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Spatiotemporal Variations in the Carbon Sequestration Capacity of Plateau Lake Wetlands Regulated by Land Use Control under Policy Guidance

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Abstract: Lake wetlands play a crucial role in mitigating climate change. Human activities and climate change impact the carbon sequestration capacity of lake wetlands. However, this process is intricate. Clarifying the decisive factors that affect carbon sequestration is crucial for preserving, utilizing, and enhancing the carbon sequestration capacity of plateau lake wetlands. Here we analyzed the regulatory role of land use under policy guidance on the carbon sequestration capacity of the plateau lake wetland of Caohai (CHLW), SW China. The results show that: (1) The cumulative carbon sequestration varied significantly from 1990 to 2020, with the highest carbon sequestration of 15.80×10^5 t C in 1995 and the lowest of 3.18×10^5 t C in 2020, mainly originating from endogenous carbon sequestration within the plateau lake wetlands. (2) As of 2020, the carbon stock of CHLW was approximately 2.54×10^8 t C. (3) The carbon sequestration in CHLW experienced a dynamic change process of decrease-increase-decrease over 30 years, mainly influenced by land use changes under policy regulation, with human and natural factors accounting for 91% and 9%, respectively. (4) Under three simulated scenarios (Q1, Q2, and Q3), the ecological priority scenario exhibited positive regulation on the carbon sequestration of CHLW and the entire protected area in 2030 and 2060, with the highest increase in carbon sequestration. This scenario is consistent with the current conservation policy, indicating that the current protection policy for CHLW is scientifically reasonable. This research demonstrates how land use and climate changes impact carbon storage in wetlands, with consideration of policy guidance. It provides references for utilizing and conserving lake wetlands worldwide, ultimately achieving the dual goals of wetland conservation and carbon neutrality.

Keywords: plateau lake wetlands; land use change; carbon sink; carbon sequestration; local policies

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1. Introduction

Humanity is facing tremendous challenges brought on by global climate warming. The fundamental approach to addressing climate issues and achieving carbon neutrality is through "emission reduction" and "carbon sequestration" [1]. Carbon storage plays a crucial role in regulating the carbon balance of ecosystems and is vital to regulating regional climate. Along with forest carbon reservoirs, wetlands, one of the three major ecosystems, also play an essential role in carbon storage. In the wake of the 2009 Climate Change Conference, researchers have increasingly focused on the part of wetlands in the global carbon cycle. Numerous scholars have researched its ability to sequester carbon, making it a popular topic of study [2–6]. Research on the ability of wetlands to sequester carbon on a global scale started with estimating the carbon storage in estuarine and rice paddy wetlands [7]. With the progress of technology, there has been a revolutionary development in the research of global wetland distribution and carbon storage estimation [8]. Weston [9] and other researchers have explored the mechanisms of carbon sequestration in coastal wetlands, investigating the connection between temperature, sea-level rise rates, and sediment. Studies conducted by Bogard [10] and other researchers have examined the functionality

of wetlands. They have also analyzed the extent to which restored wetlands maintain the same carbon cycling patterns as the original natural ecosystems. Chiara et al. [11] quantitatively analyzed wetland soil carbon turnover rate variations. Most researchers have focused on wetland carbon storage, carbon sequestration rates, wetland restoration, and other related topics [12–14].

Moreover, some researchers have argued that wetlands possess a significant carbon sequestration potential that surpasses that of other ecosystems by ten times. This makes them pivotal in combating global climate change and maintaining equilibrium in the carbon cycle [15,16]. Lakes, being a type of wetland, have a considerable capacity for carbon sequestration. Their anaerobic ecological conditions result in lower organic matter decomposition rates [17]. As our society has rapidly developed, human actions have had differing impacts on wetland ecosystems and their ability to store carbon. Among these ecosystems, lake wetlands have been identified as one of the most affected by human activity [18]. Research on lake wetlands has primarily focused on aspects such as the chemical properties of lake wetland water, eutrophication, and the impacts of climate change [19–23]. However, there has been limited research on how the carbon sequestration capacity of lake ecosystems is jointly regulated by human and climatic factors under policy influence [24–26], particularly regarding how local policies affect the carbon sequestration capacity of lake basin wetland ecosystems, which remains largely unexplored. This study takes the typical plateau lake wetland, Caohai, as the research object, estimates its carbon sequestration from 1990 to 2020, and analyzes the impacts of two influencing factors under policy guidance on the carbon sequestration capacity and carbon storage of CHLW. Additionally, the research predicts how carbon sequestration may change under various future land use scenarios. The research findings can assess the carbon sequestration capacity of CHLW and provide a decision-making basis for their conservation and management.

2. Site Description and Methods

2.1. Site Description

The Caohai Nature Reserve (CHNR) is in the northwestern part of Weining Yi, Hui, and Miao Autonomous County, Guizhou Province, China. It is situated between 104°00′ and 104°30′ east longitude and 26°44′ and 27°01′ north latitude. The recent water area of the lake in the Caohai reaches 50 square kilometers, making it the largest plateau freshwater lake in Guizhou Province. The CHLW is part of the Yangtze River system and is primarily supplied by precipitation and groundwater. It has a perennial effective catchment area of 96 square kilometers, with an average annual rainfall of 881.81 mm. The yearly runoff reaches 8–9 million cubic meters. The maximum depth of Caohai Lake is 5 m, and the water area varies seasonally due to changes in rainfall. The Caohai region has a subtropical plateau monsoon climate, with an average annual temperature of 10.5 °C. The highest temperatures occur in July, while the lowest temperatures occur in January (Figure 1).

2.2. Methods

2.2.1. Estimating Carbon Sequestration

Wetland ecosystems are unique due to the overlap between terrestrial and aquatic environments. This contributes to their diversity in carbon sequestration types and distribution patterns. Research on wetland carbon sequestration has encompassed diverse climatic regions and wetland classifications. The primary focus of these studies has been to estimate the carbon storage in terrestrial and aquatic carbon pools. As a typical lake wetland with karst landform features, CHLW should focus on estimating carbon sequestration in hydrophytes, bodies of water, and sediments as components of the aquatic carbon pool.

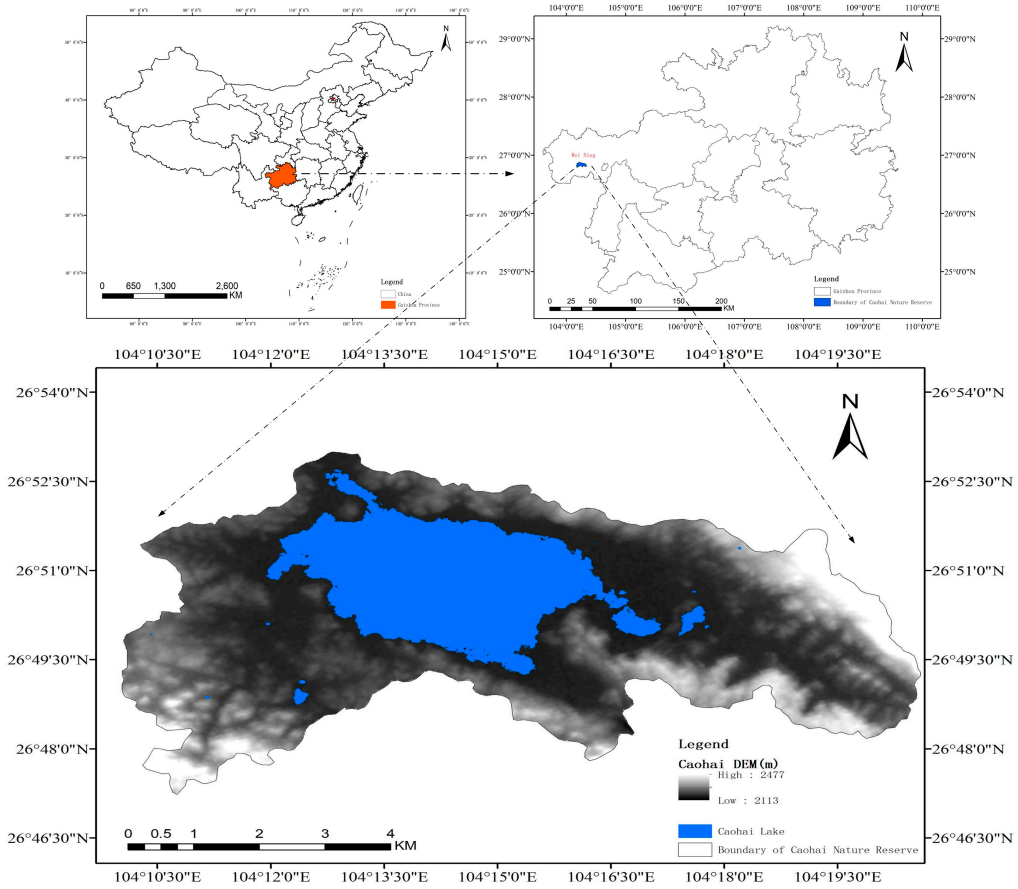

Figure 1. Location of Caohai Nature Reserve.

(1) Carbon Sequestration by Wetland Vegetation

To estimate carbon sequestration in wetland vegetation, the usual practice is to evaluate the biomass above and below the ground. Standard techniques for this purpose involve measuring plots in the field, using non-invasive estimation methods, employing satellite data for remote sensing-based estimation, and utilizing models for remote sensing biomass estimation. Based on published data from CHLW and scholars' measurements of plant biomass at different periods, the carbon sequestration of wetland vegetation in CHLW is estimated. The vegetation in CHLW mainly includes emergent plants, submerged plants, floating-leaved plants, and free-floating plants. Vegetation carbon density is typically calculated by multiplying the vegetation biomass by its corresponding carbon conversion coefficient. The carbon conversion coefficient (ρ) is usually assumed to be 0.5 [27,28]. The calculation formula for vegetation carbon sequestration in CHLW is

$$DC = \rho \times S \times Q \quad (1)$$

In the formula, DC represents the carbon sequestration of vegetation carbon storage in CHLW (t); ρ is the carbon conversion coefficient; S represents the vegetation area of CHLW (m^2); Q represents the vegetation biomass of CHLW (t C/hm^2).

(2) Carbon Sequestration in Wetland Water Bodies

Caohai is a lake wetland primarily composed of water bodies and vegetation. However, there have been relatively few calculations regarding water body carbon sequestration. In this study, we have improved the calculation method for water body carbon sequestration based on the approach proposed by Buffam et al. [29]. The calculation formula is

$$SC = (DOC + DIC) \times h \times S \quad (2)$$

In the formula, SC represents the carbon sequestration of water body carbon storage in CHLW, Guizhou Province (t); DOC is the concentration of dissolved organic carbon in water (mg/L); DIC is the concentration of dissolved inorganic carbon, primarily bicarbonate (HCO^{3-}), in water (mg/L); h is the depth of the lake (m); S represents the water area of CHLW.

(3) Carbon Sequestration by Wetland Sediment

The burial of organic matter in sediments has a substantial carbon sink effect in lakes. The extended period of submerging wetland sediments limits the speed of organic matter decomposition. Consequently, carbon sequestration in lake bottom sediments is notably high and constitutes the primary element of the lake carbon pool. Organic matter originates mainly from remnants of aquatic plants and animals, microorganisms, plankton, and organic contributions from external water cycles. Typically, estimation is conducted using sediment bulk density (g/cm^3), sediment sampling thickness (m), organic carbon content (%), and sediment area (m^2) [30].

$$GC = H \times d \times C \times S \quad (3)$$

In the formula, GC represents the carbon storage capacity of the surface sediment in CHLW sediments (t); H represents the dry bulk density of the CHLW sediments; d represents the thickness (m) of the CHLW sediments (g/cm^3); C represents the organic carbon content in the CHLW sediment (%); S represents the area of the CHLW sediment (m^2).

2.2.2. Simulation of Land Use and Prediction of Carbon Sequestration

(1) PLUS model

In the study, the land use types of CHNR in 2030 were simulated using the PLUS model. Based on the current development, status affected land use changes in the CHNR across three scenarios—Q1 (natural development), Q2 (urban expansion), and Q3 (ecological priority). The land use transition matrices under different scenarios represent the conversion rules between other land classes. Zero indicates the prohibition of conversion to any land class, while one indicates allowed modification (Table 1). The weights in the simulation process were set based on the proportion of different land class conversions.

Table 1. Land Use Transition Matrices under Different Scenarios (a: Cultivated Land; b: Forest Land; c: Grassland; d: Wetland; e: Construction Land).

	Q1					Q2					Q3				
	a	**b**	**c**	**d**	**e**	**a**	**b**	**c**	**d**	**e**	**a**	**b**	**c**	**d**	**e**
a	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
b	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0
c	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0
d	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0
e	1	1	1	1	1	0	0	0	0	1	0	11	1	0	1

(2) InVEST model

This study estimates the carbon sequestration in CHLW from 1990 to 2020 based on three components: water, vegetation, and sediment. The research findings of various scholars are relied upon for this estimation. According to the InVEST model, the estimated carbon sequestration in the CHLW for 2030 is predicted. The InVEST model calculates carbon sequestration based on four carbon pools: aboveground biomass, belowground biomass, soil carbon, and dead organic carbon. The model also references and compares previous research results. The data referenced in this study are presented in Table 2.

Table 2. Sources of carbon density values for different land use types [31] (GL: Cultivated land (km^2); FL: Forest land (km^2); GD: Grassland (km^2); WL: Water land (km^2); CL: Construction land (km^2).

Land Use Types	Aboveground Biomass	Belowground Biomass	Soil Carbon	Dead Organic Carbon
GL	46.5	80.7	108.4	1.0
FL	20.4	67.5	170.0	7.8
GD	4.3	86.5	89.0	0
WL	0	0	0	0
CL	0	0	71.0	0

Spatial and temporal differences in carbon density can occur, which often requires applying model corrections to the collected data. Finally, the carbon pool data for the study area is obtained (please see Table 3). Research conducted by various scholars, including S.A. Alam [32], Giardina [33], and Chen G.S. [34], has shown a clear and strong correlation between carbon density and both temperature and precipitation. Therefore, this study tidies up Formulas (4) and (5), which include carbon density equations and correction coefficients, to adjust the carbon density in the study area.

$$C_{SP} = 3.3968 \times MAP + 3996.1\left(R^2 = 0.11\right) \tag{4a}$$

$$C_{BP} = 6.798 \times e^{0.054 \times MAP}\left(R^2 = 0.70\right) \tag{4b}$$

$$C_{BT} = 28 \times MAT + 398\left(R^2 = 0.47\right) \tag{4c}$$

$$K_{BP} = \frac{C'_{BP}}{C''_{BP}} \tag{5a}$$

$$K_{BT} = \frac{C'_{BT}}{C''_{BT}} \tag{5b}$$

$$K_B = K_{BP} \times K_{BT} = \frac{C'_{BP}}{C''_{BP}} \times \frac{C'_{BT}}{C'_{BT}} \tag{5c}$$

$$K_S = \frac{C'_{SP}}{C''_{SP}} \tag{5d}$$

Table 3. Corrected Carbon Densities for Various Land Use Types in the Study Area.

Land Use Types	Aboveground Biomass	Belowground Biomass	Soil Carbon	Dead Organic Carbon
GL	14.0	24.3	98.0	1
FL	6.1	20.3	158.7	7.8
GD	1.3	26.0	80.5	0
WL	0	0	148 [This study]	0
CL	0	0	64.2	0

In the formula, CSP represents the corrected soil carbon density (t/hm^2). CBP represents the biomass carbon density calculated based on annual precipitation (t/hm^2). CBT represents the biomass carbon density calculated based on temperature (t/hm^2). MAP represents the yearly precipitation in the study area (mm). MAT represents the annual average temperature in the study area (°C). KBP represents the correction coefficient for biomass carbon density based on precipitation. KBT represents the correction coefficient for biomass carbon density based on temperature. KB represents the overall correction

coefficient for biomass carbon density. KS represents the correction coefficient for soil carbon density. C′ represents the carbon density in the CHNR, and C″ represents the collected carbon density data.

As the study area is relatively small and the carbon density data were collected from Guizhou Province and nearby cities, the temperature and precipitation data used in the formulas were also obtained from Guizhou Province. The data were obtained from the "Guizhou Statistical Yearbook" and took a multi-year average, with an annual average temperature of 16 °C and an average yearly precipitation of 1141.4 mm. The CHNR data are based on station data, with an average yearly temperature of 12.35 °C and an average annual rainfall of 919.1 mm.

2.2.3. Correlation Analysis

This paper examines the relationship between carbon sequestration and various factors, such as land use, temperature, and precipitation, in a lake wetland. To do so, the study employs Origin and RDA analysis. The Origin2021 software is used to conduct correlation analysis and calculate *p*-values. Afterwards, the RDA double sequence influence analysis is used to determine the proportion of anthropogenic and natural factors that influence carbon sequestration. Finally, the results of both analyses are compared, and the accuracy verification of the Origin analysis results makes the analysis results more scientific and reliable.

2.3. Data Source and Statistical Analysis

To investigate the relationship between land use, climate, and carbon sequestration in the study region and make projections for land use and carbon sequestration by 2030, data from seven time periods (1990, 1995, 2000, 2005, 2010, 2015, and 2020) were analyzed. These data include land use, location, climate, population, economic data, and estimated data on carbon sequestration in wetlands such as wetland vegetation and water bodies.

The land use data were obtained from the TM remote sensing images of the Landsat satellite in the United States, and the extraction was performed on the Google Earth Engine (GEE) platform. The spatial resolution of these images was 10 m. The data on wetland vegetation area, biomass, lake chemical characteristics, and annual runoff were obtained from literature retrieved from the CNKI (China National Knowledge Infrastructure) database. The temperature and precipitation tabular data were sourced from the National Centers for Environmental Information (NCEI), a National Oceanic and Atmospheric Administration (NOAA) division in the United States. The data from the climate station at Weining National Reference Climate Station, located within a 2 km linear distance from the CHNR, were used.

The PLUS model was used to predict land use changes in three different scenarios: Q1 (natural development), Q2 (urban expansion), and Q3 (ecological priority). Subsequently, the InVEST model was used to estimate carbon sequestration. In the PLUS model, the selection of driving factors considered natural and economic factors in the research area. Six raster datasets were chosen: population, GDP, temperature, precipitation, DEM (Digital Elevation Model), and slope. The data were sourced from the Resource and Environment Sciences and Data Center (https://www.Resdc.cn (accessed on 3 December 2022)).

The CHNR vector boundary data were created using the coordinate point information released by the People's Government of Guizhou Province in 2018. The data underwent coordinate point format conversion and projection using ArcGIS 10.8 software and was drawn per the planning map of the CHNR. The masking method in ArcGIS 10.8 software was applied to extract the driving factor data based on the vector boundary map of the CHNR. The raster data used in the study were geometrically corrected and projected, and the coordinate axes were unified to WGS_1984 UTM_zone_48N. The daily precipitation and temperature data obtained were subjected to statistical analysis using Microsoft Office Excel 2019 to derive the annual mean temperature and annual precipitation data.

3. Results and Discussion

3.1. Spatiotemporal Variations in Land Use Types and Carbon Sequestration in the Caohai Nature Reserve

3.1.1. Land Use Change and Prediction in the CHNR

The CHNR boundary was vectorized using ArcGIS 10.8, and land use type maps for seven different periods of the reserve were extracted through the GEE platform. Using the PLUS model, we conducted a simulation of land use change in the CHNR for 2030. Land use change in 2030 under three scenarios was obtained (Table 4).

Table 4. Dynamic changes in land use types in CHNR from 1990 to 2030 (GL: Cultivated land; FL: Forest land; GD: Grassland; WL: Water land; CL: Construction land; Q1: natural development-scenario; Q2: urban development scenario; Q3: Ecological priority scenario).

Year (a)	GL (hm^2) (%)	FL (hm^2) (%)	GD (hm^2) (%)	WL (hm^2) (%)	CL (hm^2) (%)
1990	5493.81 (57.23%)	679.06 (7.07%)	679.06 (7.07%)	1366.68 (14.24%)	94.31 (0.98%)
1995	4390.34 (45.73%)	1105.43 (11.51%)	1105.43 (11.51%)	1992.53 (20.76%)	112.86 (1.18%)
2000	4370.69 (45.53%)	1030.84 (10.74%)	1030.84 (10.74%)	2018.95 (21.03%)	211.52 (2.20%)
2005	5158.85 (53.74%)	786.49 (8.19%)	786.49 (8.19%)	1964.62 (20.46%)	209.05 (2.18%)
2010	4984.88 (51.93%)	976.55 (10.17%)	976.55 (10.17%)	1842.34 (19.19%)	364.32 (3.80%)
2015	4158.97 (43.32%)	755.14 (7.87%)	755.14 (7.87%)	2007.07 (20.91%)	868.68 (9.05%)
2020	4958.45 (51.65%)	677.76 (7.06%)	677.76 (7.06%)	2098.39 (21.86%)	574.95 (5.99%)
Overall amplitude	−535.36 (−9.74%)	−1.30 (−0.19%)	−675.70 (−34.37%)	731.71 (54.00%)	480.65 (510.00%)
2030 (Q1)	4786.08 (49.86%)	727.15 (7.57%)	1221 (12.72%)	2200.01 (22.92%)	665.76 (6.93%)
2030 (Q2)	4792.79 (49.92%)	718.95 (7.49%)	1215.62 (12.66%)	2174.99 (22.66%)	697.66 (7.27%)
2030 (Q3)	4262.32 (44.40%)	981.32 (10.22%)	1446.01 (15.06%)	2382.77 (24.82%)	527.57 (5.50%)

Based on the remote sensing images and acquired data of the CHNR, it is evident that various land types underwent varying degrees of change from 1990 to 2020. Cultivated land, forest land, and grassland generally decreased in area, while wetland and construction land increased. Based on the policy development process of the CHNR in Guizhou Province and in line with the research conducted by several studies [35–37], it can be inferred that in around 1990, the reserve underwent certain events such as flood discharge and land reclamation, leading to a significant drop in water levels and a significant expansion of cultivated land. Starting in 1991, the management of the reserve strengthened its control over the CHNR, leading to the restoration of water levels and the gradual replacement of cultivated land by wetland, resulting in a reduction in developed land area. In 1990, the primary land use type in the CHNR was cultivated land, with the minor site occupied by construction land and the wetland area ranking third among the five land use types. By 2020, the wetland area ranked second among the five land use types, and the construction land area increased annually. The changing trend in land use reveals the extent and direction of anthropogenic disturbances within the nature reserve.

In the Q1 scenario from 2020 to 2030, the changes in land area across various regions follow similar trends observed from 2010 to 2020. The arable land size decreased by 1.97%, while the wetlands and construction land areas continued to expand. In the Q2 scenario,

the construction land area increased by 375.70 hm^2, representing a growth rate of 3%. Most of the expansion in construction land came from the conversion of cultivated land. In the Q3 scenario, grassland, forest land, and wetland areas increased, while cultivated land and construction land decreased. During the simulation, wetlands were designated as restricted areas, and the wetland area increased under all three scenarios.

The boundary of the CHNR Reserve has been outlined through the generation of a vector map utilizing coordinate points and location information provided in the 2017 announcement from the Guizhou Provincial People's Government titled "Announcement of the Guizhou Provincial People's Government on the Scope and Boundary of Cao Hai National Nature Reserve in Guizhou Province". Land-type extraction was then performed using the GEE platform, and layer rectification, reclassification, and resampling were performed using ArcGIS 10.8. The final result is the land use type map of CHNR for seven periods from 1990 to 2020 (Figure 2). The map shows that the wetlands area has significantly increased from 1990 to 2020, mainly in the southeastern part of the nature reserve. The size of the construction land has been progressively expanding each year, primarily in the northeastern part of the nature reserve.

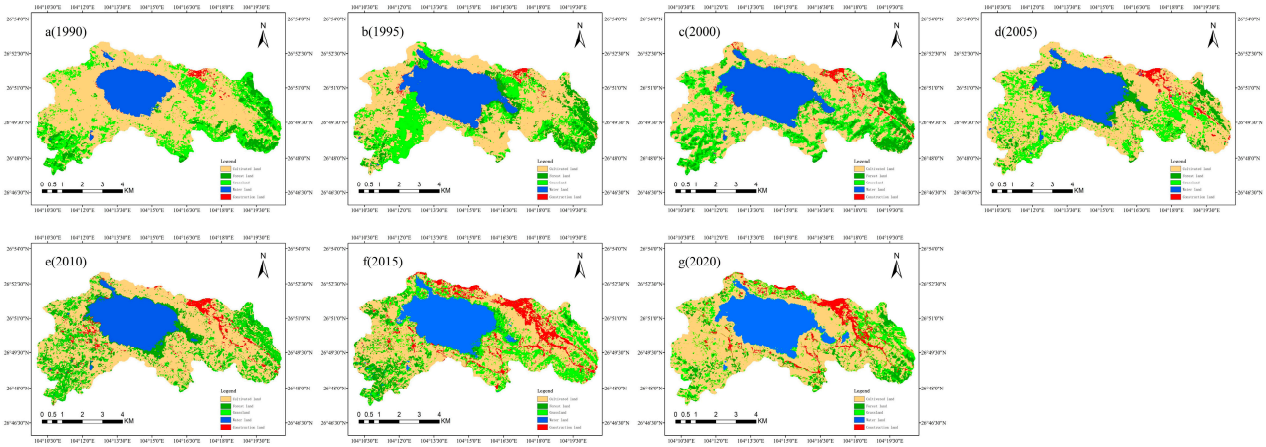

Figure 2. Land Use Type Map of CHNR from 1990 to 2020 ((**a**) 1990; (**b**) 1995; (**c**) 2000; (**d**) 2005; (**e**) 2010; (**f**) 2015; (**g**) 2020).

Based on the above, using the 2020 land status map of CHNR as the baseline data, the PLUS model was used to simulate land use changes in three scenarios for the year 2030 (Figure 3). Scenario Q1 refers to a situation with no restrictions except for the existing wetland areas as the limited expansion areas. Scenario Q2 involves a 30% increase in the expansion of construction land into other land uses, excluding the current wetland areas as restricted expansion areas. Scenario Q3 includes a 20% expansion of wetlands and forests into other land uses while reducing the proliferation of construction land by 30%. The land-use change has significant impacts on carbon storage and emissions in the Grass Sea Nature Reserve, which is consistent with the findings of Yabo et al. [38].

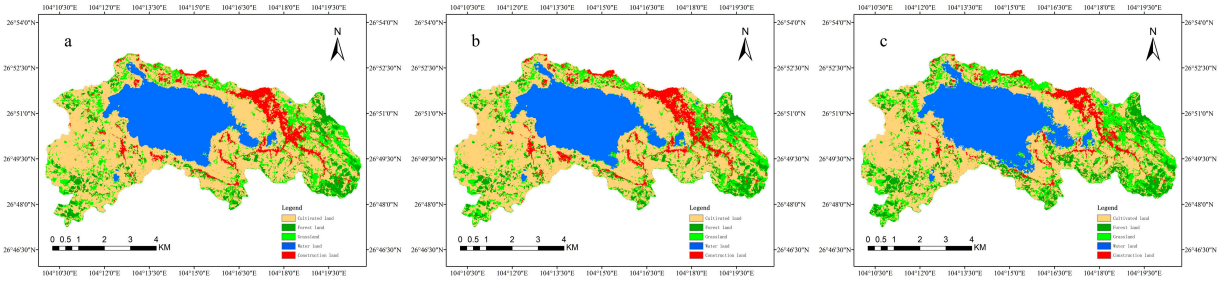

Figure 3. Land Use Type Prediction of CHNR under Different Scenarios in 2030.((**a**): natural development; (**b**): urban expansion; (**c**): ecological priority).

3.1.2. Various Carbon Sequestration in CHLW

The estimation of carbon sequestration in CHLW primarily focuses on the wetland water body, wetland vegetation, and wetland sediments. Due to the lack of liquidity in the lake throughout the year, the decomposition rate of deposition at the lake bottom is slow, resulting in the gradual accumulation of sediment thickness over time. The decomposition rate of bottom sediments is prolonged, forming a relatively stable carbon reservoir. Surface sediments represent recently accumulated materials, and by examining their chemical properties and physical attributes, it is possible to reflect the influence of human activities and climate change on the CHLW within a recent time range. Therefore, the estimation of sediment carbon sequestration in this study is based on surface sediments, as changes in carbon sequestration in surface sediments provide a more intuitive representation of the impact of human and natural factors on carbon sequestration in CHLW. Through meticulous screening and analysis with Citespace, this research has extracted relevant literature [39–54] and compiled data on carbon sequestration at CHLW from 1985 to the present. The study estimates the carbon sequestration and storage in water bodies, vegetation, and sediments during different periods. Finally, the InVEST model has predicted carbon sequestration in the CHLW from 2030 to 2060 (Table 5).

Table 5. Carbon Storage Changes in CHLW from 1990 to 2030 (W: water; P: plant; Se: sediment).

Year (a)	Type	Carbon Sequestration (10^3 t C)	Total Carbon Sequestration (10^5 t C)	Carbon Storage (10^8 t C)	Carbon Density (t/hm^2)
1990	W P Se	3.51 0.65 1080.98	10.85	2.50	794.00
1995	W P Se	3.52 0.63 1576.01	15.80	2.52	793.04
2000	W P Se	5.26 0.91 472.96	4.79	2.52	237.32
2005	W P Se	5.08 1.86 468.92	4.76	2.53	242.21
2010	W P Se	4.85 2.57 574.50	5.82	2.53	315.86
2015	W P Se	7.39 1.97 523.40	5.33	2.54	265.44
2020	W P Se	4.93 2.03 310.71	3.18	2.54	151.39
2030	Q1 Q2 Q3	— — —	3.33 3.29 3.61	2.55 2.54 2.56	151.39

Based on the data and Formulas (1)–(3), we estimated the carbon sequestration and storage of CHLW. Here are the estimation results: Among the seven periods, the carbon sequestration in CHLW was highest in 1995, with a value of 15.80×10^5 t C. Carbon sequestration reached its lowest point in 2020, with a value of 3.18×10^5 t C. From 1995 to 2005, carbon sequestration fluctuated significantly, decreasing by nearly 70%. During the period from 2005 to 2010, carbon sequestration increased. However, from 2010 to 2020, carbon sequestration decreased year by year, showing a general exponential decline. As

of 2020, the carbon storage in CHLW was approximately 2.54 × 10^8 t C. By 2030, under different simulated scenarios, the Q2 scenario had the lowest carbon sequestration in wetlands, while the Q3 scenario had the highest, showing an overall increasing trend. The magnitude of wetland carbon sequestration mainly depends on the wetland area and the carbon density of the sediments.

From 1990 to 2020, the carbon sequestration in the water bodies underwent dynamic changes of increase-decrease-increase-decrease (Figure 4). The maximum carbon sequestration value occurred in 2015, reaching 7.39 × 10^3 t C. The minimum carbon sequestration value occurred in 1990, measuring 3.51 × 10^3 t C. The amount of carbon stored in water bodies is mainly determined by precipitation, groundwater recharge, and the concentration of bicarbonate ions in the water. The concentration of bicarbonate ions is affected by the level of carbonate weathering in the nearby karst topography.

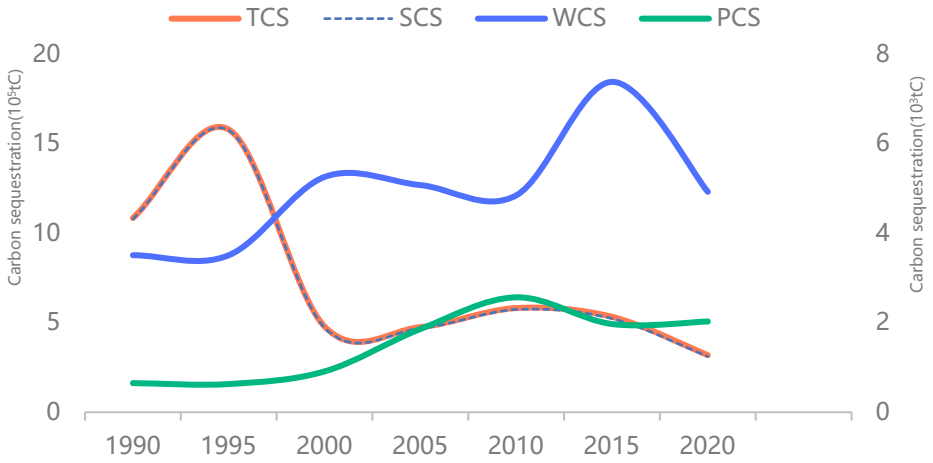

Figure 4. Carbon storage changes in CHLW from 1990 to 2020 (TCS: Total Carbon Sequestration; WCS: Water Carbon Sequestration; PCS: Plant Carbon Sequestration; SCS: Sediment Carbon Sequestration. TCS and SCS are based on the primary vertical axis; WCS and PCS are based on the secondary vertical axis).

From 1990 to 2020, vegetation carbon sequestration underwent a dynamic increase-decrease-increase. The maximum carbon sequestration value of vegetation occurred in 2010, reaching 2.57 × 10^3 t C, while the minimum value occurred in 1995, amounting to 0.63 × 10^3 t C. The level of carbon sequestration in vegetation is linked to the amount of plant biomass and the extent of vegetation coverage. Lower vegetation coverage was observed in 1990 and 1995.

The carbon sequestration of lake bottom sediments fluctuated from 1990 to 2020, with a pattern of decrease, increase, and decrease. The highest value of sediment carbon sequestration was recorded in 1995, reaching 1576.01 × 10^3 t C, while the lowest was in 2020, with only 310.71 × 10^3 t C. The amount of organic matter in the deposits directly impacts the sediment's carbon sequestration capacity, making it a crucial factor to consider.

Throughout the study period, the amount of carbon sequestered closely mirrored the trend of sediment carbon sequestration. The highest recorded total carbon sequestration was in 1995, reaching 15.80 × 10^5 t C, while the lowest was in 2020, at 3.18 × 10^5 t C. Sediment carbon sequestration was the dominant contributor to overall carbon sequestration, making it the most crucial element of carbon capture and storage in CHLW.

Overall, in the total carbon sequestration of the CHLW, sediment carbon sequestration has the highest proportion, followed by water carbon sequestration, and plant carbon sequestration has the lowest ratio. This is because the CHLW's water carbon pool mainly receives organic carbon through precipitation and groundwater recharge [55]. The plant carbon pool primarily relies on the plants and their ability to absorb organic matter from the water [45]. The amount of carbon sequestered in the sediment carbon pool depends on the deposition of vegetation, aquatic biomass, and organic matter in the surrounding

environment [55]. Environmental changes can also affect the amount of organic matter in lake sediments, such as pesticides and fertilizers on nearby arable land, the discharge of residential and industrial wastewater, and other substances from human activities along the lake [56]. Based on the data collected, between 1990 and 1995, the CHLW experienced the most significant impact from external factors. However, this influence gradually decreased from 2000 to 2010, and minimal external impact was observed from 2015 to 2020.

3.1.3. Prediction of Carbon Sequestration in CHNR

To clarify the proportion of carbon sequestration contributed by the CHLW and its relationship with the overall carbon sequestration in the CHNR, carbon sequestration in the CHNR and the wetland within the CHLW was predicted using the InVEST model. The research results can provide a basis for the future development and pattern construction of CHNR and validate the rationality of the current developmental approach. Carbon sequestration was simulated and predicted based on land-use scenarios under three scenarios. This resulted in the carbon sequestration prediction map for the CHNR in 2030 (Figure 5) and the conceptual diagram illustrating the carbon sequestration dynamics between 2020 and 2060 (Figure 6). Furthermore, the process of carbon sequestration within CHLW from 2030 to 2060 was also simulated (Figure 7).

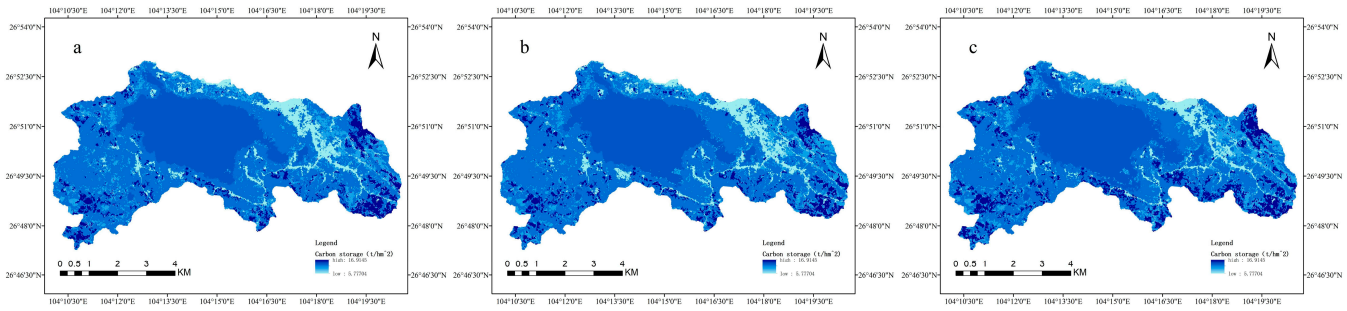

Figure 5. Carbon Sequestration in the CHNR under Different Scenarios in 2030 ((**a**) Q1 (natural development scenario); (**b**) Q2 (urban development scenario); (**c**) Q3 (Ecological priority scenario)).

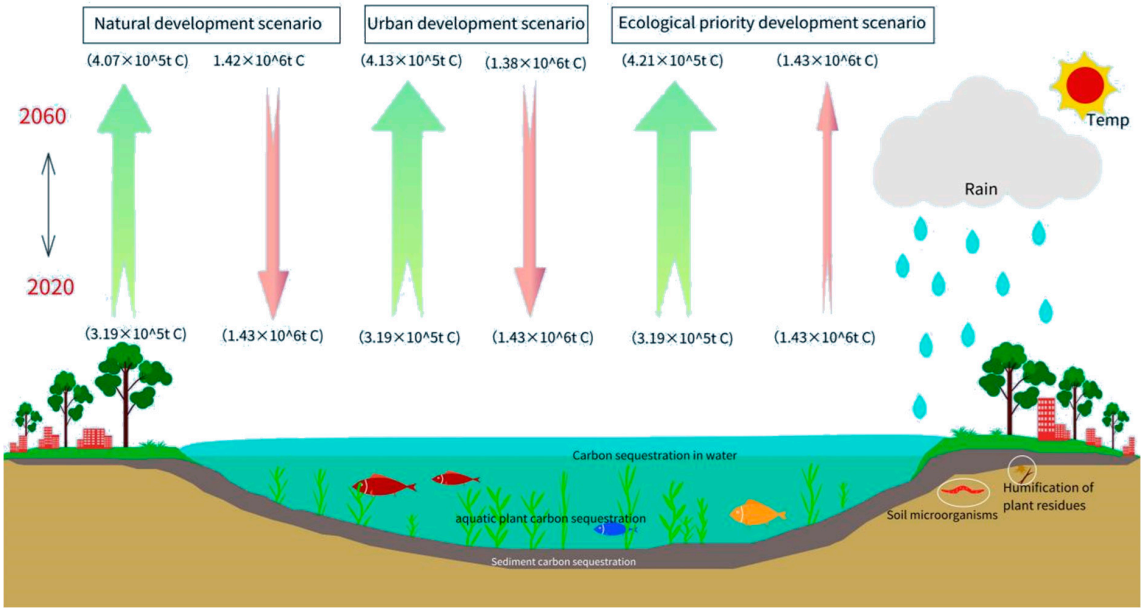

Figure 6. Conceptual diagram of carbon sequestration changes in the CHNR from 2020 to 2060. (Green arrows represent carbon sequestration in the CHLW. Red arrows represent carbon sequestration in the CHNR. The thickness of the arrows represents the magnitude of the changes. Upward arrows indicate an increase, while downward arrows indicate a decrease.)

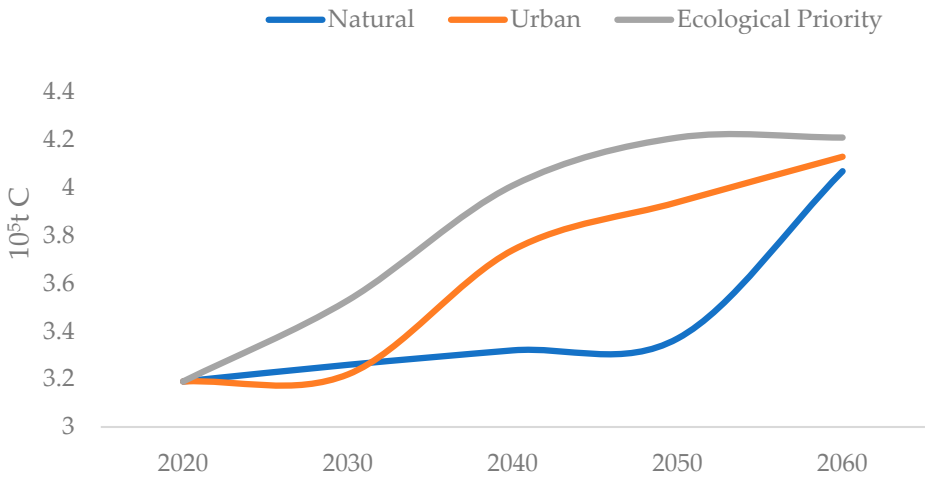

Figure 7. Carbon Sequestration Trend in the CHLW from 2020 to 2060.

Since the study area has an obvious classification of land use, it is clear from the figure that construction land has the least carbon sequestration and forest land has the most considerable amount of carbon sequestration. Soil carbon density, biomass, and area size all affect the amount of carbon sequestration. Forest ecosystems are widely acknowledged as the most substantial carbon reservoirs and, consequently, have the highest carbon sequestration capacity. Conversely, the expansion of construction land negatively impacts the quality of natural habitats, disrupts ecological balance, and increases carbon emissions while reducing carbon absorption. Consequently, the amount of carbon sequestered by such sites is minimal. This finding aligns with previous research by Dewa [57], who explored the relationship between carbon emissions and temperature in the rapidly developing metropolitan region of Tambolaka, Indonesia, indicating that rapid urban expansion increases carbon emissions and leads to a temperature rise. Studies conducted by Li Jinpu [58] and others also demonstrate that expanding construction land is the primary cause of regional carbon storage decline.

Observing the conceptual diagram and trend graph, it can be noted that the carbon sequestration in the CHLW and CHNR varies to different degrees under three scenarios. The carbon sequestration in CHLW shows a consistent uptrend in three scenarios, with the highest increase in the Q3 scenario and continuing to rise annually. However, the overall carbon sequestration declines in the Q1 and Q2 scenarios, although the CHNR wetland experiences a slight increase. The drop is relatively minor in the Q1 scenario but more significant in the Q2 scenario, with a decline of almost 3.50%. In the Q3 scenario, the CHNR carbon sequestration slightly increases, but the shift is minimal. Based on the predicted results, development trends, and actual conditions, the carbon sequestration in the CHLW under the three scenarios will reach a threshold by 2050. The carbon sequestration rate in the Q1 scenario experiences a slow increase but sees a significant growth rate in 2050. This could be due to the construction land area reaching saturation while the wetland area increases substantially. In the Q2 scenario, the carbon sequestration decreases before rising again, causing the growth rate to decline from high to low. This is because of the limitations in the expansion area, where the construction land area experiences an initial increase before stabilizing, while the wetland area expands and reaches saturation between 2040 and 2050. In the Q3 scenario, wetland carbon sequestration continues to rise and will peak in 2050.

Based on the scenario in Q1, conserving the CHLW can enhance the wetland's ecological quality and carbon sequestration potential. However, this may result in a decline in the overall carbon sequestration capacity of the CHNR. In the Q3 conservation scenario, enhancing the proportion of forests and wetlands while reducing construction land area leads to a considerable increase in the total carbon sequestration capacity of the CHLW and CHNR. This aligns with the current conservation and management measures of the

CHNR and suggests that these policies positively impact ecological restoration and carbon sequestration capacity enhancement in the region. Furthermore, based on the current conservation and planning efforts, the carbon sequestration of CHLW is projected to reach its peak value by 2050, and the wetland's carbon sequestration capacity will stabilize, restoring the ecological environment. In future planning of the CHNR, priority should be given to conserving the ecological environment by increasing the proportion of forest and wetland areas and reducing the expansion of construction land, thereby enhancing the carbon sequestration capacity of the CHNR.

3.2. Contribution of Carbon Sequestration to CHLW Spatio-Temporal Variations

Ecological carbon sequestration represents the carbon storage capacity of an ecosystem during a specific stage, and the carbon sequestration quantity fluctuates due to external influences. This study conducts a comparative analysis of factors influencing carbon sequestration in CHLW, focusing on precipitation and temperature as climate change factors and land use change as a factor influenced by human activities. The aim is to identify the primary factors influencing carbon sequestration in CHLW and, finally, explore the trend of carbon sequestration in CHLW under policy interventions.

3.2.1. Impact of Climatic Changes

The level of carbon sequestration in wetlands is affected by various factors, including climate change, which is a gradual and ongoing process. This study analyzed daily temperature and precipitation data from Weining National Climate Station, located within 2 km of CHNR. The data were obtained from the National Centers for Environmental Information (NCEI) under the National Oceanic and Atmospheric Administration (NOAA) in the United States. The temperature data were averaged from 1990 to 2020 (Figure 8).

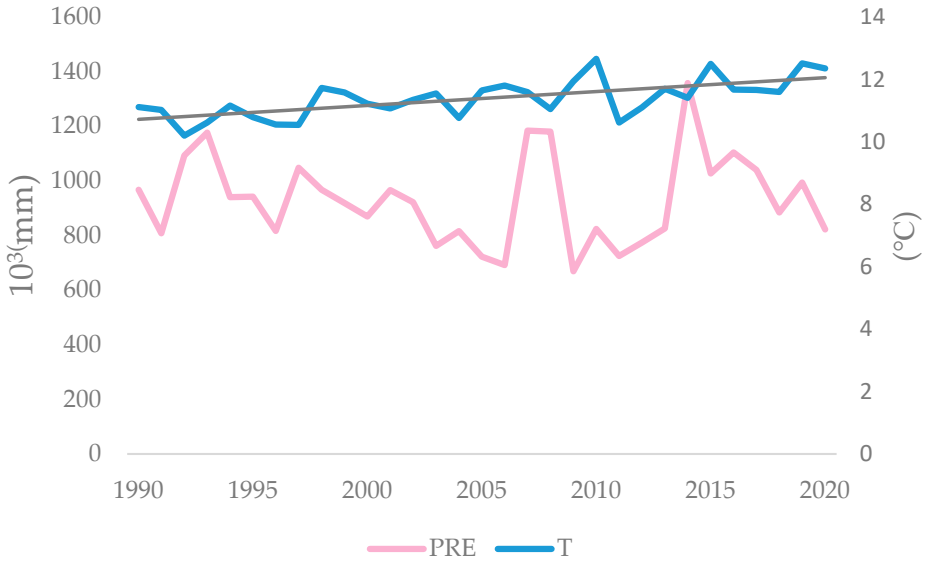

Figure 8. Temperature and Precipitation Trends in CHNR from 1990 to 2020.

After examining the graph, it is clear that the CHNR went through significant changes in rainfall and a consistent temperature increase from 1990 to 2020, resulting in a total rise of 1.5 °C. A correlation analysis was conducted using the Origin 2022 software to determine the relationship between temperature, precipitation, and their impact on water, plants, sediments, and total carbon sequestration (Figure 9).



Figure 9. Correlation Analysis of Carbon Sequestration in CHLW and Climate Change (TCS: Total Carbon Sequestration; WCS: Water Carbon Sequestration; PCS: Plant Carbon Sequestration; SCS: Sediment Carbon Sequestration.; T: Temperature; PRE: Precipitation; *p*-value represents significance).

The analysis reveals that temperature has a significant effect on both vegetation carbon sequestration and sediment carbon sequestration. It shows a positive correlation between temperature and vegetation carbon sequestration, which means that higher temperatures increase vegetation carbon sequestration levels. Studies have shown that temperature within a specific range affects the number of planktonic organisms. When temperatures are higher, there is an increase in plant biomass, resulting in a rise in vegetation carbon sequestration [59]. Conversely, if temperatures rise, the ability of sediment to store carbon decreases. This happens because there is less rainfall, meaning less external organic matter. As a result, the sediment's organic content decreases, leading to a decrease in carbon sequestration. The amount of rainfall significantly impacts sediment carbon sequestration, and the two have a positive correlation. When more rain occurs, water flow carries organic matter from the surrounding area into the lake. This results in higher levels of organic material at the bottom of the lake, leading to an overall increase in carbon sequestration.

3.2.2. Land Use Change Regulation

As society progresses, human actions have a more significant impact on the environment. However, our interference can cause ecological imbalances, harm the environment, and reduce wetlands' ability to store carbon. Based on the developmental history of the CHNR, land use change data were selected as indicators of human activities. The degree of land use change in different land use types within the CHNR from 1990 to 2020 was considered a human-induced factor (Figure 10).

According to the analysis of correlation and goodness of fit, wetlands play a significant role in water and vegetation carbon sequestration processes. Results indicate a positive correlation between wetlands and both of these factors. Larger wetland areas contribute to increased carbon sequestration in water bodies, and the expansion of water bodies is linked to better vegetation coverage. The alteration of forest land, grassland, and construction land usage significantly impacts sediment carbon sequestration. Research reveals a negative correlation between sediment carbon sequestration and construction land. When there is a rise in construction land, sediment carbon sequestration decreases. This is because

expanded construction land negatively affects the ecological environment of the CHNR, causing a drop in carbon sequestration capacity and a decrease in carbon sequestration. An increase in forest land and grassland areas positively correlates with sediment carbon sequestration. This is because they improve the surrounding ecological environment, enhancing the wetlands' carbon sequestration capacity.

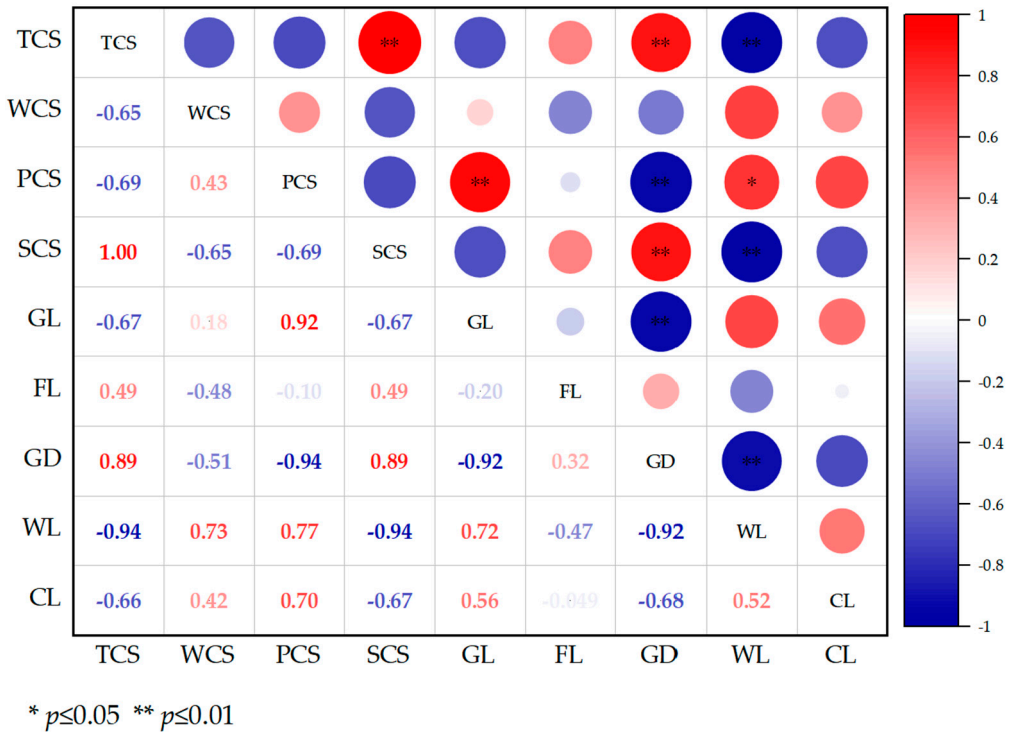

Figure 10. Correlation Analysis of Carbon Sequestration in CHLW and Land Use Change (TCS: Total Carbon Sequestration; WCS: Water Carbon Sequestration; PCS: Plant Carbon Sequestration; SCS: Sediment Carbon Sequestration; GL: Cultivated land; FL: Forest land; GD: Grassland; WL: Water land; CL: Construction land; *p*-value represents significance).

3.2.3. Verification of Carbon Sequestration in CHLW and Influencing Factors Based on RDA Analysis

The overall correlation analysis of RDA between land use, climate change, and carbon sequestration in CHLW was conducted to verify the above Origin correlation analysis. The analysis results, as shown in Figure 11, reveal that the cumulative contribution of variance in carbon sequestration-impact factor for the first two axes is 77.54%, with climate change contributing 9% and land use regulation contributing 91%. The figure shows that precipitation, forest land, and grassland positively correlate with the first ordination axis. In contrast, wetlands, construction land, cultivated land, and temperature negatively connect with the first ordination axis. Wetland and grassland correlate positively with the second ordination axis, while temperature, precipitation, forest land, construction land, and cultivated land negatively correlate with the dual ordination axis.

Carbon sequestration in water bodies and vegetation is positively associated with wetlands, cultivated land, construction land area, and temperature. On the other hand, it is negatively correlated with precipitation, grassland, and forest land area. However, sediment and total carbon sequestration show the opposite pattern. These findings align with the correlation analysis conducted in Origin 2022 and demonstrate high credibility for both analyses.

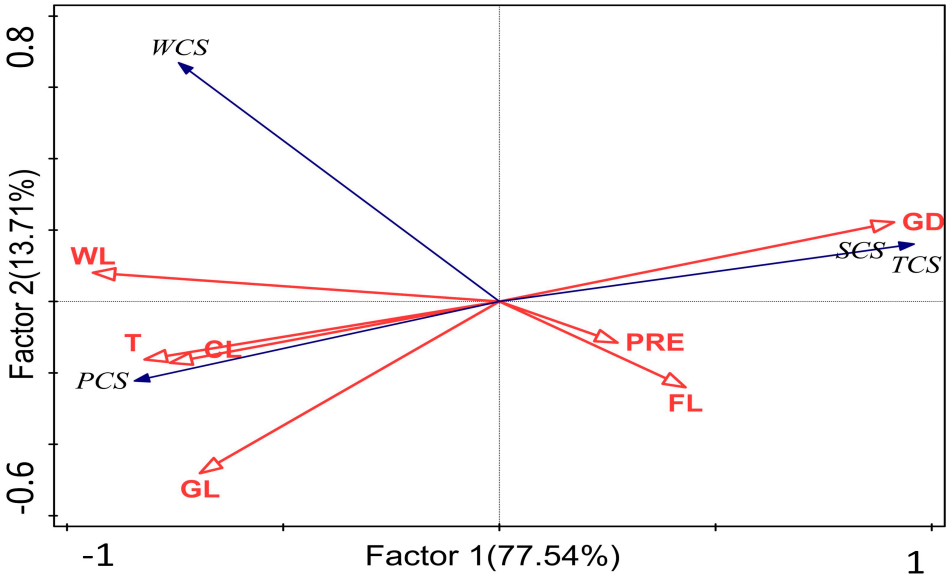

Figure 11. RDA Double Sequence Diagram of the Relationship between Carbon Storage and Impact Factors (TCS: Total Carbon Sequestration; WCS: Water Carbon Sequestration; PCS: Plant Carbon Sequestration; SCS: Sediment Carbon Sequestration; GL: Cultivated land; FL: Forest land; GD: Grassland; WL: Water land; CL: Construction land; T: Temperature; PRE: Precipitation; The red arrows represent the influencing factors; The black arrow represents the amount of carbon sequestration).

3.2.4. Changes in Carbon Sequestration in CHLW under Policy Guidance

The change in carbon sequestration in CHLW is affected by the above-mentioned influencing factors and is related to policy orientation. This study examines the changes in carbon sequestration in the CHLW based on research and policy documents related to establishing, developing, and protecting the CHNR. Throughout its history, the CHNR has undergone several phases of development and interaction between humans and the environment. These factors have impacted the ecological environment and the reserve's ability to sequester carbon, ultimately affecting the carbon levels in the CHLW during different periods (Figure 12). The CHNR has undergone three stages of development since its restoration by the government in 1982: "emergency protection", "tourism development", and "strict management" [57] (Table 6).

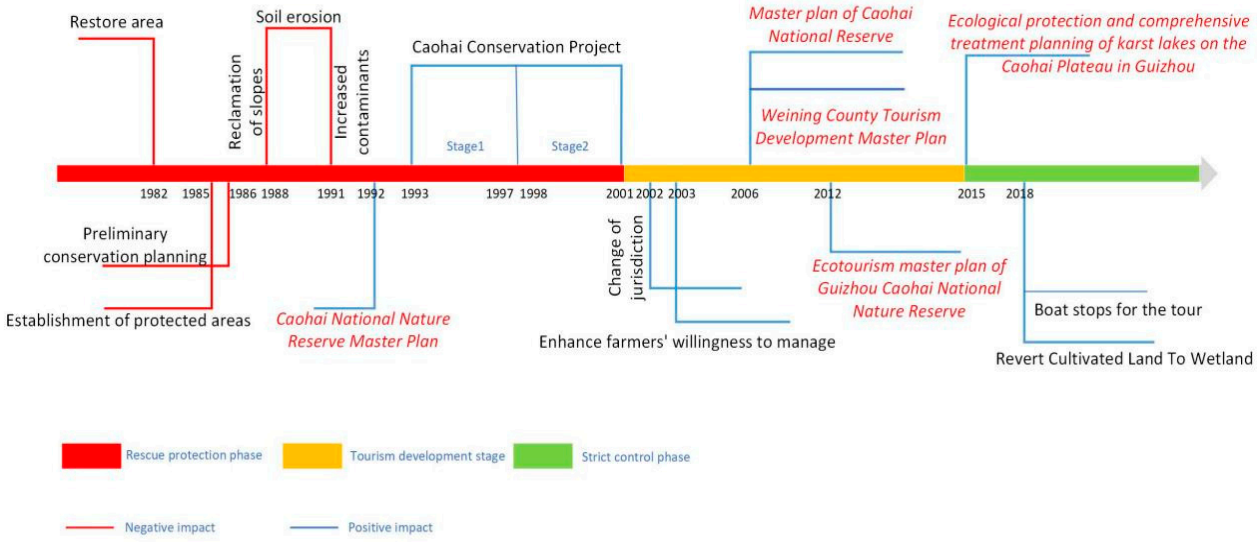

Figure 12. Development Chart of Wetland Policies in the CHNR.

Table 6. Policy Development and Carbon Sequestration Changes in the CHNR from 1990 to 2020.

Development Stage	Time	Policy	Types of Human Activities	Effect	Total Carbon Sequestration (10^5 t C)
Emergency Protection	1985–1995	"Overall Plan of Caohai National Nature Reserve"	Flood discharge and drainage, land reclamation around the lake, wastewater discharge, and chemical fertilizer and pesticide pollution	Damage to the ecological environment and water quality of the lake and an increase in sediment content at the lake bottom.	10.85–15.80
Tourism Development	2000–2015	"Overall Plan of Caohai National Reserve", " Overall Plan for Tourism Development in Weining County"	Boat fishing, tourism and sightseeing	Human activities impact the natural environment of the Grass Sea, leading to an increase in the input of foreign organic substances	4.76–5.82
Strict Management	2015–2020	"Ecological Conservation and Integrated Management Plan for the Grassland-Lake Plateau Karst Lakes in Guizhou"	"Urban retraction and lake restoration", "Village retraction and lake restoration", "Farmland retraction and lake restoration", "Pollution control and lake purification", "Afforestation and lake conservation"	Improved ecological environment quality and restoration of pollution reduction and carbon sequestration capacity in the Grass Sea	3.18–5.33

The CHNR was founded in 1985 and has taken many actions towards ecological restoration. Sadly, the water level of the CHLW has not increased but instead decreased. Between 1990 and 1995, the reserve underwent flood discharge, drainage, and land reclamation activities around the lake, significantly harming the surrounding ecological environment. As a result, the water area decreased, and the lake had less aquatic vegetation [60]. Meanwhile, farmers near the lake used extensive amounts of pesticides and fertilizers to improve their crop yield and release significant quantities of domestic and industrial wastewater into the lake. As a result, a large amount of organic material was built up on the bottom of the lake. During 1990 and 1995, the organic matter content in the lake sediment was high, resulting in increased carbon sequestration in the wetland during these specific timeframes. It should be noted that the carbon sequestration during these two periods does not represent the natural carbon sequestration capacity of the CHLW itself. The buildup of polluted sediments at the bottom of a lake can cause contamination and harm to the ecosystem. As a result, less carbon was sequestered by vegetation and water in the same year.

The CHNR was designated as a national-level nature reserve in 1992. An "Overall Plan of Caohai National Nature Reserve" was created, focusing on the area's development and preservation. Projects focused on safeguarding the CHNR have been underway since 1994, with steady progress toward restoring its ecological balance. Around 2000, effective control measures were implemented in the reserve, reducing the influx of pollutants such as fertilizers, pesticides, and sewage from the surrounding areas. The decrease in organic matter in the sediments led to a significant reduction in sediment carbon sequestration, which restored its natural carbon storage capacity. During the same period, there was an increase in carbon sequestration in vegetation and water bodies, which can be attributed to improved ecological quality. This increase also contributed to a higher proportion of the total carbon sequestration. Between 2000 and 2005, the CHNR tourism industry was

established, capitalizing on its natural beauty. The Caohai Management Bureau created the "Overall Plan of Caohai National Reserve (2005–2015)"; the Weining County government developed the "Overall Plan for Tourism Development in Weining County (2005–2020)", which led the way for tourism development in the CHNR. As the number of external tourists rapidly increases, their activities are once again impacting the ecological environment of the reserve. This has led to an increase in organic substances being introduced from external sources. During the same period, there was an increase in sediment accumulation and carbon sequestration. However, the carbon sequestration during this period still does not represent the carbon sequestration capacity that the CHLW would naturally capture.

The CHNR has been taking action since 2015 to preserve the environment. They have implemented measures such as "returning farmland to the lake", "returning cities to the lake", and "returning villages to the lake". During this period, there has been an improvement in the ecological environment, and the input of external organic matter has decreased. This has led to a reduction in carbon sequestration. In 2018, to improve the environmental quality of the CHNR, all boat tours were halted, and the area was officially closed to boating tourism. To this day, the reserve has primarily restored its original ecological environment, becoming a pristine nature reserve free from external pollution. Based on the estimated carbon sequestration in the CHLW described earlier, the carbon sequestration in 2020 was approximately 3.18×10^5 t C, primarily derived from internal carbon sources within the CHLW. After a thorough evaluation of carbon sequestration alterations in the lake wetland, it has been observed that policy-driven land use changes have positive and negative impacts on ecological preservation. Effective land use planning can enhance the overall quality of the environment and make the surrounding area more habitable. To ensure optimal protection of ecological quality, it is crucial to customize safety, planning, and development strategies based on the unique characteristics of each region. In the future, To effectively preserve and develop lake wetlands, it is crucial to establish suitable opening periods that account for current conditions. Regular monitoring and maintenance of the wetlands should also be carried out to promote the enhancement of ecological quality and increase their capacity for carbon sequestration.

4. Conclusions

The amount of carbon sequestration in the CHLW has experienced fluctuating changes, with a pattern of decrease, increase, and then decrease again. Land use accounts for 91% of these impacts, while climate change accounts for 9%. It is evident that human actions significantly impact the ecological environment and carbon sequestration capacity of the CHNR. Climate change primarily affects the water and sediment in the CHLW, while land use significantly impacts vegetation and water body carbon sequestration. Considering the influence of policy factors, human factors encompass not only land use changes but also various aspects of daily human activities, behaviours, and traffic within the region. Under the guidance of policy factors at different times, the carbon sequestration in the CHLW exhibits significant variations. Still, it does not solely represent the intrinsic carbon sequestration capacity of the wetland. As of 2020, CHLW has successfully sequestered approximately 3.18×10^5 t C of carbon, restoring its natural carbon sequestration capacity. Additionally, the carbon storage of wetlands is about 2.54×10^8 t C.

Under three scenario simulations, the ecological priority mode significantly impacts optimizing the environmental environment and enhancing carbon sequestration capacity in the CHLW and the entire nature reserve. This scenario effectively enhances the CHNR carbon sequestration capacity, aligning with the conservation policies. After decades of protection and planning, government policy guidance has played a vital role, indirectly influencing its carbon sequestration capacity. As a national nature reserve, it possesses high carbon sequestration capacity, and its carbon sequestration potential should be noticed.

Lake wetlands belong to one of the wetland types and have a significant potential for carbon sequestration. Nevertheless, due to the progress of society, lake wetlands have undergone critical degradation. The condition of global lake wetlands is concerning, as they

are currently experiencing severe degradation. This is evidenced by the eutrophication of lake water [61], the intensified degradation of aquatic vegetation [62], and the subsequent release of large amounts of carbon dioxide into the atmosphere. In the face of global climate change, it is crucial to restore and protect lake wetlands, improve their ecological quality, and enhance their carbon sequestration capacity, as this can be a practical approach to mitigating climate change. When it comes to utilizing and conserving wetlands in the future, it is crucial to preserve their natural state, limit human activity in the surrounding areas, increase wetland carbon sequestration capabilities, and focus on the relationship between land use changes driven by policies and reducing pollution in wetlands while also mitigating carbon emissions.

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