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A Study on the Spatiotemporal Dynamics of Land Cover Change and Carbon Storage in the Northern Gulf Economic Zone of Guangxi Based on the InVEST Model

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Abstract: In recent years, the international community has increasingly focused on the "dual carbon" issue, as human-induced land use changes significantly impact ecosystem structure and carbon cycling. This study analyzes land use changes in the economic zone of the northern Gulf of Guangxi from 1980 to 2020, utilizing the InVEST model to simulate spatiotemporal changes in carbon storage and conducting zoning studies through spatial analysis. The findings reveal that ① forest land and arable land dominate the northern Gulf of Guangxi's land use, with notable changes observed in forest land, unused land, and construction land areas. Forest land and construction land have increased by 1761.5 km^2 and 1001.19 km^2, respectively, while unused land has decreased by 1881.18 km^2 from 2000 to 2020. ② The total carbon storage values in the northern Gulf of Guangxi in 1980, 2000, and 2020 were, respectively, 504.91 × 10^6/t, 487.29 × 10^6/t, and 500.31 × 10^6/t, with the expansion of construction land and conversion of forest land being the main reasons for the decrease in carbon storage. ③ In the northern Gulf of Guangxi, there is a slight upward trend in total carbon storage values over time. Spatially, higher carbon storage values are observed in mountainous and hilly areas at high altitudes, while the central and southern coastal areas exhibit lower carbon storage values. ④ The local spatial autocorrelation results reveal that Pu Bei County exhibits high–high clustering of carbon storage, while He Pu County undergoes a transition from high–low to low–low clustering, and several other administrative areas in Beihai demonstrates low–low clustering. Due to the imperative of economic development, the expansion of urban construction land encroaches upon ecological land, resulting in a decline in carbon storage. Therefore, in the Northern Gulf of Guangxi, it is essential to implement measures such as reforestation and establish ecological protection areas such as forests, grasslands, and wetlands to develop effective carbon sequestration methods and compensate for the carbon loss caused by the expansion of construction land.

Keywords: carbon storage; LULCC; InVEST model; Northern Gulf Economic Zone; spatial autocorrelation analysis

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1. Introduction

Climate change has significant impacts on ecosystems and economic sustainability. The global economy is currently undergoing a critical phase of transition towards green and low-carbon practices, with nations worldwide actively responding to the United Nations' call to accelerate efforts towards "emission reduction and carbon sequestration". At the United Nations General Assembly in 2020, China explicitly outlined its visionary goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060, thus contributing to China's innovative solutions and robust capabilities in the global fight against climate change. As one of the largest carbon reservoirs globally, terrestrial ecosystems play a pivotal role in determining both the total value and distribution of "green carbon" storage. Land use and land cover change (LUCC) can significantly alter the spatial and temporal dynamics of terrestrial ecosystems, serving as a crucial factor influencing regional carbon storage capacities and fluctuations [1]. Therefore, investigating the impact of land use changes on carbon storage variations, comprehensively assessing the influence of different land use types on the spatiotemporal distribution of carbon storage, exploring strategies for optimizing land use structure, and enhancing regional ecosystem carbon storage are imperative steps towards enhancing regional ecosystems and contributing to the achievement of dual carbon goals.

In recent years, domestic and international experts and scholars have estimated the carbon storage of single or complex ecosystems from different perspectives and spatial scales and explored the interrelationships between different land use types and carbon storage [2–4]. In the study of land use change, Aquino (2024), a foreign researcher, highlighted the significant interplay between hydrological factors, climate conditions, and wetland vegetation dynamics within LULCC environments. [5]; Nohemi et al. (2024) examined the connection between water changes and land use transformations in the Mexican basin, revealing that the expansion of urban land surface areas led to an increase in drainage volume within the study region [6]; Colman et al. (2024) explored the factors driving vegetation loss in the Brazilian savanna and suggested policy measures to balance production and conservation, drawing on their research findings [7]. Regarding the research on carbon storage, most scholars' studies combine models to analyze historical land use changes and spatiotemporal variations in carbon storage and conduct simulation predictions, which have reference significance for the subsequent research in this paper. InVEST (integrated valuation of ecosystem services and trade-offs). The InVEST model was collaboratively developed by Stanford University, The Nature Conservancy (TNC), and the World Wildlife Fund (WWF) to simulate changes in both the quantity and value of ecosystem services under various land cover scenarios. One of this model's key advantages is its ability to visualize assessment results. Gao et al. (2023) utilized System Dynamics (SDs), PLUS, and InVEST models to project land use changes and associated carbon storage in Heilongjiang from 2030 to 2050, showing that transforming construction land into arable land boosted carbon storage by 102.71×10^6/t. [8]. Pan (2023) conducted an extensive analysis of the shifts in land use and carbon sequestration capacity spanning the years 2000 to 2020. To forecast the effects of changes in land use types on regional carbon sequestration, the study employed the Future Land Use Simulation (FLUS) model. This model was used to evaluate the potential outcomes under three distinct development scenarios: prioritizing urban expansion, focusing on the protection of cultivated land, and emphasizing ecological conservation [9]. Xie et al. (2022) integrated the InVEST model with the CA–Markov model to conduct a comprehensive analysis of the spatial and temporal dynamics of ecosystem carbon storage in Changzhi City over the period from 2000 to 2030. This study also delved into the intricate relationship between carbon sources and sinks, aiming to uncover patterns and trends within the specified timeframe [10]. Zhao (2023) used the PLUS model to predict the spatial distribution of carbon storage on the Qinghai-Tibet Plateau in 2030 and 2060 under scenarios of inertia development, farmland protection, and ecological priority [11]. Hernández-Guzmán et al. (2023) conducted an in-depth analysis and forecasted the spatial and temporal variations in carbon storage resulting from changes in land use across the hydrological basins along the western coastline of central Mexico [12]. L. Bamière et al. (2022) evaluated the impact of agricultural practices in France on biomass and soil organic carbon storage at various temporal and spatial scales [13]. Derek T et al. (2023) conducted a thorough analysis to quantify how variations in land use data across different regions of Canada affect the levels of carbon density. Their research aimed to measure the specific impact of land use changes on carbon density, providing valuable insights into the relationship between these factors [14]. Chalchissa et al. conducted a detailed analysis of the fluctuations in soil organic carbon storage across Africa, considering the impacts of extreme climate conditions and Land Use Land Cover Change (LULCC) scenarios [15].

In the Chinese academic field, the calculation of carbon storage primarily relied on traditional assessment methods in the early stages, such as the biomass method and the stock volume method. For instance, Xu et al. (2009) estimated the forest carbon storage of 31 provinces and cities in China over the past 30 years using the biomass conversion factor method while also establishing models for stand-level volume, biomass, and carbon storage based on measured data in the northeastern forest region [16]. However, traditional assessment methods are subject to interference from both subjective and objective factors, resulting in certain limitations that hinder their ability to comprehensively reflect actual conditions. To overcome these shortcomings, researchers are increasingly inclined to adopt modeling approaches to calculate land use change, aiming to enhance the efficiency of assessments and the scientific validity of the results. Consequently, there has been an increasing trend towards using models to calculate land use changes [17]. Zheng (2024) utilized the InVEST model to compute ecosystem carbon storage and carbon density in the northern Shanxi region from 1990 to 2019 [18]. Peng et al. (2024) analyzed land use changes in the Beijing–Tianjin–Hebei region from 2000 to 2020 and simulated the spatiotemporal changes in carbon storage using the InVEST model, combined with spatial autocorrelation analysis [19]. Previous studies have employed InVEST in conjunction with FLUS, PLUS, and other models for simulation and prediction. For example, Liu et al. (2019) coupled the FLUS-InVEST model to simulate China's land ecosystem carbon storage in 2100 from the perspective of land use, filling the gap in the nationwide-scale simulation and prediction of carbon storage [20]. Liu (2021) combined the CA–Markov model to predict the spatiotemporal changes in ecosystem carbon storage in the Shule River Basin [21]. Wu et al. (2016) used the cellular automaton (CA) model to simulate the distribution of urban land in Guangdong Province in 2040, assessing the impact of future urban growth on carbon storage [22]. Zheng et al. (2024) combined the PLUS model to analyze the dynamic changes and influencing mechanisms of land use and carbon storage in the Guangdong–Hong Kong–Macao Greater Bay Area [23]. Currently, most scholars tend to utilize the FLUS model to analyze and explore the impact of future land cover changes on carbon storage while also proposing corresponding insights and strategies in their research [24–26]. These models, owing to their robust simulation capabilities and adaptability, effectively capture the potential impacts of various land use types and their transitions on carbon storage. This provides scientific evidence for policymakers, facilitating the achievement of sustainable land management and ecological conservation objectives. At the same time, by utilizing relevant models, researchers can not only predict future trends in land use changes but also analyze how these changes affect carbon storage and release. This, in turn, provides valuable insights for mitigating climate change and protecting the ecological environment, holding significant importance for both practical applications and academic research.

Currently, there is ample research in the literature at the provincial, municipal, and river basin scales. However, there has been relatively little focus on carbon storage changes in Guangxi, particularly in the Northern Gulf region. The Northern Gulf urban agglomeration boasts strategic locational advantages, being part of initiatives such as the "China's Two Coasts and Two Bays Economic Belt", the "ASEAN Economic Community", and the "Western Land-Sea New Channel". In line with the spirit of the 14th Five-Year Plan, the regional government actively promotes the construction of the Northern Gulf urban agglomeration, emphasizing the need to "jointly safeguard the clear waters of the bay". This entails firmly preserving the ecological foundation of the Northern Gulf, enhancing zoning control over land and marine ecological environments, bolstering the resilience of natural ecosystems like forests and wetlands, and expediting the development of urban construction and operation models that foster green, low-carbon circulation. In this study, we analyzed land use changes from 1980 to 2020 using the InVEST model to examine carbon storage changes in the Northern Gulf over the past four decades. By employing spatial autocorrelation techniques for zoning and considering policy factors, we aim to explore the impact of land use changes on carbon storage. This research provides valuable insights into achieving high-quality development in the Northern Gulf of Guangxi and constructing a livable, business-friendly blue bay urban agglomeration.

2. Study Area and Data Source

2.1. Study Area

The Northern Gulf Economic Zone (Figure 1), located at the southwestern tip of China's coastal region, encompasses the southern part of the Guangxi Zhuang Autonomous Region and the northern coastal land of the Northern Gulf. The study area covers an area of 4.25×10^4 km^2, situated at low latitudes and influenced by a subtropical monsoon climate, resulting in a warm climate with abundant precipitation. With a permanent population of approximately 22.8286 million people, it comprises six administrative regions: Nanning, Beihai, Qinzhou, Fang Cheng Gang, Yulin, and Chong Zuo. Positioned at the intersection of the South China Economic Circle, the Southwest Economic Circle, and the ASEAN Economic Circle, the Northern Gulf Economic Zone holds strategic importance as the sole coastal area in the western development region. Its adjacency to ASEAN countries via both land and sea borders underscores its significance for national regional development strategies and international regional economic cooperation initiatives.

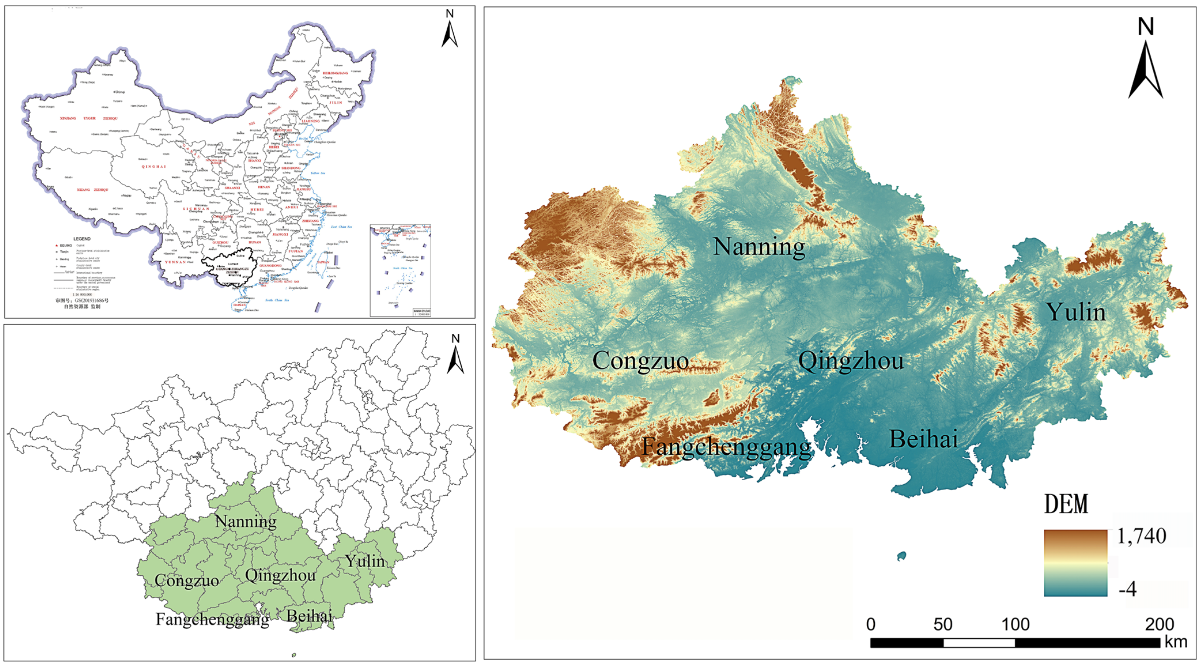

Figure 1. The Northern Gulf research area. Note: The Chinese part of the map indicates that the map is a standard map produced by the Ministry of Natural Resources of China without sovereignty issues, and the approval number is GS No. (2019) 1686.

2.2. Data Source

The digital elevation model (DEM) with a resolution of 30 m × 30 m for the study area was obtained from the Geographic Spatial Data Cloud Platform (http://www.resdc.cn/, accessed on 5 March 2024). Land use data, sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences, also has a resolution of 30 m. This dataset includes land cover information for the study area in 1980, 2000, and 2020. Land cover categories were consolidated into seven types: arable land, forest land, grassland, water bodies, construction land, unused land, and marine areas. Carbon density data for different land use types were classified into four categories: aboveground biomass, belowground biomass, soil organic matter, and dead organic matter. By integrating the carbon density coefficients with the land use raster data for each year into the InVEST model, this model performs spatial analysis and statistical calculations on the input data to derive the carbon stocks for each grid cell or region. Subsequently, the results are imported into ArcGIS for quantitative analysis to obtain the carbon stock data for various land cover types. Due to the challenges associated with field sampling, carbon density data suitable for the study area were selected based on the relevant literature from the autonomous region and neighboring provinces and municipalities [19–21], as summarized in Table 1.

Table 1. The carbon density of different land use types/Mg·hm^{-2}.

Land Use Type	Aboveground Carbon Density	Underground Carbon Density	Soil Carbon Density	Carbon Density of Dead Organic Matter
Cropland	13.5	2.7	17.34	1
Forest	58.3	14.58	19.73	3.5
Grassland	3.01	13.53	16	1
Waters	0.21	0	0	0
Building	1.2	0.93	12.48	0
Unused land	2.1	0	11.36	0
Ocean	0.21	0	0	0

3. Research Methods

3.1. Construction of the InVEST Model

Within the InVEST model, the carbon storage module is categorized into four fundamental carbon reservoirs: aboveground biomass carbon (encompassing carbon within all aboveground plant materials), belowground biomass carbon (in live root systems), soil carbon (comprising organic carbon distributed in both organic and mineral soils), and dead organic matter (in litter and standing or fallen dead trees) [18]. Utilizing land cover classifications, the average carbon density for each of these four carbon pools is computed. The total carbon storage within the study area is then derived by aggregating data from these pools for each land use type and multiplying by the corresponding land area. The calculation process is outlined below:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{1}$$

$$C_{total} = \sum_{i=1}^{n} C_i S_i \tag{2}$$

In the equation, C_{total} represents the total carbon storage; S_i denotes the total area of land use type i; C_i represents different land use types; i indicates the total carbon storage in each carbon pool; and n is the categorical variable for land use types.

3.2. Land Use Transition Matrix

The land use transition matrix is a research method that accurately reflects the structural characteristics of land use changes and reflects the trends of land use transitions. Using ArcGIS, spatial overlays were performed on land use maps from 1980, 2000, and 2020, followed by the analysis and data visualization of the resulting land use change maps. The land use transition matrix was obtained by calculating the areas of land-type transitions, including land-type conversion and land-type retention. The following is the calculation formula [27]:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & \cdots & S_{1n} \\ S_{21} & S_{22} & S_{23} & \cdots & S_{2n} \\ S_{31} & S_{32} & S_{33} & \cdots & S_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ S_{n1} & S_{n2} & S_{n3} & \cdots & S_{nn} \end{bmatrix} \tag{3}$$

3.3. Spatial Autocorrelation Analysis

Spatial correlation analysis encompasses both global spatial autocorrelation and local spatial autocorrelation. These methods serve to gauge the extent of spatial clustering among spatial variables and depict whether spatial units and attribute features exhibit spatial correlation with neighboring features, indicating either aggregation or dispersion [28]. In this study, the research area is delineated into counties, and the local spatial autocorrelation of carbon storage is portrayed using LISA maps. The formula for local spatial autocorrelation is as follows:

$$MI_i = \frac{(x_i - \overline{x})}{S^2} \sum_{j \neq i} w_{ij}\left(x_j - \overline{x}\right) \quad (4)$$

In the formula, I_i is the local Moran's I value at location i, x_i is the observation value at location *i*, $\overline{x}$ is the average of all observation values, s^2 is the variance in the observation values, and W_{ij} is the spatial weight between locations i and j, typically determined based on distance. $\Sigma_{j \neq i}$ indicates the summation over all locations j that are different from location i.

$MI_i \in [-1, 1]$: If the result is positive, it signifies that the phenomenon under investigation demonstrates spatial aggregation characteristics in the vicinity, where areas with high observed values are often surrounded by similarly high values. Conversely, a negative result suggests that the spatial aggregation of the phenomenon consists of dissimilar values in neighboring areas. A result of zero denotes no spatial correlation between the area and its adjacent regions.

4. Results

4.1. Land Use and Its Transition Changes

Based on the primary land classification standard, the spatial distribution of land use in the Northern Gulf region of Guangxi in 1980, 2000, and 2020 was analyzed using ArcGIS, as depicted in Figure 2. The findings reveal that forests and arable land are the predominant land use types, collectively constituting over 80% of the total land area. Forest coverage is extensive, whereas arable land is sporadically distributed due to topographic constraints [29]. From 1980 to 2020, discernible shifts in land use patterns were observed in the Northern Gulf region, characterized notably by a surge in construction land and an expansion of the marine area within the study domain. This transformation is accompanied by a reduction in arable land, grassland, and unused land. The proportion of arable land decreased from 29.54% in 1980 to 28.54%, while forest land increased from 56.83% to 59.23%. Conversely, grassland and water area proportions decreased by 3.03% and 1.71%, respectively, while construction land escalated from 3.28% in 1980 to 4.66%. The most conspicuous change occurred in the unused land category, plummeting from 2.64% to 0.04%. Across the forty-year span, various degrees of decline were observed in arable land, grassland, water area, and unused land, whereas forest land and construction land exhibited growth. Regarding spatial distribution, the proliferation of construction land is predominantly concentrated around the central provincial capital of Nanning and the southern coastal cities. Population growth and capital inflows emerge as pivotal factors propelling the rapid expansion of construction land over the preceding four decades [30–32].

4.2. The Transition of Land Use Types

Between 1980 and 2020, aside from conversions within the same land category, the total area of land type transitions in the Guangxi Northern Gulf region amounted to 6859.66 km^2, with 2969.16 km^2 observed from 1980 to 2000 and 3890.50 km^2 from 2000 to 2020, respectively (Table 2, Figure 3). Notably, significant changes were observed in cultivated land areas, primarily transitioning to forest land and built-up areas. Particularly noteworthy is the period from 2000 to 2020, during which the rate of conversion to these two land types increased. The conversion of cultivated land to built-up areas covered 629.03 km^2, representing an increase of approximately 1.6 times compared to the preceding period, largely due to support from national and regional development policies. On 14 January 2008, the State Council approved the "Development Plan of Guangxi Northern Gulf Economic Zone (2006–2020)", followed by the issuance of the "Notice of the People's Government of Guangxi Zhuang Autonomous Region on Promoting the Open Development of Guangxi Northern Gulf Economic Zone" by the People's Government of Guangxi Zhuang Autonomous Region on 17 December 2008. Additionally, the National Development and Reform Commission (2017) formulated the "277th Plan for Construction of the Urban Agglomeration Framework of 'One Bay, Two Axes, One Core, and Two Poles". Furthermore, the area of cultivated land converted to forest land and grassland from 2000 to 2020 exceeded that of the period from 1980 to 2000, which is attributed to the implementation of two rounds of projects returning farmland to forests and grasslands since 1999, aimed at promoting ecological civilization construction and regional socio-economic development.

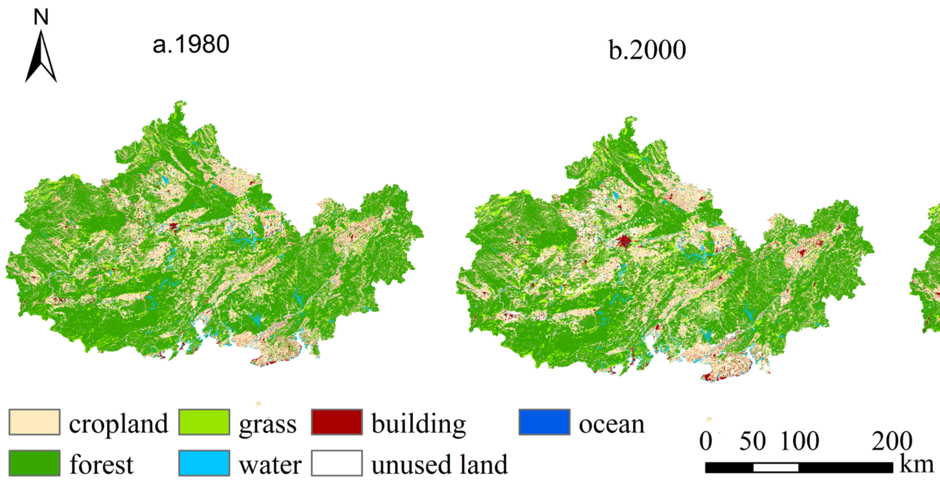

Figure 2. Land use area, percentage, and dynamics in Guangxi Northern Gulf from 1980 to 2020.

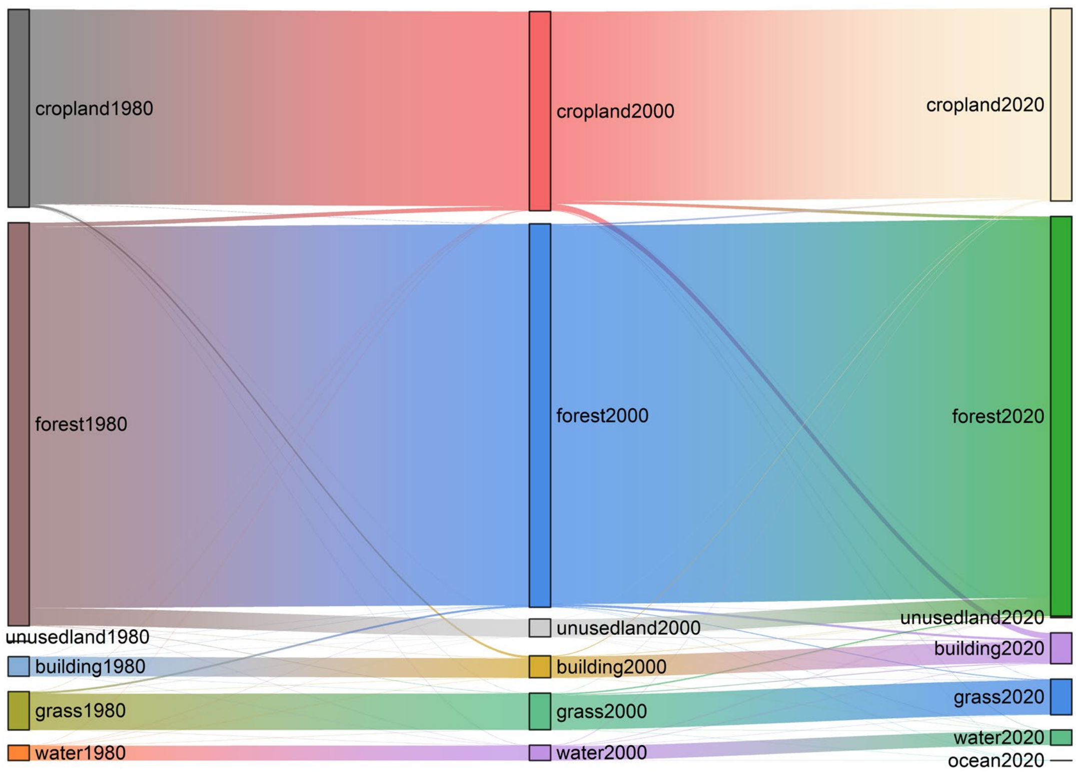

Figure 3. The land use type transitions in Guangxi Northern Gulf from 1980 to 2020.

Table 2. Land use area, percentage, and dynamics in Guangxi Northern Gulf from 1980 to 2020.

Land Use Type	1980		2000		2020		1980–2020 Annual Change Rate/%
	Area	%	Area	%	Area	%	
Cropland	21,329.60	29.54	21,189.10	29.34	20,623.20	28.54	−0.17
Forest	41,037.40	56.83	43,159.90	59.77	42,798.90	59.23	0.21
Grass	3918.97	5.43	4116.17	5.70	3801.02	5.26	−0.15
Waters	1649.36	2.28	1624.16	2.25	1620.49	2.24	−0.09
Building	2366.64	3.28	2080.76	2.88	3367.83	4.66	2.12
Unused land	1907.36	2.64	24.79	0.03	26.18	0.04	−4.93
Ocean	-	-	15.45	0.02	21.73	0.03	-

4.3. Temporal and Spatial Changes in Carbon Storage

4.3.1. Characteristics of Temporal Changes in Carbon Storage

The total carbon storage and carbon pool storage for the North Bay from 1980 to 2020 were estimated using the InVEST model, as shown in Figure 4. The results indicate that the total carbon storage in the Guangxi Northern Gulf in 1980, 2000, and 2020 was 504.91×10^6/t, 487.29×10^6/t, and 500.31×10^6/t, respectively. There was a decrease of 17.62×10^6/t from 1980 to 2000 and an increase of 13.02×10^6/t from 2000 to 2020.

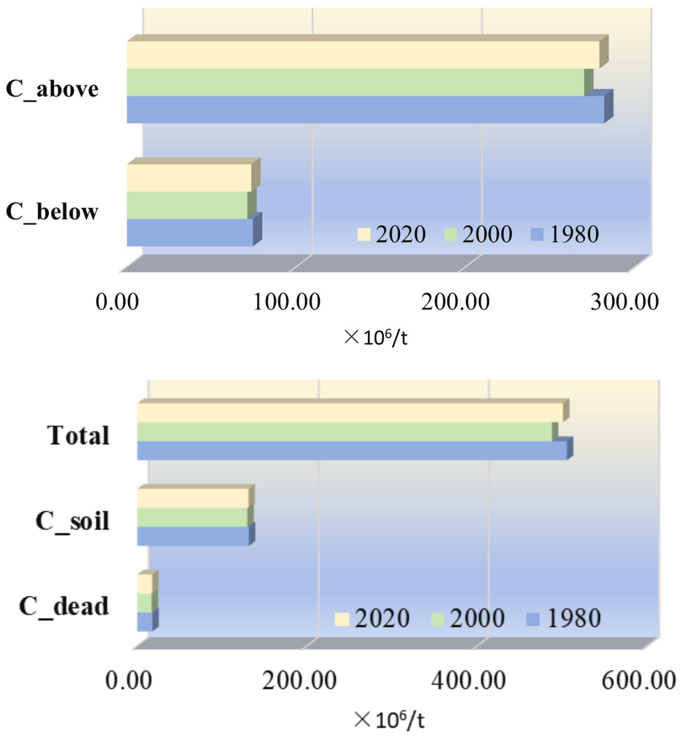

Figure 4. The variation in carbon storage of the primary carbon pools from 1980 to 2020.

Overall, after a decline in the first phase from 1980 to 2000, the total carbon storage rebounded in the second phase from 2000 to 2020. The aboveground biological carbon stock decreased from 281.76×10^6/t in 1980 to 269.94×10^6/t in 2000 and then rebounded to 278.95×10^6/t in 2020, resulting in reductions of 11.81×10^6/t and an increase of 9.01×10^6/t over these forty years. The underground biological carbon stocks were 74.41×10^6/t, 71.11×10^6/t, and 73.42×10^6/t for 1980, 2000, and 2020, respectively, showing little overall change. The soil organic carbon stocks were 131.11×10^6/t, 129.34×10^6/t, and 130.52×10^6/t, while the dead organic carbon stocks were 17.64×10^6/t, 16.89×10^6/t, and 17.42×10^6/t, indicating that the changes in these two carbon pools were not significant.

Table 3 illustrates that in the Northern Gulf region of Guangxi, forest land has the largest proportion of total carbon storage, followed by arable land. Forest land carbon storage accounts for 82.16%, 80.94%, and 82.22% of the total carbon storage in the three periods, respectively. From 1980 to 2000, the area of forest land decreased by 2122.2 km^2, resulting in a carbon storage reduction of 20.4 × 10^6/t; from 2000 to 2020, the area of forest land increased by 1762.70 km^2, leading to a carbon storage increase of 16.93 × 10^6/t. In the first stage, apart from a slight increase in unused land, construction land, and arable land, total carbon storage decreased significantly. In the second stage, the carbon storage of forest land and construction land increased slightly, but this change was minimal. Total carbon storage has shown a fluctuating upward trend over the past four decades.

Table 3. The carbon storage of various land types in the Northern Gulf region from 1980 to 2020.

Land Use Type	**1980**		**2000**		**2020**	
	C (×10^6)/t	**%**	**C (×10^6)/t**	**%**	**C (×10^6)/t**	**%**
Cropland	73.19	14.50	73.67	15.12	71.23	14.24
Forest	414.81	82.16	394.41	80.94	411.34	82.22
Grass	13.81	2.73	13.14	2.70	12.75	2.55
Waters	0.03	0.01	0.03	0.01	0.03	0.01
Building	3.04	0.60	3.46	0.71	4.92	00.98
Unused land	0.03	0.01	2.57	0.53	0.04	00.01
Ocean	0.00	0.00	-	-	0.00	00.00
Total	504.91	100	487.29	100	500.31	100

4.3.2. Features of Spatial Variations in Carbon Storage

The spatial distribution of carbon storage in the study area for the years 1980, 2000, and 2020, as assessed by the InVEST model (Figure 5), reveals pronounced spatiotemporal heterogeneity. Situated in the hilly terrain of the Northern Gulf region in Guangxi, the area benefits from favorable rainfall conditions, fostering dense forest cover and resulting in a relatively stable spatial distribution pattern of carbon storage. Urbanized zones such as Nanning, Beihai, Yu Zhou District in Yulin City, and Port District in Fang Cheng Gang City are characterized by predominantly artificial surfaces, leading to generally lower levels of carbon storage, which are attributed to the influence of economic and social development. Conversely, areas in the southwest of the Northern Gulf, such as Chong Zuo City and Shang Si County in Fang Cheng Gang, lie within the distribution range of the Wan Mountains, encompassing high-altitude mountainous and hilly terrains that exhibit robust carbon sequestration capabilities in ecological land use. These regions consistently maintain high levels of carbon storage throughout the year.

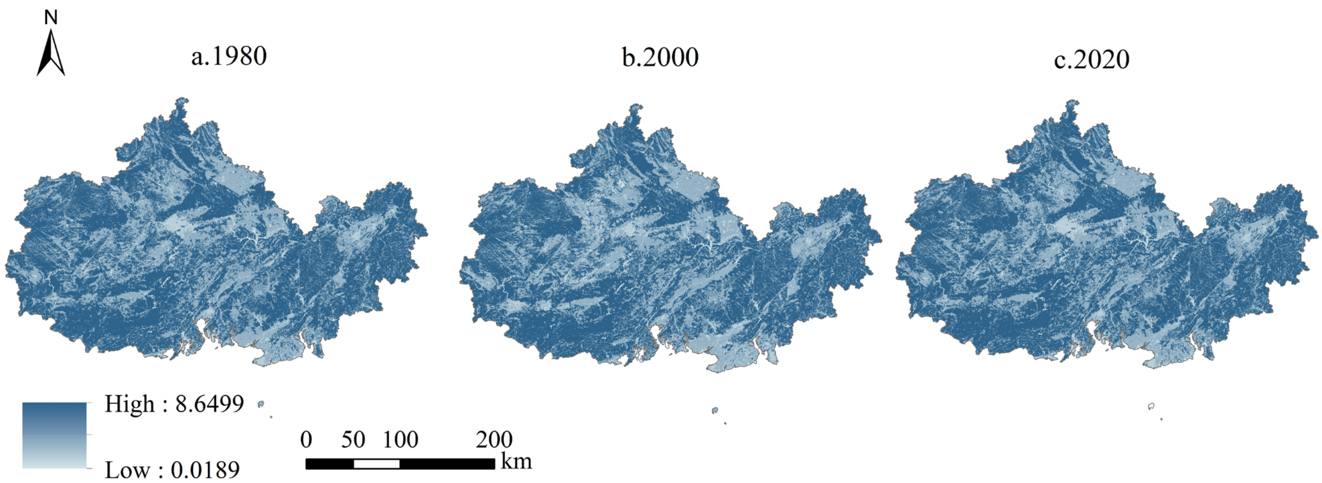

Figure 5. The spatial distribution of carbon storage in the Northern Gulf region from 1980 to 2020.

To provide a more visually informative representation of carbon storage dynamics in the Northern Gulf region of Guangxi, this study conducted a different calculation on carbon storage across three time periods and reclassified them into three categories: increase, stable, and decrease (as depicted in Figure 6). The findings reveal that the overall carbon storage in the study area remained relatively stable, with some regions exhibiting aggregation while others showed scattered distribution. From 1980 to 2000, there was a general trend of declining carbon storage, particularly notable in central areas typified by Nanning City and the southern coastal regions. Conversely, from 2000 to 2020, carbon storage values notably increased in the northwest, specifically in Wu Ming District and Xi Xiang Tang District. This upturn can largely be attributed to the implementation of the "2018 Nanning Green Mine Creation Work Plan" by the municipal government, designating Wu Ming and Xi Xiang Tang as official green mining demonstration areas. This initiative has bolstered ecological restoration efforts in these local areas, consequently influencing the observed increase in regional carbon storage.

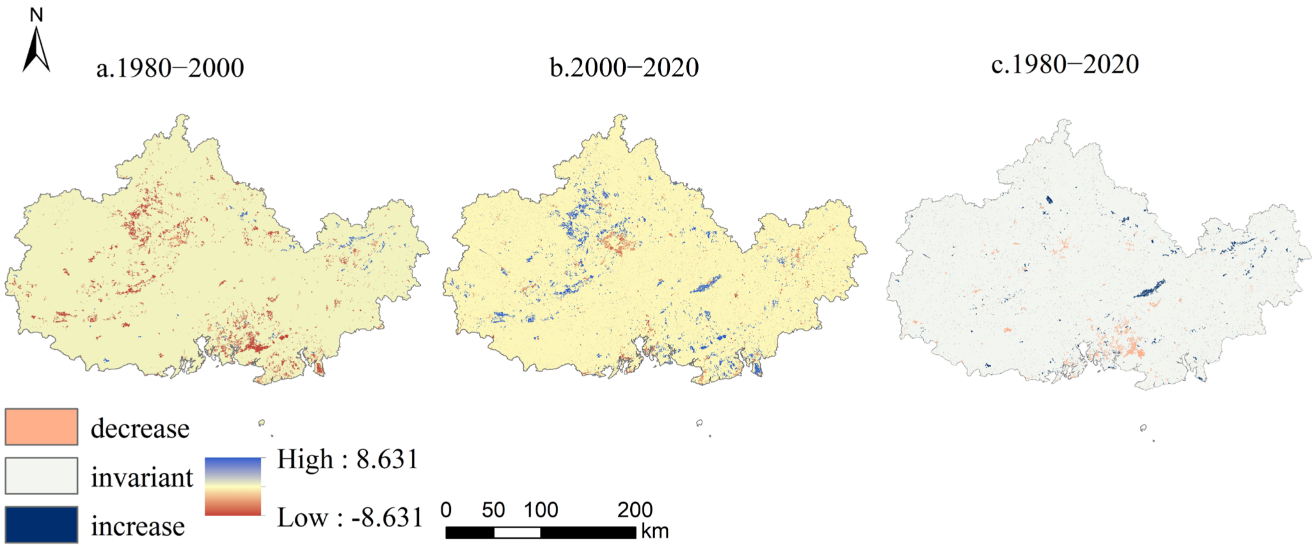

Figure 6. Spatial changes in carbon storage in the Northern Gulf from 1980 to 2020.

Between 1980 and 2020, the overall carbon storage remained relatively stable. However, noticeable declines were observed in certain areas, such as Nanning, the capital city of Guangxi province, and Qinzhou in the south. This reduction in carbon storage can be attributed to urban expansion, which led to the conversion of significant amounts of farmland and forestland into construction land. Conversely, areas experiencing significant increases in carbon storage include Ling Shan County and Yu Zhou District. The growth in carbon storage in these areas was influenced by policy directives. For instance, in 2015, Ling Shan County initiated the protection of the Ling Dong Reservoir water source area as the "Number One Project" in ecological construction, marking the beginning of a concerted effort in ecological development. Subsequently, in 2018, the autonomous region government approved the "Three-Year Action Plan for the Construction of Ecological and Environmental Protection Infrastructure in Guangxi (2018–2020)", further emphasizing the commitment to ecological protection and infrastructure development.

4.4. Spatial Autocorrelation Analysis of Carbon Storage

ArcGIS was employed to conduct the zoning statistics of carbon storage, while GeoDa software (https://geodacenter.github.io/) was used for the spatial autocorrelation analysis of the spatial distribution characteristics of carbon storage in the northern part of the Northern Gulf region. Spatial weights were established based on distance, with 50 km. The results reveal that in the global spatial autocorrelation analysis, the test point data exhibit dispersion across the second and third quadrants. Moran's I values for the years

1980, 2000, and 2020 were 0.253, 0.290, and 0.263, respectively, suggesting a spatial positive correlation among adjacent areas of carbon storage in the Northern Gulf region, albeit with a non-significant level of correlation strength.

The local spatial autocorrelation is depicted in Figure 7, revealing similarities in the spatial distribution characteristics of carbon storage. (1) Pu Bei County stands out as the sole region where carbon storage has experienced consistent growth over the past four decades. Within a 50 km radius, encompassing areas like Bo Bai County and Ling Shan County, high-value zones of carbon storage are observed, resulting in a clustering of high-value storage. The enhancement in forest coverage, attributed to national and regional afforestation and reforestation initiatives, has notably bolstered regional carbon storage. (2) The districts of Hai Cheng, Yin Hai, and Tie Shan Gang in Beihai City, alongside Xing Ye County in Yulin City, exhibit low carbon storage levels and spatial aggregation. This phenomenon is linked to urbanization demands, leading to the conversion of ecological land into urban areas and consequently diminishing the region's carbon sequestration capacity. (3) The relatively elevated carbon storage in Ping Xiang City in the southwest region during 1980–2000 is attributable to the higher carbon storage in the surrounding areas, resulting in a low–high clustering status. (4) The transition from high–high clustering to low–low clustering in He Pu County from 1980 to 2020 is attributed to the convergence of carbon storage values in adjacent areas.

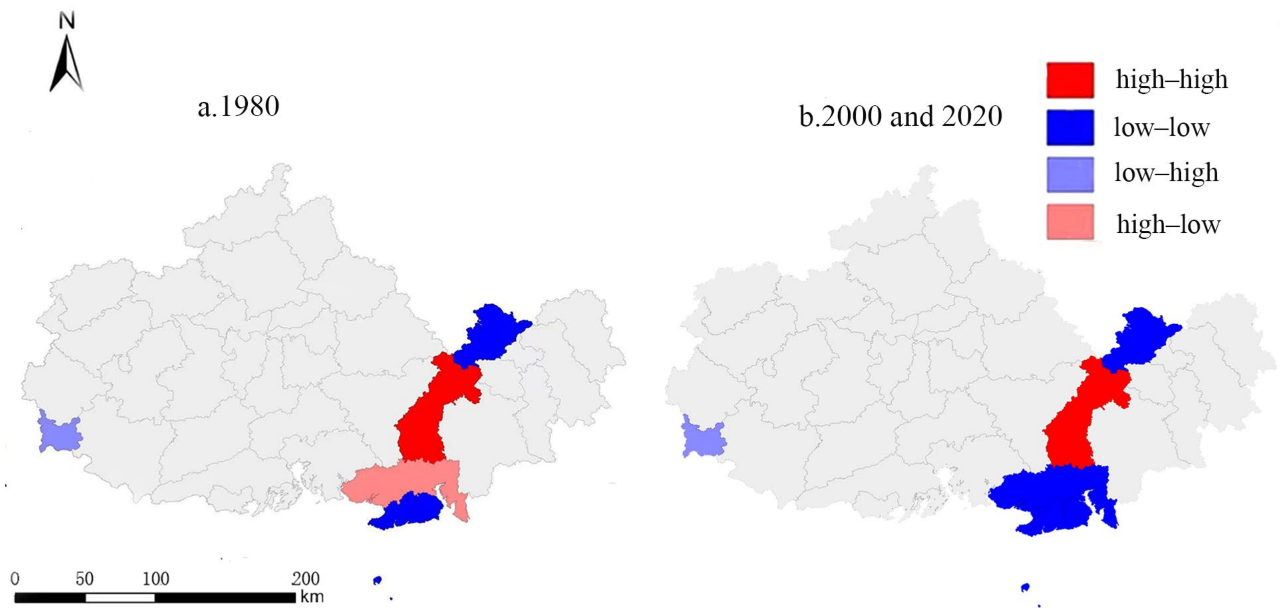

Figure 7. Local spatial autocorrelation of carbon storage from 1980 to 2020.

5. Discussion

Discussing the Influencing Factors of Carbon Storage Variation, Research Limitations, and Planning Recommendations

(1) Factors Influencing the Spatiotemporal Variations in Carbon Storage in the Northern Gulf Region. Terrestrial ecosystems represent one of the world's primary carbon reservoirs, and changes in land use patterns have a direct impact on terrestrial ecosystems, thereby influencing the spatiotemporal distribution of regional carbon storage. The results of this study indicate a trend of initial decline followed by a subsequent increase in carbon storage in the Northern Gulf region from 1980 to 2020. During the first phase, influenced by the rapid economic development of the region, urbanization accelerated, and urban construction entered a peak period, leading to a large-scale conversion of high-density carbon cropland and woodland into construction land, thereby diminishing the carbon sequestration capacity of the regional ecosystem. In the second phase, carbon storage exhibited a slight increase as cropland and unused

land were converted into woodland with a higher carbon sequestration capacity. This increase can be attributed to the emphasis on both economic development and environmental protection by the Guangxi Zhuang Autonomous Region since the 21st century. A series of local laws and regulations, enacted in conjunction with the national green development strategy, have limited land development and utilization to a certain extent. During this period, the expansion of urban construction land has encroached upon ecological lands such as cropland and woodland. However, with the implementation of a series of ecological protection and restoration projects such as the "Grain for Green Project", "Natural Forest Protection Project", "Ecological Restoration of Abandoned Mines", and "Urban Afforestation Project", woodland has been protected and restored to some extent, leading to a balance in carbon storage in local areas. It is evident that the expansion of construction land is the main cause of carbon storage loss, which is a conclusion consistent with the findings of most scholars [33–35].

(2) Spatial Correlation of Carbon Storage. The fluctuations in carbon storage within the research area predominantly stem from urbanization-driven land expansion, wherein ecological land undergoes conversion into built-up areas, thereby impacting carbon sequestration. In recent years, a heightened governmental focus on ecological civilization development has led to a deceleration in land development rates. Concurrently, there is an increased emphasis on ecological conservation alongside economic advancement, which has partially mitigated the degradation of the carbon sequestration function of ecological land, consequently elevating the region's carbon sequestration capacity. Nonetheless, certain regions continue to experience declines in carbon sequestration due to the encroachment of low-carbon-density urban areas into high-carbon-density land, resulting in carbon loss. In conclusion, the implementation of ecological conservation policies, guided by the ethos of "Green mountains and clear waters are as valuable as mountains of gold and silver", stands to bolster the ecosystem's carbon sequestration potential. Hence, future development endeavors in the Northern Gulf region of Guangxi should prioritize scientifically informed land planning and utilization, reinforce the safeguarding of ecological lands such as farmlands and forests, and foster the sustainable development of the regional ecosystem. At the same time, land use change is not only reflected in the study of historical periods but also focuses more on the future trends of land use changes. Given the rapid socio-economic development seen, rational land use planning significantly impacts the future economic development of regions and the variation in regional carbon stocks [36]. Therefore, future research should emphasize incorporating models for scenario simulations of Future Land Use [37–40] and extending the time scale of the study.

(3) Limitations of the Study. Research on the spatiotemporal dynamics of land use and carbon storage in the northern Gulf region of Guangxi remains relatively scarce. From a macroscopic perspective, Zhao Yin Zheng [25] utilized the FLUS-InVEST model to analyze and forecast the ecological spatial carbon storage of the Northern Gulf urban agglomeration. From a microcosmic viewpoint, Huang Xing [41] delved into the evolutionary traits of organic carbon storage in the northern Gulf tidal flats after the invasion of Spartina alterniflora. The novelty of this investigation lies in its visual representation of the spatial heterogeneity of carbon storage in the northern Gulf of Guangxi and the execution of spatial autocorrelation analysis at the county level to unravel the potential drivers behind areas of high and low carbon storage aggregation. However, this study harbors certain constraints. Firstly, variability exists in the selection of carbon density parameters across different studies for various regions, leading to subjectivity in parameter determination. This study relied on carbon density values in Guangxi from two scholars [25,42] as a reference without undergoing corrections based on the carbon density formula, thereby introducing subjective bias. Secondly, carbon density is subject to temporal variations and multifaceted

influences. The InVEST model computation process did not factor in fluctuations stemming from topographical, climatic, hydrological, and vegetative factors, thereby engendering uncertainties in the assessment outcomes. Henceforth, future research endeavors should embark on investigations and monitor carbon density across diverse land use types in the Northern Gulf region and amalgamate pertinent studies for numerical rectifications.

(4) Recommendations for Future Land Use Planning. The primary contributor to carbon storage depletion during the initial phase within the study area stemmed from the conversion of arable land and forests into built-up areas. This encroachment of urban development on ecological land leads to the fragmentation of ecological spaces, consequently exacerbating carbon storage losses. In the subsequent phase, urban development in the Northern Gulf Economic Zone prioritizes the simultaneous development of ecological civilization alongside economic growth. Policies and regulations, such as the establishment of nature reserves, the enactment of forest protection laws, and the advancement of ecological governance and restoration efforts, have effectively safeguarded forested areas with higher carbon storage, thus maintaining the total carbon storage in the Northern Gulf region at a relatively high level. Furthermore, the successful implementation of ecological restoration and construction initiatives, such as the "Grain for Green" program and afforestation projects in specific regions, has resulted in localized increases in carbon storage. Government policies supporting environmental protection and regional sustainable development can promote an increase in regional carbon storage. Therefore, the Northern Gulf region should continue to adhere to initiatives such as returning farmland to forests and implementing ecological protection and restoration projects to balance the carbon losses caused by built-up area expansions and achieve high-quality regional development.

6. Conclusions

This study investigates the variations in carbon sequestration in the Northern Gulf region of Guangxi from 1980 to 2020 and its associated influencing factors. The findings reveal a trend of an initial decline followed by subsequent recovery in carbon sequestration, primarily attributable to urbanization, which has resulted in the conversion of agricultural and forested lands into developed areas, leading to a reduction in carbon stocks. Our specific conclusions are given as follows:

(1) In the Northern Gulf of Guangxi, land use types are primarily composed of forests and arable land, together accounting for 85% of the total. Forests are mainly distributed in the southwest and eastern regions, while arable land is scattered across the central areas. From 1980 to 2020, there were varying degrees of reduction in arable land, water bodies, and unused land, while there was an increase in built-up areas and marine areas. Forests and grasslands experienced a slight decrease after an initial increase.

(2) The total carbon storage values from 1980 to 2020 were 504.91×10^6 t, 487.29×10^6 t, and 500.31×10^6 t, respectively. During the period from 1980 to 2000, the total carbon storage in the Northern Gulf decreased by 17.62×10^6 t, primarily due to the expansion of built-up areas and the conversion of forests. However, from 2000 to 2020, there was an increase in the total carbon storage of 13.02×10^6 t, attributed to the effectiveness of ecological protection and restoration projects.

(3) From a temporal perspective, the first 20 years from 1980 to 2020 witnessed significant fluctuations in carbon storage, with a decline of 3.49%. However, over the subsequent 20 years, influenced by the concept of ecological civilization, there was greater emphasis on environmental protection during the development process, leading to a reduction in the rate of carbon storage loss.

(4) The dynamic distribution of carbon storage at the county level in the northern part of the Northern Gulf in Guangxi exhibits spatial clustering characteristics among regions with similar values. From a spatial perspective, the overall carbon storage in

the Northern Gulf tends to be higher in high-altitude mountainous forest areas and lower in the central and southern coastal areas. This is manifested by the tendency of high-carbon resource areas to be adjacent to other high-carbon resource areas, while low-carbon resource areas tend to be adjacent to other low-carbon resource areas.

In summary, the impact of ecological conservation and restoration efforts has led to a partial increase in carbon storage. This study highlights how the changes in land use are a significant driver of carbon stock reduction and recommends the ongoing implementation of policies such as afforestation to align economic development with ecological sustainability, thereby fostering high-quality regional growth. Additionally, the research suggests enhancing the monitoring of carbon density and scenario modeling in future studies to effectively address the effects of land use changes. By combining ecological conservation measures with rational land use, we can promote the coordination between economic development and sustainability, thereby supporting the achievement of high-quality growth.

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Institutional Review Board Statement: The purpose of this study is to explore the relationship between land use and regional carbon storage using models. The research content does not involve humans or animals and is therefore exempt from ethical review and approval.

Informed Consent Statement: This study is not applicable to this context.

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

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