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A Study of Carbon Stock Changes in the Alpine Grassland Ecosystem of Zoigê, China, 2000–2020

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Abstract: Terrestrial carbon sequestration capacity is an important indicator of ecosystem service function, and the carbon storage value can reflect the climate regulation capacity of the regional ecological environment. The Zoigê alpine grassland is a representative area of the Qinghai-Tibet Plateau grassland ecosystem, with carbon sequestration types such as alpine grassland and marsh meadow and also an important water-conserving area in the upper reaches of the Yangtze River and the Yellow River. In this study, based on the land use/cover change pattern of the Zoigê alpine grassland region from 2000 to 2020, the carbon density coefficients corrected by the regional average annual precipitation and temperature factors were used to assess the carbon stocks of the Zoigê alpine grassland for three periods from 2000 to 2020 using the InVEST model. The results showed that the carbon stocks of the Zoigê alpine grassland region were 786.19 Tg, 780.02 Tg, and 775.22 Tg in 2000, 2010, and 2020, respectively, with a cumulative loss of 10.97 Tg and carbon densities of 183.70 t/ha, 182.26 t/ha, and 181.14 t/ha, showing a decreasing trend year by year. The carbon stock of the grassland ecosystem is the absolute contributor to the regional carbon stock, and the carbon stock accounts for 75.28% of the total carbon stock. The increase in the cultivated land area with a lower carbon density and the decrease in the grassland area with a higher carbon density are the main factors leading to the decrease in the carbon stock in the regional ecosystem of the Zoigê alpine grassland.

Keywords: Zoigê alpine grassland; ecosystem; carbon stock; InVEST model

Citation: Qu, R.; He, L.; He, Z.; Wang, B.; Lyu, P.; Wang, J.; Kang, G.; Bai, W. A Study of Carbon Stock Changes in the Alpine Grassland Ecosystem of Zoigê, China, 2000–2020. *Land* **2022**, *11*, 1232. https://doi.org/10.3390/land11081232

Academic Editor: Nima Madani

Received: 23 June 2022
Accepted: 30 July 2022
Published: 4 August 2022

1. Introduction

Global terrestrial ecosystems are being affected by climate change as well as human activities, and their service functionality is declining. The process is accompanied by a series of ecological and environmental problems, such as desertification and soil erosion [1], while carbon storage in terrestrial ecosystems is an important component of global carbon storage and plays a crucial role in mitigating climate change [2]. Land use/cover change (LUCC) is one of the most direct manifestations of human activities on regional carbon stock changes [3,4]. Changes in land cover type lead to changes in the structure, processes, and functions of the original ecosystem, affecting the material cycle and the energy flow of the ecosystem, accompanied by significant carbon loss [5].

The terrestrial carbon sequestration capacity is an important indicator of ecosystem service functions, and regional carbon stock values can reflect the climate regulation capacity of terrestrial ecosystems. Weiss et al. [6] used a variety of coupled Earth system models for ecological simulations, all of which showed that land use change is a major contributor to the global loss of land carbon stocks. Changes in land use types are often accompanied by significant carbon exchange [7], and carbon emissions due to land use change are increasing globally [8]. Zhang et al. [4] showed that China's terrestrial ecosystems lost 219 Tg-C to LUTC from 1980–1995 and 60 Tg-C from 1995–2010.The analysis also found that the increasing impact of land use/land exchange on carbon reduction in China is mainly due to the insufficient growth rate of forest land to meet the increasing carbon sequestration demand, the accelerated disappearance of grasslands, and the rapid habitat expansion [9–11].

In recent years, the gradual increase in studies on the carbon stock estimation of different ecosystems at multiple scales has made it possible to visualize the results of regional ecosystem carbon stock projections. Strohbach et al. [12] used a stratified random sampling method to measure carbon stocks on 190 sample plots in 19 land cover categories to estimate the aboveground carbon stocks of trees in the central European city of Leipzig and mapped carbon stocks in space. With the development of information technology, model simulation-based carbon stock estimation methods have emerged. Compared with other research methods, the InVEST model is a comprehensive assessment model that can quantify multiple ecosystem service functions; enable spatial mapping of carbon stock spatial distribution and dynamic changes; reflect the relationship between land use changes and carbon stocks; and achieve the dynamic quantification of ecological service function values [13]. For example, Li et al. [14] used the FLUS model to simulate the land use pattern under three scenarios up to 2030 and used the InVEST model to assess the carbon stock in Changchun, northeast China, from 2010 to 2030. Zhu et al. [5] used the carbon storage and sequestration module of the Ecosystem Services and Tradeoffs (Invest) model to assess ecosystem carbon stocks over the past 35 years in the northwest arid zone of China and to discuss the effects of land use change on terrestrial ecosystem carbon stocks. Yang et al. [15] used the InVEST model to assess the carbon stock in the Yellow River basin for six periods from 2005 to 2030 based on the land use/cover change pattern in the Yellow River basin, resulting in a regional year-by-year carbon stock distribution map.

The Zoigê alpine grassland is an important water-conserving area in the upper reaches of the Yangtze River and the Yellow River, with subtypes of alpine grassland and marsh meadow, and is a representative area of the grassland ecosystem in the Qinghai-Tibet Plateau [16,17]. Yang et al. [18] showed that the changes of soil organic carbon in the alpine grassland were more sensitive than the temperate grassland during the grassland transformation process. In particular, during the carbon loss process, the carbon loss rate of the alpine grassland was 3.3 and 7.3 times higher than that of the temperate grassland in 1–5 and 6–10 years, respectively [19,20]. Grasslands in alpine regions are sensitive to climate change, and climate change and inappropriate human activities are more likely to affect the balance of grassland carbon pools and even cause the reversal of carbon sinks [21]. Therefore, this paper investigates the carbon sequestration capacity of the ecosystem in this region from 2000 to 2020 and its spatial distribution characteristics through the InVEST model; explores the changes in the carbon sequestration capacity of the regional grassland ecosystem and its distribution pattern; quantitatively evaluates the ecosystem service function in the study area; and provides a scientific basis for improving the ecological benefits of the alpine grassland in Zoigê.

2. Overview of the Study Area and Research Methods

2.1. Study Area Overview

The Zoigê alpine grassland is located at the northeast edge of the Tibetan Plateau, with coordinates ranging from 31°48′4″~34°48′28″ and 100°47′35″~103°39′37″ and an average elevation of 2392~5057 m. The area is a plateau grassland, shallow-mound, swamp landscape, containing major carbon-fixing vegetation, with a very typical Tibetan Plateau alpine grassland swamp ecosystem. The study area is also considered to be one of the most important water-conserving areas in the upper reaches of the Yellow River and Yangtze River [22,23]. The administrative division is under the jurisdiction of the Gansu and Sichuan provinces, including Zoigê, Aba, and Hongyuan counties in Sichuan Province and Luqu and Magu counties in Gansu Province, with a total area of about 42,797 km^2 (Figure 1). The peat bog in this region is a typical wetland type, a typical plateau wetland of the world, and the largest concentrated distribution area of plateau peat bog in China [24–27].

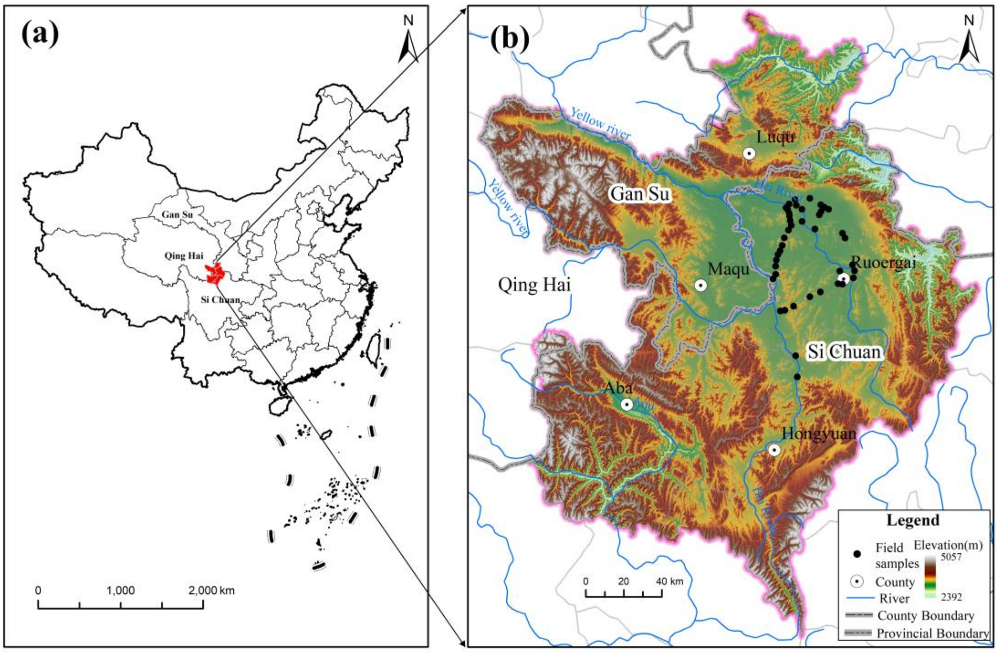

Figure 1. (**a**) The geographical location of the Zoigê alpine grassland in China. (**b**) Overview map of Zoigê alpine grassland study area.

2.2. Data Source

2.2.1. Land Use Classification Data

The land use data were downloaded from the National Basic Geographic Information Center (http://www.globallandcover.com) (accessed on 13 December 2021) at a spatial resolution of 30 m × 30 m. The GlobeLand30 classification utilizes 30 m multispectral imagery, a dataset consisting of Landsat TM5, ETM+ multispectral imagery, and HJ-1 multispectral imagery, images, and China Environmental Disaster Reduction Satellite (HJ-1) multispectral images. The data include 10 land cover types: arable land, forest, grassland, shrubland, wetland, water body, tundra, manmade surface, bare land, and glacier and permanent snow. According to the third-party validation, the product classification accuracy reached 83%. Nine primary types of land use types in the study area were selected: arable land, forest, grassland, shrubland, wetland, water body, manmade surface, bare land, and glacier and permanent snow, and a total of three periods were selected for the years 2000, 2010, and 2020.

2.2.2. Field Collection

Obtained from field measurements and calculations in the study area during peak plant growth in August 2017, the soil data included the organic carbon content, soil bulk, and soil thickness of each soil layer. After the aboveground portion was surveyed, soil samples from 0 to 10 cm were collected by randomly drilling three times within each sample plot with a 5 cm-diameter soil auger and placed in self-sealing bags for the subsequent determination of each index in the laboratory. The biomass data included aboveground biomass and belowground biomass (0–30 cm); aboveground biomass was selected from 1 m × 1 m grass sample plots with three replications, and aboveground biomass was mowed flush, dried, and weighed to obtain dry weight. The belowground biomass was removed by root washing, sealed, and bagged and brought back to the laboratory for drying and weighing (accuracy 0.01 g).

2.2.3. Soil Carbon Density Data in China

The soil organic carbon content data were downloaded from the National Ecosystem Science Data Center (NESDC) 2010s China Terrestrial Ecosystem Carbon Density Dataset (http://www.cnern.org.cn/data/meta?id=40579) (accessed on 8 March 2022). The dataset covers major ecosystem types, such as forest, grassland, farmland, wetland, and scrub, and includes vegetation aboveground carbon density, vegetation belowground carbon density, and soil organic carbon density at different depths (0–20 cm and 0–100 cm).

2.2.4. Meteorological Data

WorldClim (https://www.worldclim.org/data/index.html) (accessed on 20 December 2021) obtained the mean minimum temperature (°C), mean maximum temperature (°C), and total precipitation (mm) for the study area from 2010–2018, with a spatial resolution of 21 km^2.

2.2.5. Carbon Pool Calculation Data

Above/below carbon density: above/below carbon density was calculated according to the biomass conversion factor method [28] with the following formula.

$$C_{above/below} = AGB/BGB \times k \quad (1)$$

where C_{above} and C_{below} are aboveground plant carbon density and belowground plant carbon density ($g{\cdot}m^{-2}$), respectively; AGB and BGB are the field-measured aboveground and belowground biomass ($g{\cdot}m^{-2}$) in 2017; k is based on the IPCC method using a fixed carbon content factor of 0.45.

Soil carbon density: data on the soil properties were at selected sample points and include the organic carbon content, the average volume, and the soil thickness (0~10 cm) of the soil surface layer. The soil organic carbon content was determined using the concentrated sulfuric acid-potassium dichromate external heating method; the soil capacity was determined for different soil layers using the ring knife method. The base soil carbon density data were obtained by the formula. The carbon density of the surface soil was calculated as follows.

$$C_{soil} = TOC \times y \times H \quad (2)$$

where C_{soil} is the soil organic carbon density ($g{\cdot}m^{-2}$); TOC is the organic carbon content ($g{\cdot}g^{-1}$); y is the average soil species capacity ($g{\cdot}m^{-3}$); and H is the average surface layer thickness (m) of each soil species.

The carbon density of dead organic matter is relatively small and difficult to estimate in the overall carbon pool; so, it was not considered in this study for the time being. In summary, the results of three types of carbon density in the Zoigê alpine grassland were obtained by calculation (Table 1).

Table 1. Carbon density and correction table for each land use component of Zoigê alpine grassland (unit: Mg/ha).

Land Use Type	Aboveground Carbon Density	Correction Results	Underground Carbon Density	Correction Results	Soil Carbon Density	Correction Results
Cropland	5.81	5.86	28.5	28.57	31.5	31.53
Woodland	31.53	22.87	55.92	45.63	146.88	132.46
Grassland	35.50	35.58	36.50	32.55	132.61	110.80
Water bodies	-	-	0	0	0	0
Wetland	23.52	18.64	57.33	64.31	156.38	148.69
Planted surface	0	1.50	0	0	0	0
Shrubland	8.25	8.26	2.62	2.68	102.55	85.75
Bare land	0	0	0	0	0	0
Snow and ice	0	0	0	0	0	0

2.3. Research Methodology

2.3.1. InVEST Model Carbon Stock Module

In this study, the carbon storage and sequestration module of the InVEST model (Integrated Valuation of Ecosystem Services and Trade-offs) was used to estimate the carbon stocks of regional ecosystems. The model contains a series of sub-modules to simulate the effects of land cover change on the ecosystem service functions. The carbon storage module divides ecosystem carbon storage into four basic carbon pools: aboveground biogenic carbon (carbon in all living plant material above the soil), belowground biogenic carbon (carbon present in the living root system of plants), soil carbon (organic carbon distributed in organic and mineral soils), and dead organic carbon (carbon in dead trees, standing or fallen). The model calculates the total carbon stock in the study area with the following equation.

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{\text{dead}} \quad (3)$$

C_{total} is the total carbon stock in the watershed (Mg/ha), C_{above} is the aboveground carbon stock (Mg/ha), C_{below} is the belowground carbon stock (Mg/ha), C_{soil} is the soil carbon stock (Mg/ha), and C_{dead} is the dead organic carbon stock (Mg/ha). Meanwhile, using the carbon density and land use data of each category, the carbon stock of each land use type in the region was calculated by the formula:

$$C_{totali} = (C_{abovei} + C_{belowi} + C_{soili} + C_{\text{deadi}}) \times A_i \quad (4)$$

where i is the average carbon density of each land use and A_i is the area of the land use.

2.3.2. Correction of Carbon Stock Simulation Results

The carbon density data used in this study are regional study data, and the carbon density values change with the specific climatic factors [29]; so, regional numerical corrections need to be made to make them more closely match the real carbon density distribution in the study area. It has been shown that the effectiveness of the regional precipitation significantly affects the variation of the biological and soil organic carbon density in alpine grasslands rather than temperature [30]. Therefore, the equations in Ahirwal et al. [31] and Alam et al. [32] were referred to as the equations for correcting the precipitation factor, and Yang et al. [18] and Gupta et al. [33] were referred to for the equations for correcting the annual mean temperature.

$$C_{SP} = 3.3968 \times P + 3996.1 \qquad \left(R^2 = 0.11\right) \quad (5)$$

$$C_{BP} = 6.7981e^{0.00541P} \qquad \left(R^2 = 0.70\right) \quad (6)$$

$$C_{BT} = 28 \times T + 398 \qquad (R^2 = 0.47,\ P > 0.01) \quad (7)$$

where C_{SP} is the soil carbon density (kg·m^{-2}) based on annual precipitation, C_{BP} and C_{BT} are the biomass carbon density (kg·m^{-2}) based on annual precipitation and mean annual temperature, respectively, P is the mean annual precipitation (mm), and T is the mean annual temperature (°C).

$$K_{BP} = \frac{C'_{BP}}{C''_{BP}} \quad (8)$$

$$K_{BT} = \frac{C'_{BT}}{C''_{BT}} \quad (9)$$

$$K_B = K_{BT} \times K_{BP} \quad (10)$$

$$K_S = \frac{C'_{SP}}{C''_{SP}} \quad (11)$$

where K_{BP} and K_{BT} are the correction factors of precipitation and temperature for biomass carbon density, C'_{BP} and C''_{BP} are the biomass carbon density data based on the annual precipitation for the Zoigê grassland and the Qinghai-Tibet Plateau, respectively; C'_{BT} and C''_{BT} are the biomass carbon density data based on annual mean temperature for the Zoigê grassland and the Qinghai-Tibet Plateau, respectively; C'_{SP} and C''_{SP} are the soil carbon density data based on the annual mean temperature for the Zoigê grassland and the Qinghai-Tibet Plateau, respectively; K_B and K_S are the correction factors of biomass carbon density and soil carbon density, respectively. C'_{SP} and C''_{SP} are the soil carbon density data obtained from the annual mean temperature of the Zoigê grassland and the Qinghai-Tibet Plateau, respectively; K_B and K_S are the biomass carbon density correction coefficients and soil carbon density correction coefficients, respectively. The corrected carbon densities of the various carbon pools in the Zoigê grassland region are shown in Table 1.

3. Results and Analysis

3.1. Carbon Stock Changes in Zoigê Grassland from 2000 to 2020

In the study, the 0–10 cm soil organic carbon density data from the Chinese terrestrial ecosystem carbon density dataset of the 2010s [28] were used to validate the carbon stocks estimated by the InVEST model; the validation results showed that the carbon stocks in the Zoigê alpine grassland region, estimated based on the sample strip survey and the InVEST model, had good significance (Figure 2), and the linear fit results were significantly different ($p < 0.05$), but at the same time, there were differences in the time scale between the two datasets as well as the geographical environmental specificity, which led to a lower degree of equation fit.

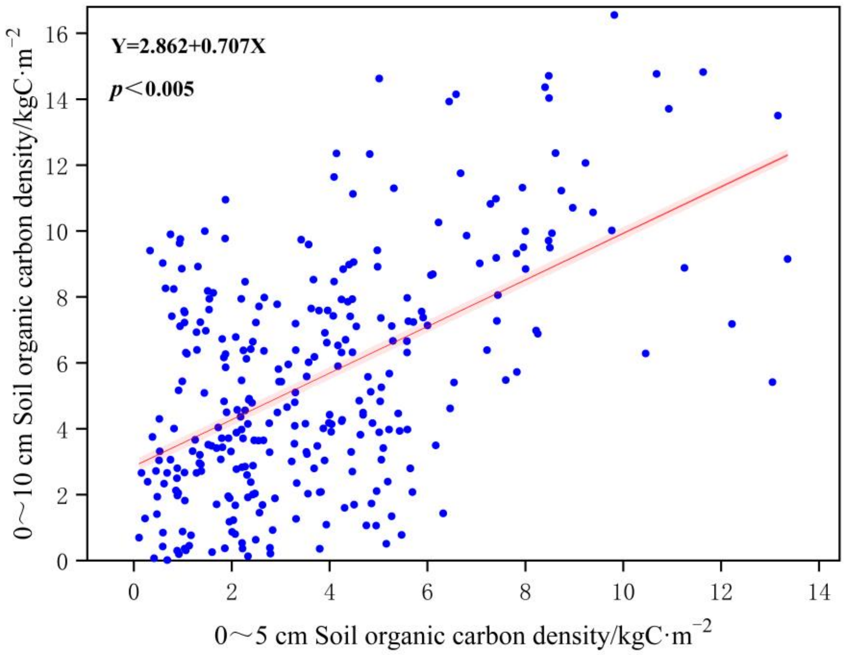

Figure 2. Carbon Density Verification.

The carbon stock data of the Zoigê alpine grassland region in 2000, 2010, and 2020 were calculated using the carbon module in the InVEST model (Table 2, Figure 3), respectively. Quantitatively, the total carbon stocks in the study area were 786.19 Tg, 780.02 Tg, and 775.22 Tg in the years 2000, 2010, and 2020, respectively, with an overall decreasing trend and a cumulative loss of 10.97 Tg. Among them, the regional carbon stocks decreased by 6.17 Tg from 2000 to 2010, with a decrease of 0.78%; from 2010 to 2020, the regional carbon stock decreased by 4.8 Tg, or 0.62%.

During 2000–2020, the changes of the aboveground carbon stock, the underground root carbon stock, and the soil carbon stock all showed a decreasing trend, among which the soil stock decreased significantly, while the sensitivity of the total carbon stock to different types of carbon density was analyzed; as shown in Figure 4a–c, the linear fits of total carbon density with the aboveground, underground, and soil were significantly positive ($p < 0.05$).

Table 2. Carbon stocks of various types in Zoigê alpine grassland (Unit: Tg).

Years	Aboveground Carbon Density	Underground Carbon Density	Soil Carbon Density	Carbon Storages Total
2000	135.86	158.04	492.29	786.19
2010	133.66	158.43	487.93	780.02
2020	131.35	158.38	485.49	775.22

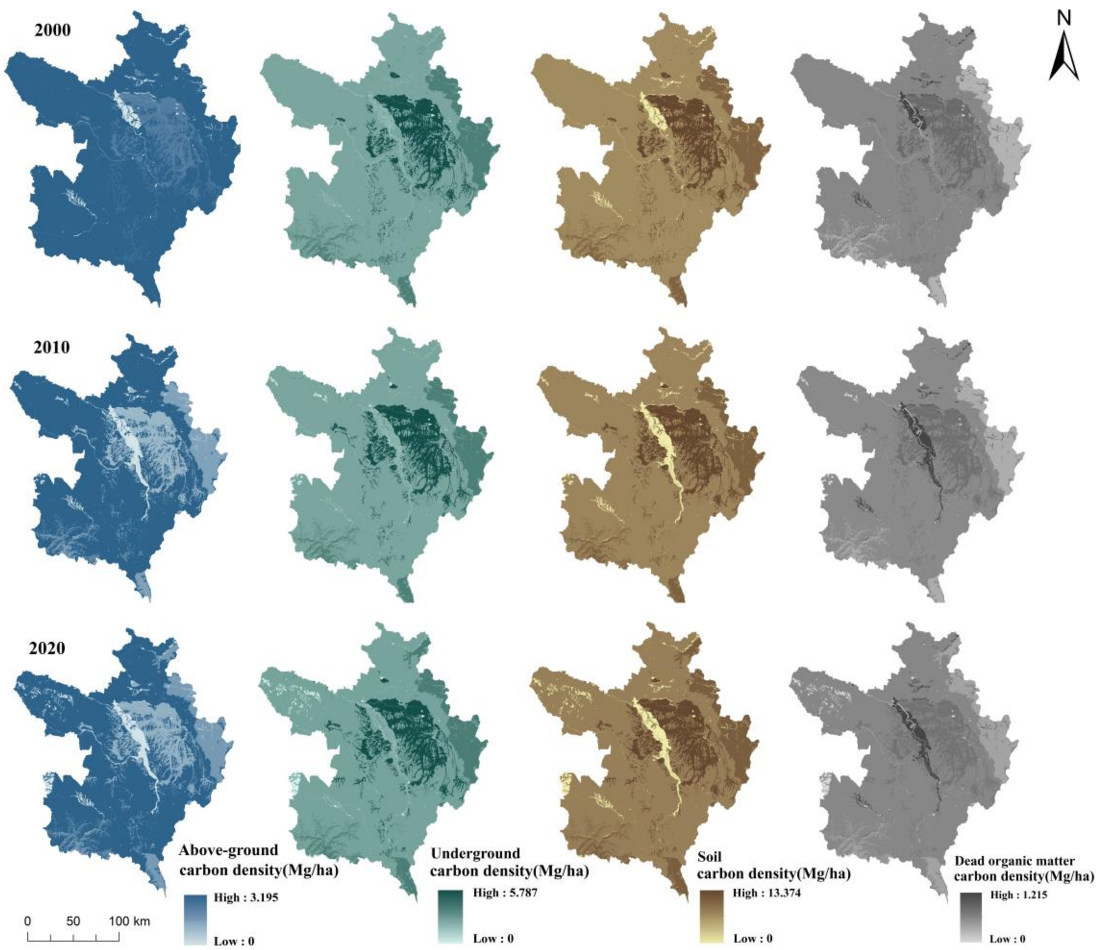

Figure 3. Distribution of various types of carbon pools in Zoigê alpine grassland.

The contribution values of the carbon stocks of the different land use types in the Zoigê alpine grassland to the total regional carbon stocks were, in descending order: grassland, wetland, woodland, cropland, manmade surface, and shrubland. From the perspective of land use types (Table 3), the carbon stocks of the different land use types in the Zoigê alpine grassland varied slightly in different periods [34]. The main manifestations are the forest, wetland, shrubland, cropland, and manmade ground carbon storage increased and the grassland, cropland, shrubland, and carbon storage decreased, among which the wetland carbon storage increased more obviously. During the period of 2000–2020, Zoigê County implemented the "Sichuan Ruoerge Internationally Important Wetland Protection and Restoration Project" to take the plowing back to wet, sowing grass. During the period of 2000–2020, Zoigê County implemented the "Sichuan Zoigê Internationally Important Wetland Protection and Restoration Project", taking biological measures, such as returning wetlands to the soil, sowing grass, and fertilizing; the wetland area increased by 572.64 km^2, an increase of 12.44%, and the carbon stock increased by 13.83 Tg, accounting for 15.36% of the total regional carbon stock [35,36]. From 2000 to 2020, the total area of grassland was 33,052.38 km^2 at the maximum, accounting for 77.23% of the total area of the region, and the carbon storage accounted for 72.14% of the total carbon storage in the region, which is the most important carbon pool in the Ruoerjia region. The area of woodland accounts for 10.35% of the whole region, and the carbon stock accounts for 11.34% of the total carbon stock in the region, and its area as a whole shows an increasing trend and is one of the main carbon pools in the study area.

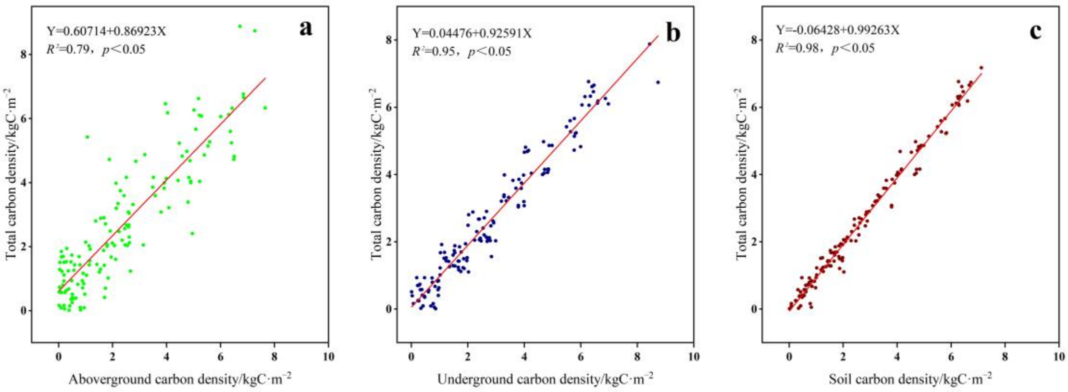

Figure 4. Sensitivity of carbon density of various carbon pools to total carbon density.

Table 3. Land use type changes and carbon stocks in the Zoigê alpine grassland area from 2000 to 2020 (unit: area-square kilometers; share-%; Tg).

Land Use Types	2000			2010			2020		
	Area (Km^2)	**Percentage (%)**	**Carbon Stock**	**Area (Km^2)**	**Percentage (%)**	**Carbon Stock**	**Area (Km^2)**	**Percentage (%)**	**Carbon Stock**
Artificial surface	44.21	0.10	0.0066	69.57	0.16	0.0104	98.54	0.23	0.0148
Bare ground	-	-	0	106.30	0.25	0.00	226.37	0.53	0.00
Cropland	657.22	1.54	5.2118	1206.31	2.82	9.5661	1174.74	2.74	9.3157
Forest	4199.73	9.81	87.4805	3926.12	9.17	81.7810	4429.80	10.35	92.2729
Glacial snow	0.42	0.00	0	0.43	0.00	0.00	204.75	0.48	0.00
Grassland	33,052.38	77.23	620.7237	32,315.32	75.51	606.8816	31,248.74	73.01	586.8514
Shrubland	-	-	0	0.35	0.00	0.0037	0.24	0.00	0.0026
Water bodies	241.42	0.56	0	187.32	0.44	0.00	239.55	0.56	0.00
Wetland	4602.41	10.75	111.1484	4986.08	11.65	120.4139	5175.06	12.09	124.9777
Total	42,797.82	100.00	824.5711	42,797.82	100.00	818.6568	42,797.82	100.00	813.4351

3.2. Spatial Variation Characteristics of Carbon Stock in Zoigê Grassland

Based on the carbon storage data of 2000, 2010, and 2020 in the study area, the spatial distribution map (Figure 5) shows that the carbon sequestration area is clustered in the middle and distributed in all directions, and the carbon storage has a more obvious spatial variation. The areas with high carbon storage are mainly located in the swampy wetlands in the central part of the study area, with the highest value of 21.74 t/ha; administratively, they are located in the territory of Zoigê County and part of the northern part of Hongyuan County, where the land use types are mainly wetlands and grasslands, and the Zoigê Plateau, as the main distribution area of peatlands in China, has a strong carbon storage capacity. The areas with low carbon storage are mainly located in Luqu County, the southern part of Magqu County, and Aba County, and the regional land use type is mainly grassland and arable land, with the lowest value of 0 t/ha, mainly in Hongyuan County and Magqu County, and the main land type is water (glacial snow, rivers, etc.).

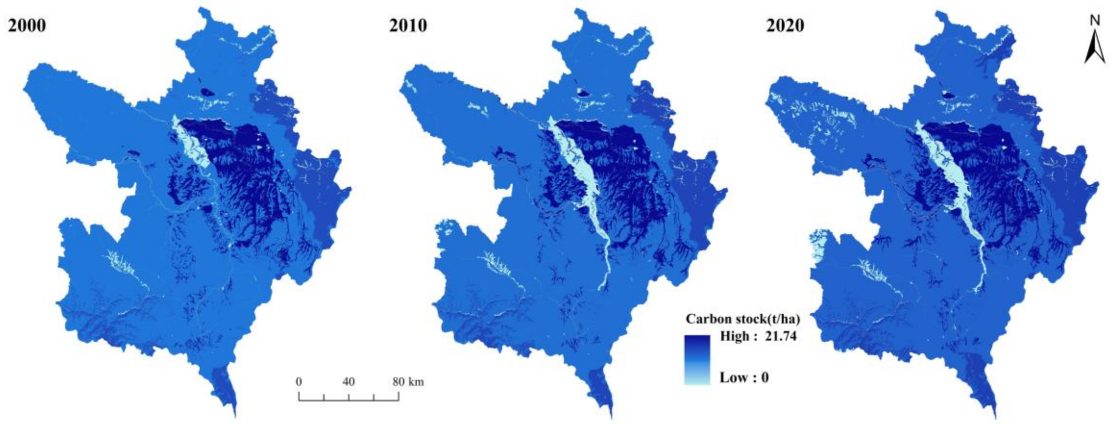

Figure 5. Spatial distribution of carbon stocks in the Zoigê alpine grassland area during 2000–2020.

In order to more clearly reflect the spatial changes of the carbon stocks in the Zoigê grass area, the spatial change values of carbon stocks from 2000 to 2020 were divided into three categories: decreasing, basically unchanged, and increasing. The raster subtraction operation was performed on the carbon stock distribution maps before and after the two periods to obtain the increase and decrease of each raster value. The 2000–2020 carbon stocks in most areas remained basically unchanged (Figure 6), accounting for 95.77% of the total watershed area; the area where the carbon stocks decreased was 1202.61 km^2, accounting for 2.81% of the total watershed area; the land type was mainly cultivated land encroaching on the wetlands, and it was concentrated. The area of carbon stock increase was 607.73 km^2, accounting for 1.42% of the total watershed area, mainly in the northeastern part of Ruoerge County, while the distribution in Hongyuan County was less and more scattered. The overall spatial variation of carbon stock in most areas was small, and the area of carbon stock increase and decrease accounted for 4.23% of the total area. The large changes were mainly distributed in the wetland and river areas in the central part of the region, where human agricultural activities are frequent and the arable land area is increasing. Due to the implementation of ecological and environmental policies, such as the returning of the farmland to wetlands, the wetland area is expanding and the carbon stock is showing an increasing trend [37].

3.3. Land Use Type Change in Zoigê Grassland and Its Effect on Carbon Stock

Grassland is the most widely distributed in the study area, while cropland, wetland, and manmade surface are mainly distributed in the swampy wetland area in the central part of the region; woodland is distributed in the eastern and southern parts of the region, and the rest of the land types are more scattered (Figure 7). During the study period, relative changes occurred in all the types of land (Table 4). From 2000–2020, land use changes in the region were mainly of the arable land and manmade surface, with the area of arable land increasing by 517.52 km^2 or 44.05%, mainly in the swampy wetland and river areas of Zoigê County and Magu County; the area of manmade surface increased by 54.33 km^2, intersecting with the area of wetland and river areas of Zoigê County and Magu County. In 2000, it increased by 55.13%; the area of woodland increased by 230.07 km^2, or 5.19%, of which the southern part of Hongyuan County had a larger growth area; the area of wetland increased by 572.64 km^2, or 11.07%, indicating that Zoigê County has been taking effective measures to protect wetland ecology in recent years. Grasslands, as an important carbon sequestration type in the region, showed a decreasing trend during the study period, with an area decrease of 1803.64 km^2, or nearly 5.46%. The reasons for this are that grasslands are sensitive to climate change, while inappropriate human engineering and overgrazing affect the balance of the grassland carbon pool.

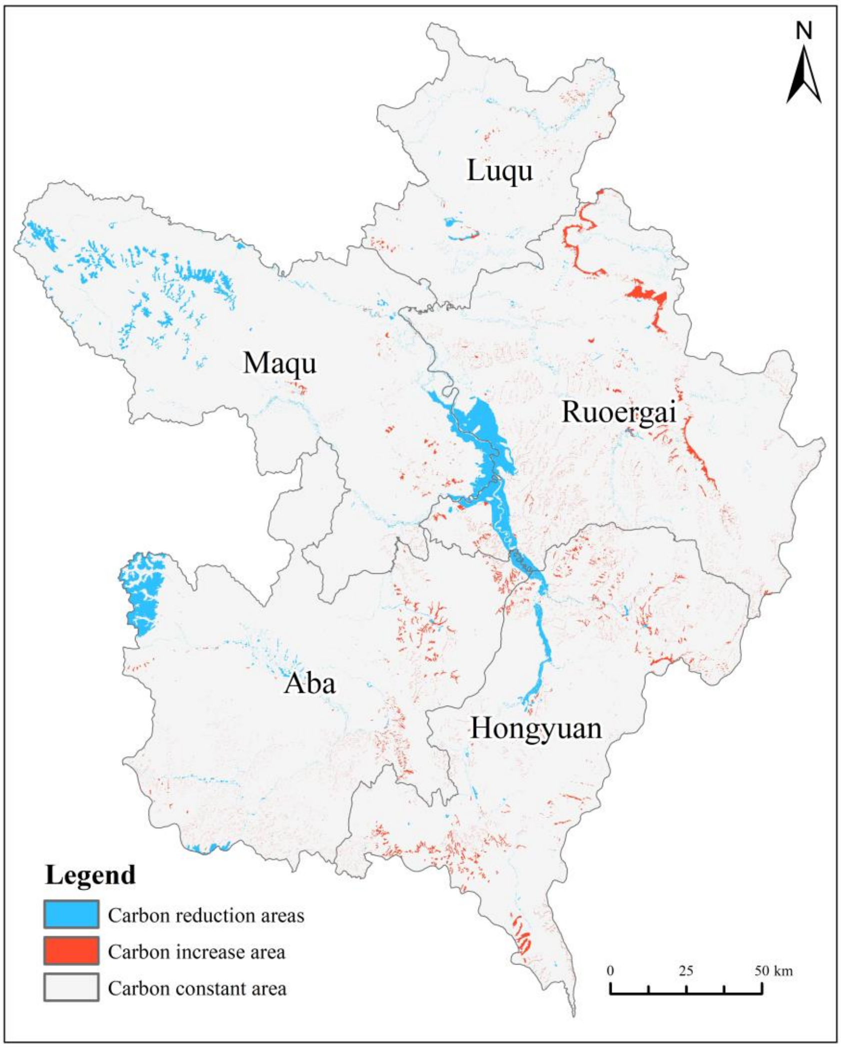

Figure 6. Changes in the spatial distribution of carbon stocks in the Ruoerge alpine grassland region during the period 2000–2020.

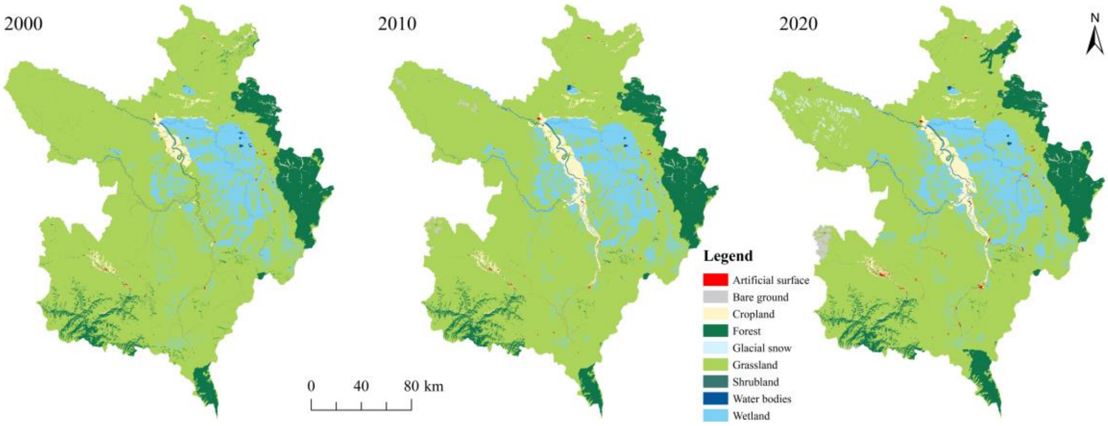

Figure 7. Spatial distribution of land use in the Zoigê alpine grassland area during 2000–2020.

Table 4. Land cover area transfer matrix of Zoigê alpine grassland from 2000 to 2020 (unit: km^2).

2020	2000						
	Artificial Surface	**Cropland**	**Forest**	**Glacial Snow**	**Grassland**	**Water Bodies**	**Wetland**
Artificial surface	29.93	11.89	0.71	-	51.14	0.63	4.17
Bare ground	0.10	-	2.95	0.01	223.12	0.24	-
Cropland	5.26	576.12	7.75	-	566.47	9.14	8.87
Forest	0.32	11.25	3843.55	-	559.42	2.37	2.18
Glacial snow	-	-	1.58	0.31	230.89	0.01	-
Grassland	8.15	42.08	337.44	0.10	30,448.38	49.56	347.08
Shrubland	-	0.01	0.00	-	0.17	0.03	0.04
Water bodies	0.28	4.03	3.80	-	73.70	126.18	30.86
Wetland	0.17	11.82	0.55	-	892.97	52.61	4209.22

The extrusion of high carbon density grasslands and wetlands dominated by cultivated land reclamation reduced the overall carbon stock in the study area. As can be seen from Table 4, land use changes led to a decrease of about 10.97 Tg in the regional carbon stock of the Zoigê alpine grassland, mainly because the population of Zoigê County increased from 76,000 to 82,000 in 2010–2020, including a 1.51% increase in the population of pure agriculture and animal husbandry; the increase in population made a large number of wetland land types in the Zoigê area transform into arable land at the same time that livestock breeding caused a decrease in grassland land The conversion of peatland, wetlands, and grasslands has reduced the regional carbon sequestration capacity, while the carbon density of the subsurface and soil has decreased sharply, resulting in the reduction in the total regional carbon stock.

The contribution values of the carbon stocks of the different land use types to the total carbon stocks in the study area are, in descending order, grassland, wetland, forest land, cropland, and manmade surface. The maximum area of grassland in the study area was 33,052.38 km^2, accounting for 77.23% of the total area and 75.28% of the total carbon stock; the area of wetland accounted for about 12.09% of the whole study area and 15.36% of the total carbon stock; the area of woodland accounted for about 10.35% of the whole study area and 11.34% of the total carbon stock. In terms of land use type changes, although the area of grassland and its carbon stock decreased, it is still the most important carbon pool in the study area, and two land use types, wetland and woodland, accounted for 26.70% of the total carbon sequestered by the overall land use types in the study area. In summary, the increase in the area of cultivated land with lower carbon density and the decrease in the area of grassland with higher carbon density are the main reasons for the decrease in the carbon stock of the ecosystem in the study area.

4. Discussion

4.1. Spatial and Temporal Variation of Carbon Stock and Its Influencing Factors

Different land cover types of the ecosystem have different carbon sequestration capacities; so, there are also large spatial and temporal differences in the carbon stocks contained in the carbon pools of different land use types in the region. This study shows that the total regional carbon stock in the Zoigê alpine grassland region showed a decreasing trend during 2000–2020, which to some extent reflects the declining function of the Zoigê grassland ecosystem. This is consistent with the findings of some scholars; for example, ZHOU et al. [38] concluded that in the wetlands in the Zoigê Plateau, after the peatland drainage, the water table dropped significantly, leading to rapid oxidative decomposition of the peat organic matter, which in turn reduced the soil organic matter thickness and decreased the soil organic carbon storage. The sensitivity results showed that total carbon density was most sensitive to changes in the aboveground carbon density (Figure 5), and ZHANG et al. [4] noted that aboveground biomass is susceptible to human activities and climate change, as well as being directly related to land use changes and vegetation development management, etc., which is consistent with the results of this study, indicating that aboveground carbon density is one of the most influential causes of total carbon density. This is consistent with the results of this study, which indicate that aboveground carbon density is one of the most influential factors on total carbon density.

In the InVEST model, there is no inter-annual variation in the parameters of carbon density across the categories; so, the conversion of different land cover types in the study area is a major factor in the change of the regional carbon stocks, and the conversion of swampy wetlands to cropland and the reduction in grassland area due to the increase in population and livestock economy in the region have reduced the regional carbon sequestration capacity to some extent. Shi et al. [39] used the InVEST model to estimate the total annual carbon stocks in the Ili Valley, and the results showed that the retreat of regional forest and grassland areas was the dominant factor in the decrease in carbon stocks. Zhu et al. [5] analyzed the impact of land use change on regional carbon stocks in the arid zone from 1980 to 2015, i.e., the expansion of construction land occupied the forest and grassland, resulting in the decrease in the regional ecosystem carbon stocks. The carbon sequestering grassland land cover type in the Zoigê alpine grassland regional ecosystem is the main carbon sink and the dominant factor affecting its carbon stock changes.

4.2. Uncertainty Analysis

In the study, we used sample strip data to estimate the carbon stock of the Zoigê alpine grassland based on the InVEST model, and validated it using the Chinese terrestrial ecosystem carbon density dataset of the 2010s [28], and the validation results showed that the carbon density estimated in this study has good robustness, and some dispersion points exist in the linear fit, which is analyzed mainly because the two datasets are different in time scale. The main reason for this is the difference in time scale between the two sets of data, and secondly, there are also geographic location and environmental specificities that lead to some bias in the data [40].

It has been shown that the horizontal distribution of organic carbon content and density in alpine wetland soils has obvious spatial heterogeneity [41], and the alpine wetland soils in Zoigê have a strong carbon sequestration capacity. Although the carbon density data corrected by temperature data are closer to the real carbon density data, the carbon density values of each type of soil are also subject to relative changes due to the influence of regional soil pH, organic matter, cation exchange capacity, total nitrogen, total phosphorus, fast-acting nitrogen, fast-acting phosphorus, fast-acting potassium, and bulk weight, etc. Therefore, it is limited to use only precipitation and average annual temperature to correct the soil carbon density in the study. Therefore, a more accurate estimation of the carbon stock in the study area requires numerical simulations combining various characteristic values of the soils, which will be an important direction for future research [9,40].

In addition, InVEST model estimates carbon stock based on land cover type changes, without taking into account the relatively important factors for the regional carbon sink, such as photosynthetic effective radiation and soil microbial activity, etc. In general, photosynthetic effective radiation can characterize soil fertility [42]; the greater the fertility of the soil, the higher the organic matter content, and the most suitable soil environment for microbial activity is neutral, with soil pH values between 6.5 and 6.5. Values from 6.5 to 7.5, which are too acidic or too alkaline, will inhibit the activity of the microorganisms in the soil [43]. Although there are uncertainties in the InVEST model, its estimation results can reflect the spatial and temporal changes of carbon stock and the response to land use changes in the Zoigê alpine grassland region from 2000 to 2020. As an important indicator of the ecosystem service function, carbon stock can reflect the state of the ecosystem in the study area and provide a reference for the coordinated economic and ecological development.

5. Conclusions

In this study, the impact of land cover change on the carbon stock in the Zoigê alpine grassland region of China from 2000 to 2020 was assessed based on the carbon stock module of the InVEST model, taking the Zoigê alpine grassland region of China as an example. Due to the increase in population and the development of regional livestock farming, the cultivated land type gradually encroaches on the wetland, which shows a continuous increase in cultivated land and artificial surface area and a decrease in the grassland area. The areas with high carbon stocks are mainly located in the central swampy wetlands of the study area, in the territory of Zoigê County and the northern part of Hongyuan County. The areas with low carbon stocks are mainly located in Luqu, the southern part of Magqu County, and Aba County, and the land use types are mainly grassland and cropland. In recent years, the carbon stock in the study area showed a trend of decreasing year by year, and the carbon stock in Zoigê alpine grassland area was 786.19 Tg, 780.02 Tg, and 775.22 Tg in 2000, 2010, and 2020, respectively, with a cumulative loss of 10.97 Tg or 1.40%. The increase in the area of arable land with lower carbon density and the decrease in the area of grassland with higher carbon density are the main reasons for the decrease in carbon stocks in the study area ecosystems, and future research should investigate the spatial heterogeneity of the carbon density distribution and the influence of the vegetation age on carbon density and improve the model accuracy by considering the influence of environmental, anthropogenic, and biochemical factors [44].The alpine grasslands have a large carbon sink potential, and the region should strengthen the protection of high carbon sequestration type ecological areas such as grasslands and wetlands; the results of the study can provide an effective scientific basis for the management of carbon pools in the alpine grasslands of Zoigê.

Author Contributions: Conceptualization, R.Q., L.H. and Z.H.; methodology, R.Q., L.H. and Z.H.; software, R.Q.; validation, R.Q., L.H. and Z.H.; formal analysis, R.Q.; investigation, R.Q., B.W., P.L., J.W., G.K. and W.B.; resources, L.H. and Z.H.; data curation, R.Q.; writing—original draft preparation, R.Q.; writing—review and editing, R.Q., L.H. and Z.H.; visualization, R.Q., L.H. and Z.H.; supervision, L.H. and Z.H.; project administration, L.H. and Z.H.; funding acquisition, L.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was sponsored by the Natural Science Foundation of Sichuan, China (2022NSFSC1040) and supported by the Independent Research Project of the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection Independent Research Project (SKLGP2021Z003).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We thank the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (Chengdu University of Technology) for this support. This study is part of the research activities conducted by the first author during his PhD studies at Chengdu University of Technology. The authors express sincere thanks to two anonymous reviewers for critical evaluation and constructive suggestions to improve the manuscript.

Conflicts of Interest: No potential conflict of interest was reported by the authors. 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.

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