequestration benefits of the grain for Green Program in the hilly red soil region of southern China. *Int. Soil Water Conserv. Res.* **2021**, *9*, 271–278. [CrossRef]
6. Li, Z.H.; Xia, J.; Deng, X.Z.; Yan, H.M. Multilevel modelling of impacts of human and natural factors on ecosystem services change in an oasis, Northwest China. *Resour. Conserv. Recycl.* **2021**, *169*, 105474. [CrossRef]
7. Hinge, G.; Surampalli, R.Y.; Goyal, M.K. Regional carbon fluxes from land-use conversion and land-use management in northeast India. *Journal of Hazardous, Toxic, and Radioactive Waste.* **2018**, *22*, 4018016. [CrossRef]
8. Friedlingstein, P. Global carbon budget 2021. *Earth Syst. Sci. Data Discuss.* **2021**, 1–191. [CrossRef]
9. IPCC. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2007.
10. Schimel, D.; Stephens, B.B.; Fisher, J.B. Effect of increasing CO_2 on the terrestrial carbon cycle. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 436–441. [CrossRef]
11. Windisch, M.G.; Davin, E.L.; Seneviratne, S.I. Prioritizing forestation based on biogeochemical and local biogeophysical impacts. *Nat. Clim. Change.* **2021**, *11*, 867–871. [CrossRef]
12. Yang, Y.H.; Fang, J.Y.; Ma, W.H.; Smith, P.; Mohammat, A.; Wang, S.P.; Wang, W. Soil carbon stock and its changes in northern China's grasslands from 1980s to 2000s. *Global Change Biol.* **2010**, *16*, 3036–3047. [CrossRef]
13. Fang, C.M. Relatively stable carbon stocks in China's grasslands. *Sci. China.* **2011**, *54*, 490–492. [CrossRef] [PubMed]

14. Fang, J.Y.; Yu, G.R.; Liu, L.L.; Hu, S.J.; Chapin, F.S. Climate change, human impacts, and carbon sequestration in China introduction. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 4015–4020. [CrossRef] [PubMed]
15. Huang, Y.; Sun, W.J.; Qin, Z.C.; Zhang, W.; Yu, Y.Q.; Li, T.T.; Zhang, Q.; Wang, G.C.; Yu, L.F.; Wang, Y.J.; et al. The role of China's terrestrial carbon sequestration 2010–2060 in offsetting energy-related CO_2 emissions. *Natl Sci. Rev.* **2022**, *9*, nwac057. [CrossRef] [PubMed]
16. Yang, Y.H.; Shi, Y.; Sun, W.J.; Chang, J.F. Terrestrial carbon sinks in China and around the world and their contribution to carbon neutrality. *Sci. China-Life Sci.* **2022**, *65*, 861–895. [CrossRef] [PubMed]
17. Xu, L.; Yu, G.R.; He, N.P.; Wang, Q.F.; Gao, Y.; Wen, D.; Li, S.G.; Niu, S.L.; Ge, J.P. Carbon storage in China's terrestrial ecosystems: A synthesis. *Sci. Rep.* **2018**, *8*, 2806. [CrossRef] [PubMed]
18. Wang, L.; Gao, J.; Shen, W.; Shi, Y.; Zhang, H. Carbon storage in vegetation and soil in Chinese ecosystems estimated by carbon transfer rate method. *Ecosphere.* **2021**, *12*, e03341. [CrossRef]
19. Le Quere, C.; Andrew, R.M.; Friedlingstein, P.; Sitch, S.; Hauck, J.; Pongratz, J.; Pickers, P.A.; Korsbakken, J.I.; Peters, G.P.; Canadell, J.G.; et al. Global carbon budget 2018. Earth Syst. *Sci. Data.* **2018**, *10*, 2141–2194.
20. Gasser, T.; Crepin, L.; Quilcaille, Y.; Houghton, R.A.; Ciais, P.; Obersteiner, M. Historical CO_2 emissions from land-use and land cover change and their uncertainty. *Biogeosciences* **2020**, *17*, 4075–4101. [CrossRef]
21. Hartung, K.; Bastos, A.; Chini, L.; Ganzenmüller, R.; Havermann, F.; Hurtt, G.; Loughran, T.; Nabel, J.; Tobias, N.; Obermeier, W.; et al. Net land-use change carbon flux estimates and sensitivities—An assessment with a bookkeeping model based on CMIP6 forcing. *Earth Syst. Dyn. Discuss.* **2021**, *2021*, 1–34.
22. Vliet, J.V.; Eitelberg, D.A.; Verburg, P.H. A global analysis of land take in cropland areas and production displacement from urbanization. *Glob. Environ. Chang.* **2017**, *43*, 107–115. [CrossRef]
23. Xie, G.; Zhang, C.; Zhen, L.; Zhang, L. Dynamic changes in the value of China's ecosystem services. *Ecosyst. Serv.* **2017**, *26*, 146–154.
24. Tang, X.L.; Zhao, X.; Bai, Y.F.; Wang, W.T.; Zhao, Y.C.; Wan, H.W.; Xie, Z.Q.; Shi, X.Z.; Wu, B.F.; Wang, G.X.; et al. Carbon pools in China's terrestrial ecosystems: New estimates based on an intensive field survey. *PNAS* **2018**, *115*, 4021–4026. [CrossRef]
25. Tian, S.; Wang, S.J.; Bai, X.Y.; Luo, G.J.; Li, Q.; Yang, Y.J.; Hu, Z.Y.; Li, C.J.; Deng, Y.H. Global patterns and changes of carbon emissions from land-use during 1992–2015. *Environ. Sci. Etechnol.* **2021**, *7*, 100108. [CrossRef] [PubMed]
26. Yu, Z.; Lu, C.Q.; Cao, P.Y.; Tian, H.Q. Long-term terrestrial carbon dynamics in the Midwestern United States during 1850–2015: Roles of land-use and cover change and agricultural management. *Glob. Chang. Biol.* **2018**, *24*, 2673–2690. [CrossRef]
27. Song, X.D.; Yang, F.; Ju, B.; Li, D.C.; Zhao, Y.G.; Yang, J.L.; Zhang, G.L. The influence of the conversion of grassland to cropland on changes in soil organic carbon and total nitrogen stocks in the The Songnen Plain of northeast China. *Catena* **2018**, *171*, 588–601. [CrossRef]
28. Deng, L.; Liu, S.; Kim, D.G.; Peng, C.; Sweeney, S.; Shangguan, Z. Past and future carbon sequestration benefits of China's grain for green program. *Glob. Environ. Change-Hum. Policy Dimens.* **2017**, *47*, 13–20. [CrossRef]
29. Wang, K.; Hu, D.; Deng, J.; Shangguan, Z.; Deng, L. Biomass carbon storages and carbon sequestration potentials of the Grain for Green Program-Covered Forests in China. *Ecol. Evol.* **2018**, *8*, 7451–7461. [CrossRef]
30. Muñoz-Rojas, M.; Jordán, A.; Zavala, L.M.; De la Rosa, D.; Abd-Elmabod, S.K.; Anaya-Romero, M. Impact of land-use and land cover changes on organic carbon stocks in mediterranean soils (1956–2007). *Land Degrad. Dev.* **2015**, *26*, 168–179. [CrossRef]
31. Zhou, Y.; Li, X.H.; Liu, Y.S. Land-use change and driving factors in rural China during the period 1995–2015. *Land-Use Policy* **2020**, *99*, 105048. [CrossRef]
32. Erb, K.H.; Kastner, T.; Plutzar, C.; Bais, A.L.S.; Carvalhais, N.; Fetzel, T.; Gingrich, S.; Haberl, H.; Lauk, C.; Niedertscheider, M.; et al. Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* **2018**, *553*, 73–76. [CrossRef] [PubMed]
33. Qiu, Z.; Feng, Z.; Song, Y.; Li, M.; Zhang, P. Carbon sequestration potential of forest vegetation in China from 2003 to 2050: Predicting forest vegetation growth based on climate and the environment. *J. Clean. Prod.* **2020**, *252*, 119715. [CrossRef]
34. Lu, M.; Zou, Y.; Xun, Q.; Yu, Z.; Jiang, M.; Sheng, L.; Lu, X.; Wang, D. Anthropogenic disturbances caused declines in the wetland area and carbon pool in China during the last four decades. *Glob. Change. Biol.* **2021**, *27*, 3837–3845. [CrossRef] [PubMed]
35. Shi, X.L.; Lu, C.X.; Cao, X.L.; Wang, T.L.; Chen, K.; He, D.; Xu, Z.; Duan, W.N.; Deng, J.F. Value assessment on forest ecosystem services in eastern typical monsoon climate zone, Great Khingan Range, CHINA. *Fresenius. Environ. Bull.* **2020**, *29*, 11253–11265.
36. Zhang, B.; Song, X.; Zhang, Y.; Han, D.; Tang, C.; Yu, Y.; Ma, Y. Hydrochemical characteristics and water quality assessment of surface water and groundwater in The Songnen Plain, Northeast China. *Water Res.* **2012**, *46*, 2737–2748. [CrossRef] [PubMed]
37. Lu, F.; Hu, H.F.; Sun, W.J.; Zhu, J.J.; Liu, G.B.; Zhou, W.M.; Zhang, Q.F.; Shi, P.L.; Liu, X.P.; Wu, X.; et al. Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 4039–4044. [CrossRef] [PubMed]
38. Tong, X.W.; Brandt, M.; Yue, Y.M.; Horion, S.; Wang, K.L.; Keersmaecker, W.D.D.; Tian, F.; Schurgers, G.; Xiao, X.M.; Luo, Y.Q.; et al. Increased vegetation growth and carbon stock in China karst via ecological engineering. *Nat. Sustain.* **2018**, *1*, 44–50. [CrossRef]
39. Zhang, Y.; Zang, S.Y.; Sun, L.; Yan, B.H.; Yang, T.P.; Yan, W.J.; Meadows, E.M.; Wang, C.Z.; Qi, J.G. Characterizing the changing environment of cropland in the The Songnen Plain, Northeast China, from 1990 to 2015. *J. Geogr. Sci.* **2019**, *29*, 658–674. [CrossRef]

40. Mackenzie, L.; Bao, K.; Mao, L.; Klamt, A.-M.; Pratte, S.; Shen, J. Anthropogenic and climate-driven environmental change in the The Songnen Plain of northeastern China over the past 200 years. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2018**, *511*, 208–217. [CrossRef]
41. IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. *Prep. Natl.* **2006**. Available online: https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (accessed on 10 April 2023).
42. Song, C.; Dodds, W.K.; Rüegg, J.; Argerich, A.; Baker, C.L.; Bowden, W.B. Continentalscale decrease in net primary productivity in streams due to climate warming. *Nat. Geosci.* **2018**, *11*, 415–420. [CrossRef]
43. Sanderman, J.; Hengl, T.; Fiske, G.J. Soil carbon debt of 12,000 years of human land-use. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 9575–9580. [CrossRef] [PubMed]
44. Zhou, Y.; Hartemink, A.E.; Shi, Z.; Liang, Z.; Lu, Y. Land-use and climate change effects on soil organic carbon in North and Northeast China. *Sci. Total Environ.* **2019**, *647*, 1230–1238. [CrossRef] [PubMed]
45. Potma Gonçalves, D.R.; Carlos De Moraes Sa, J.; Mishra, U.; Ferreira Furlan, F.J.; Ferreira, L.A.; Inagaki, T.M.; Romaniw, J.; de Oliveira Ferreira, A.; Briedis, C. Soil carbon inventory to quantify the impact of land-use change to mitigate greenhouse gas emissions and ecosystem services. *Environ. Pollut.* **2018**, *243*, 940–952. [CrossRef]
46. Scharlemann, J.P.; Tanner, E.V.; Hiederer, R.; Kapos, V. Global soil carbon: Understanding and managing the largest terrestrial carbon pool. *Carbon Manag.* **2014**, *5*, 81–91. [CrossRef]
47. Li, Z.P.; Han, F.X.; Su, Y.; Zhang, T.L.; Sun, B.; Monts, D.L.; Plodinec, M.J. Assessment of soil organic and carbonate carbon storage in China. *Geoderma.* **2007**, *138*, 119–126. [CrossRef]
48. Yang, Y.H.; Mohammat, A.; Feng, J.M.; Zhou, R.; Fang, J.Y. Storage, patterns and environmental controls of soil organic carbon in China. *Biogeochemistry* **2007**, *84*, 131–141. [CrossRef]
49. Ding, F.; Hu, Y.L.; Li, L.J.; Li, A.; Shi, S.; Lian, P.Y.; Zeng, D.H. Changes in soil organic carbon and total nitrogen stocks after conversion of meadow to cropland in Northeast China. *Plant Soil* **2013**, *373*, 659–672. [CrossRef]
50. Gao, X.Y.; Cheng, W.M.; Wang, N.; Liu, Q.Y.; Ma, T.; Chen, Y.J.; Zhou, C.H. Spatio-temporal distribution and transformation of cropland in geomorphologic regions of China during 1990–2015. *J. Geog. Sci.* **2019**, *29*, 180–196. [CrossRef]
51. Qiu, X.; Zhang, L.J.; Li, W.L.; Yu, Y.; Pan, T. Studies on changes and cause of the minimum air temperature in The Songnen Plain of China during 1961–2010. *Acta Ecologica Sinica.* **2016**, *36*, 311–320. [CrossRef]
52. Central People's Government of the People's Republic of China. Fourteenth Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Outline of Long-Term Goals for 2035. 2021. Available online: https://www.gov.cn/xinwen/2021-03/13/content_5592681.htm (accessed on 10 April 2023).
53. National Development and Reform Commission of the People's Republic of China. National Major Ecosystem Protection and Restoration Major Project Master Plan. (2021–2035). 2020. Available online: https://www.gov.cn/zhengce/zhengceku/2020-06/12/content_5518982.htm (accessed on 10 April 2023).
54. Zhang, L.; Zhou, D.C.; Fan, J.W.; Hu, Z.M. Comparison of four light use efficiency models for estimating terrestrial gross primary production. *Ecol. Modell.* **2015**, *300*, 30–39. [CrossRef]
55. Dong, G.; Zhao, F.Y.; Chen, J.Q.; Qu, L.P.; Jiang, S.C.; Chen, J.Y.; Xin, X.P.; Shao, C.L. Land-uses changed the dynamics and controls of carbon-water exchanges in alkali-saline The Songnen Plain of Northeast China. *Ecol. Indic.* **2021**, *133*, 108353. [CrossRef]
56. Liu, Z.; Dong, X.; Liu, Z. Spatiotemporal evolution of the drought and flood in Northeast China. *Adv. Mate. Res.* **2014**, *1010–1012*, 1075–1083. [CrossRef]
57. Wang, X.X.; Shen, H.T.; Zhang, W.J.; Cao, J.S.; Qi, Y.Q.; Chen, G.P.; Li, X.Y. Spatial and temporal characteristics of droughts in the Northeast China Transect. *Nat. Hazards* **2015**, *76*, 601–614. [CrossRef]
58. Houghton, R.A.; House, J.I.; Pongratz, J.; Werf, G.R.; DeFries, R.S.; Hansen, M.C.; Le, Q.C.; Ramankutty, N. Carbon emissions from land-use and land-cover change. *Biogeosci.* **2012**, *9*, 5125–5142. [CrossRef]
59. Peters, G.P.; Marland, G.; Le Quéré, C.; Boden, T.; Canadell, J.G.; Raupach, M.R. Rapid growth in CO_2 emissions after the 2008–2009 global financial crisis. *Nat. Clim. Chang.* **2012**, *2*, 2–4. [CrossRef]
60. Jiang, L.Q.; Zhang, L.J.; Zang, S.Y.; Zhang, X.Z. Accuracy assessment of approaches to spatially explicit reconstruction of historical cropland in The Songnen Plain, Northeast China. *J. Geo. Sci.* **2016**, *26*, 219–229. [CrossRef]
61. Cheng, H.; Zhu, L.; Meng, J. Fuzzy evaluation of the ecological security of land resources in mainland China based on the Pressure-State-Response framework. *Sci. Total Environ.* **2022**, *804*, 150053. [CrossRef] [PubMed]
62. Yao, X.C.; Chen, W.W.; Song, C.C.; Gao, S.Q. Sustainability and efficiency of water-land-energy-food nexus based on emergy-ecological footprint and data envelopment analysis: Case of an important agriculture and ecological region in Northeast China. *J. Cleaner Prod.* **2022**, *379*, 134854. [CrossRef]
63. Pan, G.; Xu, X.; Smith, P.; Pan, W.; Lal, R. An increase in topsoil SOC stock of China's croplands between 1985 and 2006 revealed by soil monitoring. *Agric. Ecosyst. Environ.* **2010**, *136*, 133–138. [CrossRef]
64. Zhang, C.H.; Wang, Z.M.; Ren, C.Y.; Song, K.S.; Zhang, B.; Liu, D.W. Spatial and temporal changes of organic carbon in agricultural soils of The Songnen Plain maize belt. *Trans. CSAE.* **2010**, *26*, 300–307.
65. Hong, S.B.; Yin, G.; Piao, S.; Dybzinski, R.; Cong, N.; Li, X.; Wang, K.; Peñuelas, J.; Zeng, H.; Chen, A. Divergent responses of soil organic carbon to afforestation. *Nat. Sustain.* **2020**, *3*, 694–700. [CrossRef]
66. Peng, J.; Dan, L.; Huang, M. Sensitivity of global and regional terrestrial carbon storage to the direct CO_2 effect and climate change based on the CMIP5 model intercomparison. *PLoS ONE* **2014**, *9*, e95282. [CrossRef]

67. Zhang, M.; He, H.; Zhang, L.; Ren, X.; Wu, X.; Qin, K.; Lv, Y.; Chang, Q.; Xu, Q.; Liu, W.; et al. Increased forest coverage will induce more carbon fixation in vegetation than in soil during 2015–2060 in China based on CMIP6. *Environ. Res. Lett.* **2022**, *17*, 105002. [CrossRef]
68. Tubiello, F.N.; Salvatore, M.; Ferrara, A.F.; House, J.; Federici, S.; Rossi, S.; Smith, P. The contribution of agriculture, forestry and other land-use activities to global warming, 19902012. *Global Change Biology.* **2015**, *21*, 2655–2660. [CrossRef]
69. Bai, X.; Zhang, S.; Li, C.; Xiong, L.; Song, F.; Du, C.; Li, M.; Luo, Q.; Xue, Y.; Wang, S. A carbon-neutrality-capacity index for evaluating carbon sink contributions. *Environ. Sci. Ecotechnology* **2023**, *15*, 100237. [CrossRef]
70. Sharma, G.; Sharma, L.K. Climate change effect on soil carbon stock in different land-use types in eastern Rajasthan, India. *Environ. Dev. Sustain.* **2022**, *24*, 4942–4962. [CrossRef]
71. Kong, J. Effect of land-use and cover change on carbon stock dynamics in a typical desert oasis. *Aeta Ecol. Sin.* **2018**, *38*, 7801–7812.
72. Tang, X.J.; Hutyra, L.R.; Arévalo, P.; Baccini, A.; Woodcock, C.E.; Olofsson, P. Spatiotemporal tracking of carbon emissions and uptake using time series analysis of Landsat data: A spatially explicit carbon bookkeeping model. *Sci. Total Environ.* **2020**, *720*, 137409. [CrossRef] [PubMed]
73. Yue, C. Contribution of land-use to the interannual variability of the land carbon cycle. *Nat. Commun.* **2020**, *11*, 3170. [CrossRef]
74. Hong, C.P.; Burney, J.A.; Pongratz, J.; Nabel, J.E.M.S.; Mueller, N.D.; Jackson, R.B.; Davis, S.J. Global and regional drivers of land-use emissions in 1961–2017. *Nature* **2021**, *589*, 554–561. [CrossRef]
75. Babbar, D.; Areendran, G.; Sahana, M.; Sarma, K.; Raj, K.; Sivadas, A. Assessment and Prediction of Carbon Sequestration Using Markov Chain and InVEST Model in Sariska Tiger Reserve, India. *J. Clean. Prod.* **2021**, *278*, 123333. [CrossRef]
76. Piyathilake, I.D.U.H.; Udayakumara, E.P.N.; Ranaweera, L.V.; Gunatilake, S.K. Modeling Predictive Assessment of Carbon Storage Using InVEST Model in Uva Province, Sri Lanka. Model. *Earth Syst. Environ.* **2021**, *8*, 2213–2223. [CrossRef]
77. Hansis, E. Relevance of methodological choices for accounting of land-use change carbon fluxes. *Global Biogeochem. Cycles* **2015**, *29*, 1230–1246. [CrossRef]
78. Ren, W.; Banger, K.; Tao, B.; Yang, J. Global pattern and change of cropland soil organic carbon during 1901-2010: Roles of climate, atmospheric chemistry, land-use and management. *Geogr. Sustain.* **2020**, *1*, 59–69. [CrossRef]
79. Lai, L.; Huang, X.J.; Yang, H.; Chuai, X.W.; Zhang, M.; Zhong, T.Y.; Chen, Z.G.; Chen, Y.; Wang, X.; Thompson, J.R. Carbon emissions from land-use change and management in China between 1990 and 2010. *Sci. Adv.* **2016**, *2*, e1601063. [CrossRef]
80. Zhu, E.; Deng, J.; Zhou, M.; Gan, M.; Jiang, R.; Wang, K.; Shahtahmassebi, A. Carbon emissions induced by land-use and land-cover change from 1970 to 2010 in Zhejiang, China. *Sci. Total Environ.* **2019**, *646*, 930–939. [CrossRef]