Spatial and temporal characteristics of carbon storage in Beihai City under land use change based on InVEST model

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Abstract: Land use change is a crucial factor influencing changes in carbon storage, and its impact on the carbon cycle and climate change holds significant importance. This study investigates land use changes in Beihai City, utilizing the InVEST model to assess carbon storage. It analyzes the spatiotemporal variations of carbon storage in different time periods and demonstrates the trends and spatial distribution characteristics of different land use types. The primary findings indicate that over the past two decades, cultivated land and forest land have been the main types of land use in Beihai City. Land use conversion primarily occurs between forest land and cultivated land, as well as between cultivated land and water areas. Overall, there has been an increasing trend in carbon storage within Beihai City, largely attributed to expansions in both forested areas and cultivated lands. Furthermore, there are disparities in how different conversions between various land use types contribute to carbon storage potential; notably, forested areas and unused lands exhibit higher potential for storing carbon.

Keywords: Land use change; Beihai City; InVEST model; Carbon stock.

1. Introduction

The rapid changes in land use patterns driven by the growth of the global economy and population have significantly impacted land resources, the ecological environment, the global carbon cycle, and climate change [1,2]. Assessing the impact of land use change on carbon storage is a crucial aspect of ecosystem service evaluation [3]. The InVEST model can be utilized to evaluate the impact of land use change on carbon storage [4] and provide relevant spatiotemporal characteristics analysis [5,6]. Additionally, it estimates carbon storage and its spatiotemporal differentiation [7], as well as studies and evaluates carbon storage and its spatiotemporal dynamic characteristics under two scenarios [8,9]. Based on the InVEST model, it simulates and evaluates carbon sequestration capacity in different periods while analyzing the relationship between land use change and carbon sequestration capacity [10]. The study reveals a certain connection between land use change and carbon sequestration capacity, with changes in land type impacting sequestration capacity accordingly. This investigation into the spatiotemporal characteristics of carbon storage in Beihai City under land use changes based on the InVEST model holds significant scientific significance and practical value by providing scientific support for decision-making related to carbon management, ecological protection, sustainable development, and carbon trading while serving as an important basis for local management of the carbon cycle system and ecological environmental protection.

2. Research review

2.1. Overview of InVEST model research

The InVEST model is a tool for assessing ecosystem services, which can be utilized to evaluate and quantify the contribution of natural capital to human well-being. In China, there is an increasing focus on researching and applying the InVEST model. Firstly, the model has been widely employed in domestic research for assessing and valuing ecosystem services [11] By operating and analyzing the model, it becomes possible to evaluate the supply and quality of different ecosystem services, providing a scientific basis for ecological environmental protection and sustainable development. Secondly, domestic researchers are also exploring and enhancing the application of the InVEST model by improving parameter setting, data input, interpretation of results as well as conducting targeted research on its application in water resources management, land use planning etc. Furthermore, there is also a focus on utilizing the InVEST model in policy formulation and decision support.

2.2. Review on the spatiotemporal characteristics of land use change on carbon storage

Land use changes have a significant impact on the spatial and temporal distribution of carbon stocks [12,13]. With the acceleration of urbanization and changes in agricultural production methods, land use types have undergone significant changes, resulting in changes in carbon storage. Zhu Pengfei [14] et al. used the InVEST model to analyze the changing characteristics and causes of carbon storage in the study area. The study found that the increase in the scale of urban and rural construction land, the expansion of industrial, mining and transportation land, and the increase in aquaculture water area have led to a decrease in carbon storage. The protection and restoration of forests and wetlands can help increase carbon stocks. At the same time, there are obvious spatial and temporal differences in the impact of land use changes on carbon storage. The degree of

carbon storage change in different regions and different land use types is different [15]. For example, the carbon storage of construction land is low, while the carbon storage of forests and wetlands is high [16-18]. At the same time, the impact of land use change on carbon storage also has a time delay effect, that is, changes in carbon storage may not be obvious for a period of time after land use change, and it will take a certain amount of time to appear [19]. Some studies have also found that the impact of land use change on carbon storage is affected by a combination of factors. Factors such as land use type, soil nitrogen content, climate conditions, soil moisture, etc. it will all affect changes in carbon storage [20]. Therefore, studying the spatiotemporal characteristics of land use change on carbon storage needs to consider the comprehensive effect of multiple factors.

3. Data Sources and Processing

3.1. Data source

Land use data can be obtained from the GlobeLand30 dataset released by the National Basic Geographic Information Center which provides land cover data in 2000, 2010 and 2020 with a spatial resolution of 30 meters [14,21]. Use the cropping tool in ArcGIS software to crop the original data according to administrative areas to obtain the research scope, and then reclassify the land types according to the actual situation of Beihai City. We can divide these data into six categories, including cultivated land, woodland, grassland, and water area, unused land and construction land [22-27]. Then the three-phase land use data and the carbon density in Table 1 are processed through the InVEST model to obtain the corresponding results..

Table 1. Carbon intensity of different land use types in Beihai City/t·hm−2

type of land use	Above-ground carbon density	Underground carbon density	Soil organic matter carbon density
cultivated land	24.96	4.96	16.78
woodland	107.86	26.97	17.15
grassland	5.57	25.03	21.74
waters	5.18	4.44	0
Unused land	6.29	0	0
Land for construction	21.18	1.72	11.82

Carbon density data vary due to different natural conditions and geographical environments [28,29]. The carbon density of Beihai City was estimated by consulting relevant literature and collecting corresponding carbon density data from relevant research papers or reports. Based on previous research results, it can be seen that the carbon density of land types has little difference within the same climate zone [30]. Carbon density data were collected by reviewing relevant literature. Therefore, this article refers to the research results on carbon emission coefficients and carbon densities of different land use types in Guangdong Province and Guangxi Autonomous Region, which are both in subtropical climate zones, as a reference [31], and revised them. Considering the difficulty in obtaining data on dead organic matter carbon storage and its general small amount, this study decided to set its value to 0 and not consider its impact on carbon storage. By correcting the carbon density, the soil carbon density correction coefficient was finally obtained to be 1.01, and the vegetation carbon density correction coefficient was 1.85. By multiplying the summarized carbon density data with the correction coefficient, the determined carbon density values for each land use type in Beihai City were obtaine.

3.2. Scope and overview of the study area
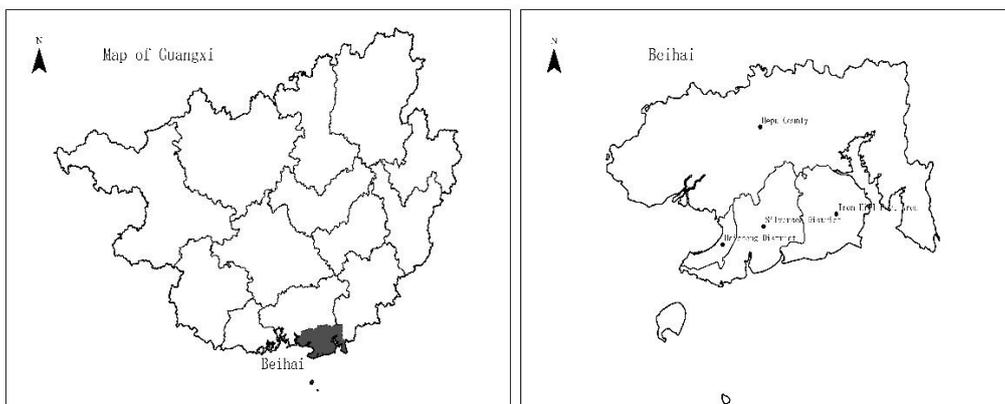
Fig.1 Geographical location of Beihai City

This article takes Beihai City, Guangxi as the research scope, located in the southeast coastal area of Guangxi. The scope of its research area generally refers to the geographical scope covering the entire Beihai City area. Beihai City has a total area of approximately 3,400 square kilometers and a population of approximately 1.39 million people (according to 2020 statistics). The city has jurisdiction over 3 districts and 1 county, including Haicheng District, Yinhai District, Tieshangang District, and Hepu County. Beihai City is located on the coast of the South China Sea and has rich marine resources and unique natural landscapes. Beihai City is also Guangxi's window to the outside world and is of great significance in promoting economic and trade cooperation between China and ASEAN countries. Land use changes in

this region have an important impact on the ecological environment and carbon storage. Therefore, studying the spatiotemporal characteristics of land use changes and carbon storage in this region provides scientific support for its sustainable development and ecological protection.
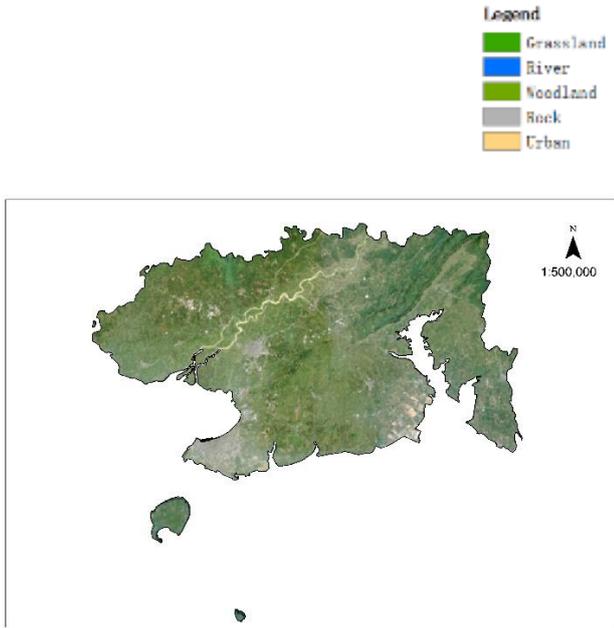

Fig.2 TM images of the study are

4. Research Methodology

4.1. Land use transition matrix and dynamics

4.1.1. Land use transition matrix

The land use transfer matrix formula is utilized to depict the relationship between different land use types in terms of their transfer. It serves to illustrate the change in area from one land use type to another within a specific time frame.

4.1.2. Intensity and dynamics of land use change

The intensity of land use change refers to the scale of transformation between different land use types, while the dynamics of land use change describes the rate at which such transformations occur [32]. Its calculation formula remains unchanged.

$$\text{LTI}_a = \frac{K_{jc} - K_{jb}}{\text{LA}_a} \times \frac{1}{T} \times 100\% \qquad (1)$$

The formula is as follows: K_{jc} and K_{jb} represent the initial and final areas of land type j in the study area a, respectively; LA_a is the total area of land type i in the study area; T denotes the research time interval. Spatially, land use dynamics refer to the velocity or frequency of changes in land use types within a specific period. It reflects the rate of land use change (Feng Jingke 2022). The characteristics of land use can be represented by a single dynamic degree of land use[32,33], with respective calculation formulas:

$$K = \frac{U_{ci} - U_{bi}}{U_{bi}} \times \frac{1}{T} \times 100\% \qquad (2)$$

In this formula, K represents the single dynamic degree of land use, U_{bi} and U_{ci} denote the area of land use type i at the beginning and end of the study area, respectively, while T represents the study interval [32,33].

4.2. Carbon density correction

The InVEST model categorizes the carbon storage of an ecosystem into four primary carbon pools: above-ground biological carbon, subsurface biological carbon, soil carbon, and dead organic carbon [34-37]. Carbon storage is calculated using the formula:

$$C_i = C_{i-above} + C_{i-below} + C_{i-soil} + C_{i-dead} \qquad (3)$$
$$C_{tot} = \sum_{i=1}^{n} C_i \times A_i \qquad (4)$$

In the above formula, a specific land-use type i, C_i represents the carbon density of that type; $C_{i-above}$、$C_{i-below}$、C_{i-soil} and C_{i-dead} indicate the aboveground vegetation carbon density (t·hm-2), belowground vegetation carbon density (t·hm-2), soil carbon density (t·hm-2), and dead organic carbon density (t·hm-2), respectively. C_{tot} denotes the total amount of stored in the entire ecosystem (t), A_i denotes the area of that type (hm2) and n denotes the number of types. Carbon density is influenced by regional climate, soil type, and other factors, therefore it's necessary to adjust the coefficient according to Beihai City's climate conditions and previous correction methods. Previous studies have shown that only precipitation was considered when assessing its impact on carbon density because temperature had a significantly lower correlation compared to precipitation.

$$C_{SP} = 3.3968 \times \text{MAP} + 3996.1 \qquad (5)$$
$$C_{BP} = 6.798 \times e^{0.0054 \times MAP} \qquad (6)$$

In the above formula, C_{SP} represents the soil carbon density adjusted for annual average rainfall (kg·m–2); MAP represents the average annual rainfall (mm), and C_{BP} represents the carbon density of biomass (kg·m–2) after the adjustment of annual average rainfall.

$$K_{BP} = C'_{BP} / C''_{BP} \qquad (7)$$
$$K_S = C'_{SP} / C''_{SP} \qquad (8)$$

In the above formula, K_{BP} represents the correction factor of biomass carbon density, K_S represents the correction factor of soil carbon density, C' and C'' represent the carbon density data of Beihai City and the carbon density data of the whole country, respectively.

4.3. InVSET model

The InVEST model is an integrated tool for assessing ecosystem services and trade-offs [38]. It was developed by The Nature Conservancy to assist policymakers and researchers in evaluating and quantifying ecosystem service values while considering trade-offs in decision-making processes. The InVEST model utilizes GIS technology and integrates ecological, economic, and spatial analysis methods.

5. Findings

5.1. Spatiotemporal changes and movements of land use

The main land use types in Beihai are cultivated land and forest land, as indicated in Fig 3 and Table 2. Cultivated land is primarily concentrated in the southern and central parts of Beihai, where the population is relatively dense, and covers a large area. Forest land, on the other hand, is mainly distributed in the northern and northeastern parts of Beihai from 2000 to 2020. During this period, construction land expanded towards the southwest while showing an increasing trend. Over the past two decades, water areas in Beihai City have been dispersed overall, mainly located at the border; grassland is also dispersed but accounts for a small proportion. The absolute value of change in area for different land use types ranks as follows: cultivated land> forest land>unused land>water>construction land. From 2000 to 2020, there has

been a gradual decrease in cultivated land area by a total of 469.09 k ㎡; conversely, forest area has shown an increasing trend year by year with a total increase of 392.66 k ㎡; construction and grassland areas have decreased overall by 0.38 k ㎡ and 3.05 k ㎡ respectively; meanwhile water areas have increased overall by a total of 15 .14k ㎡
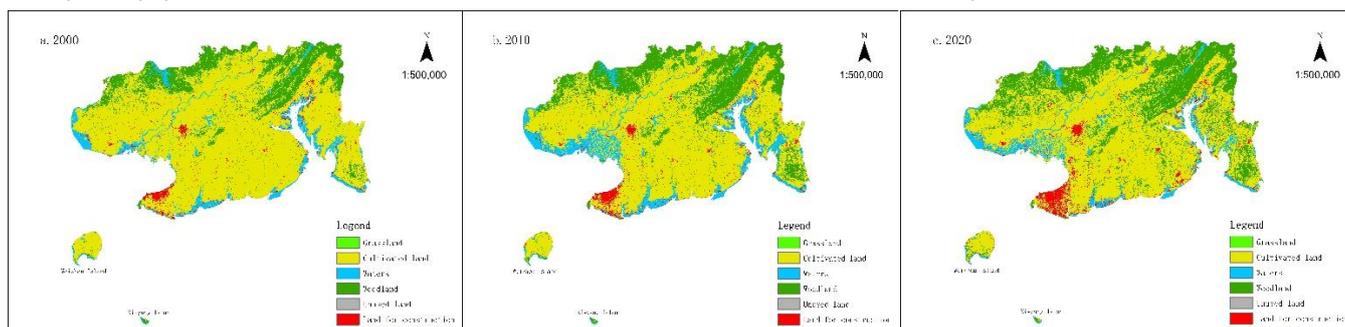
Fig.3 Spatiotemporal distribution of land use in Beihai City from 2000 to2020

Table.2 Land use change in Beihai City from 2000 to 2020

year	type	cultivated land	woodland	grassland	waters	Land for construction	Unused land
2000	Area/k㎡	2566.64	576.62	9.58	254.68	1.48	78.18
	Area Ratio/%	73.60	16.54	0.27	7.30	0.04	2.24
2000-2010	Amount of change/k㎡	-346.40	215.41	-2.73	117.66	-0.82	16.86
2010	Area/k㎡	2220.23	792.03	6.85	372.34	0.66	95.04
	Area Ratio/%	63.67	22.71	0.20	10.67	0.02	2.72
2010-2020	Amount of change/k㎡	-122.69	177.25	-0.32	-102.52	0.44	47.80
2020	Area/k㎡	2097.55	969.28	6.53	269.82	1.10	142.84
	Area Ratio/%	60.15	27.80	0.19	7.73	0.03	4.09
2000-2020	Amount of change/k㎡	-469.09	392.66	-3.05	15.14	-0.38	64.66

Table.3 Land transfer matrix of Beihai City from 2000 to 2010 (unit: k㎡)

Type of land use	cultivated land	woodland	grassland	waters	Land for construction	Unused land	total
cultivated land	2155.15	265.10	2.44	119.27	0.06	24.36	2566.39
woodland	51.76	524.24	0.02	0.38	0.00	0.10	576.50
grassland	4.13	0.04	3.40	0.64	0.08	1.29	9.57
waters	6.89	2.39	0.52	241.04	0.26	3.35	254.45
Land for construction	0.35	0.00	0.42	0.04	0.25	0.41	1.48
Unused land	1.85	0.08	0.04	10.67	0.00	65.49	78.13
total	2220.12	791.85	6.85	372.05	0.66	94.99	3486.52

Table.4 Land transfer matrix of Beihai City from 2000 to 2020 (unit: k㎡)

Type of land use	cultivated land	woodland	grassland	waters	Land for construction	Unused land	total
cultivated land	1973.62	455.59	3.57	69.85	0.17	63.58	2566.38
woodland	65.36	510.10	0.04	0.56	0.00	0.40	576.46
grassland	5.38	0.29	0.76	1.37	0.08	1.70	9.57
waters	46.03	2.87	1.97	191.99	0.73	10.70	254.29
Land for construction	0.61	0.03	0.13	0.10	0.09	0.51	1.48
Unused land	6.28	0.19	0.05	5.72	0.02	65.87	78.13
total	2097.28	969.07	6.52	269.58	1.09	142.75	3486.30

Tables 3 and 4 demonstrate the high frequency of mutual conversion among various land use types in Beihai City from 2000 to 2020, indicating a rich variety of transfer modes. During the period from 2000 to 2010, cultivated land mainly converted to forest land and unused land, with an area of 265.1k ㎡ and 24.36k ㎡ respectively; grassland primarily transferred to cultivated land and unused land, with an area of 4.13k ㎡ and 1.29k ㎡ respectively; while forest land was predominantly converted to cultivated land, with an area of 51.76k ㎡ transferred out. From 2000 to 2020, construction land exhibited relatively stable changes; cultivated land mainly converted from forestland and water areas, with areas of 65.36k ㎡ and 46.03k ㎡ respectively; while forestland experienced a significant increase by converting from

cultivated lands at an extent of 455.59k ㎡; unused lands were primarily transformed into cultivated lands.

5.2. Dynamic changes in land use

5.2.1. Intensity of change

From Table 5, it can be seen that during the period from 2000 to 2010, cultivated land and forestland experienced significant changes. The intensity of change in cultivated land was -0.99%, indicating that the area of cultivated land was decreasing; while the intensity of change in forestland was 0.62%, indicating that forestland was in the study area. continues to increase within. The change intensity of construction land and water areas was 0.05% and 0.34% respectively, while the change intensity of grassland and unused land was weaker. During the period from 2000 to 2020, the change in cultivated land in Beihai City was the most obvious, with a change intensity of -0.67%; the area of forestland, water areas and construction land increased to a certain extent, while the degree of change in grassland was weaker. The continuous increase of forest land, water areas and construction land shows that with the continuous development of Beihai City, the utilization degree of various land use types has increased, the urbanization process has also been accelerating, and the uncoordinated degree of the relationship between man and land has deepened.

5.2.2. Dynamic analysis

There are obvious differences in the dynamics of single land use of different land use types in Beihai City. From 2000 to 2010, cultivated land, grassland and unused land showed a decreasing trend; while the area of forest land, water area and construction land increased relatively significantly. From 2000 to 2020, the dynamics of single land use of construction land, forest land and water area increased relatively significantly; the dynamics of single land use of cultivated land, grassland and unused land were all negative, showing a decreasing trend.

Table.5 Land use change index of Beihai City

| Type of land use	2000-2010		2010-2020		2000-2020	
	Intensity of change/%	Single dynamics/%	Intensity of change/%	Single dynamics/%	Intensity of change/%	Single dynamics/%
cultivated land	-0.99%	-1.35%	-0.35%	-0.55%	-0.67%	-0.91%
woodland	0.62%	3.74%	0.51%	2.24%	0.56%	3.40%
grassland	-0.01%	-2.85%	0.00%	-0.47%	0.00%	-1.59%
waters	0.34%	4.62%	-0.29%	-2.75%	0.02%	0.30%
Unused land	0.00%	-5.54%	0.00%	6.67%	0.00%	-1.28%
Land for construction	0.05%	2.16%	0.14%	5.03%	0.09%	4.14%

5.3. Analysis of carbon storage change characteristics

5.3.1. Time change characteristic

From 2000 to 2020, carbon storage in Beihai City showed an increasing trend, and forest land had a greater impact on the total carbon storage of the ecosystem, and the total carbon storage of the ecosystem supplied by forest land was large. From 2000 to 2010, carbon storage showed an increasing trend, mainly due to the increase of forest area and the decrease of construction land. The total ecosystem carbon storage supplied by cultivated land and grassland area decreased, while the total ecosystem carbon storage supplied by water area and unused land increased. The carbon storage also showed an increasing trend from 2010 to 2020, which was due to the increase in forest area and the increase in the total carbon storage of the ecosystem. The total ecosystem carbon storage supplied by arable land, grassland and water area is decreasing, while the total ecosystem carbon storage supplied by construction land and water area is increasing.

5.3.2. Spatial change characteristics
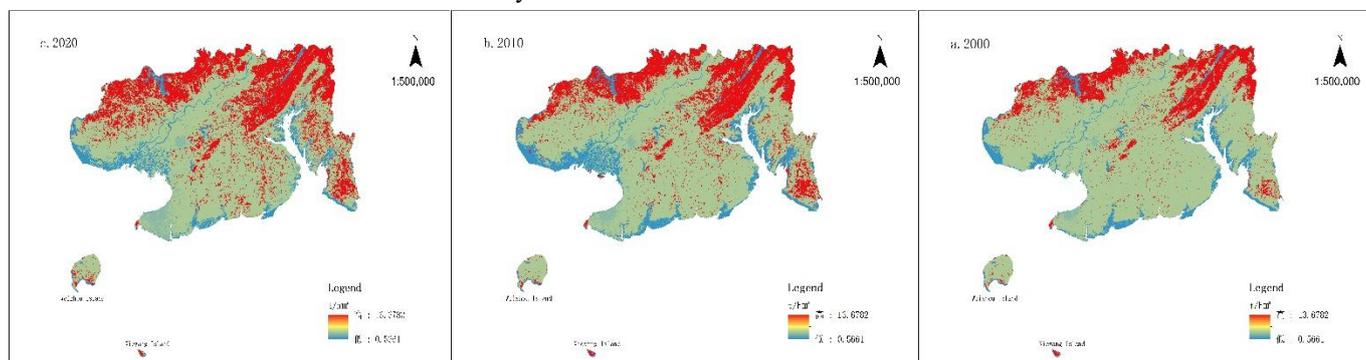
Fig.4 Distribution of carbon storage by land use type in Beihai City from 2000 to 2020

As shown in Fig 4, in 2000, Beihai City was in a subtropical humid monsoon climate with long summer and no winter, high vegetation coverage and high carbon storage. In 2010, the northern part of Beihai City had a warm, humid and rainy climate, high vegetation coverage and high carbon storage. In 2020, the area of carbon storage in the north and northeast of Beihai City will increase due to the increase of forest land area, while the area of carbon storage in the south will decrease due to the increase of construction land area.

5.4. Impact of land use change on carbon storage

In this study, by summarizing the carbon density values of different land use types in Beihai City, it is found that their order is: forest land > grassland > cultivated land > building land > unused land > water area. When using InVEST to calculate carbon stocks, the set carbon density value is fixed, so the change of carbon stocks in the study area is mainly caused by the change of land use types. As shown in Fig 5, the transfer of land types mainly occurred between cultivated land, forest land, water area and unused land. The increase of carbon storage in Beihai City mainly comes from the transfer of cultivated land to forest land and water area to cultivated land. The transfer of cropland to forest land resulted in a 479.64wt increase in carbon stocks, while the transfer of forest land to cropland resulted in a 70.52wt decrease in carbon stocks, resulting in an overall net increase of 409.12wt. In addition, the transfer of water to unused land resulted in a 2.64wt increase in carbon storage, while the transfer of unused land to water resulted in a 1.38wt loss of carbon. The conversion between cultivated land and water area resulted in a carbon reduction of 9.30wt, and the conversion between cultivated land and unused land resulted in a carbon storage reduction of 6.86wt. The conversion between construction land and other types of land has little effect on the change of carbon storage.
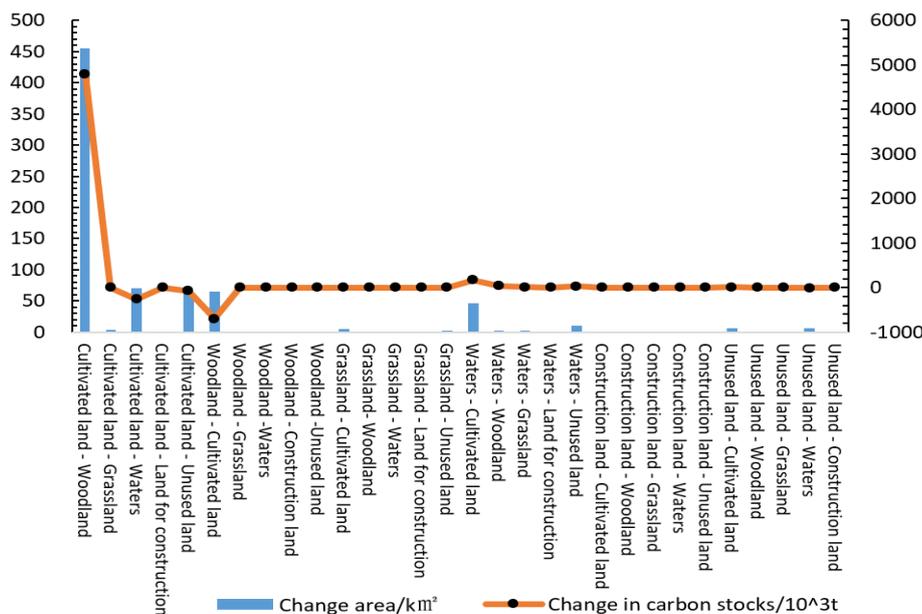

Fig.5 The impact of different types of conversion on carbon storage from 2000 to 2020

6. Discussion and conclusions

6.1. Discussion

The change in land use is primarily influenced by natural and human factors. Natural factors directly determine the composition of land types, while human factors further shape the pattern and change of land use through decision-making and management. The findings indicate that cultivated land and forest cover accounts for 87.95% of Beihai City. Situated in the southern region of Guangxi Zhuang Autonomous Region, Beihai City boasts abundant natural resources and a favorable ecological environment due to its flat terrain, warm and humid climate, and fertile soil suitable for agricultural and forestry development. The government places great emphasis on ecological environmental protection and sustainable development, implementing a series of policies to promote the conservation and rational utilization of forested areas as well as cultivated lands. Additionally, human activities also play a significant role in driving changes in land use. With the rapid economic development and accelerated urbanization, the demand for land resources is increasing. In order to meet the needs of urban construction, industrial development, and commercial services, farmland and forest land are being converted into urban construction land, industrial land, and commercial land. The adjustment of urban planning also leads to changes in land use. For example, urban expansion requires new land or adjustments in urban functional zoning necessitate changes in original land use. This aligns with Li Xiaojun's analysis on the causes of land use change [39]. Combined with policy situations, geographical locations, and other factors, reasons for transfer changes are analyzed. Government policy orientation plays a crucial role in guiding changes in land use transfer. For instance, government policies on urbanization development, rural land contracting policies, ecological environmental protection policies have an impact on land use change. Changes and adjustments in policy will result in transfers and alterations in land use. Geographical location is one of the key factors influencing changes in land use transfer. Different characteristics and location advantages of lands across different geographical areas will affect choices and transfers of their uses. For example, land located in coastal areas may be more suitable for uses such as port development, industry and tourism, while land located in inland areas may be more suitable for uses such as agriculture and forestry.

6.2. Conclusion

Over the past two decades, the primary land use types in Beihai City have been cultivated land and forest land. Cultivated land is predominantly located in the southern and central regions, with a relatively large area in densely populated areas, while forest land is mainly found in the northern and northeastern regions. The expansion of construction land has occurred primarily to the southwest, encroaching upon forested areas and resulting in a noticeable

increase in construction land area. During this period, forest land saw the greatest increase, expanding by 392.66 square kilometers, while cultivated land experienced the most significant decrease at 469.09 square kilometers. Despite covering the smallest area overall, construction land exhibited the most substantial dynamic change at 4.14%, significantly higher than other types of land use. Land use transfers primarily occurred between forest and cultivated lands as well as between cultivated lands and water bodies.

In the past 20 years, the carbon storage in Beihai City showed an increasing trend, mainly due to the increase of forest area and cultivated land area. From 2000 to 2020, the area of carbon storage in the north and northeast of Beihai City will increase due to the increase of forest land area, while the area of carbon storage in the south will decrease due to the increase of construction land area. In addition, the contribution of conversion to carbon storage is different among different land use types, and forest land and unused land have higher carbon storage potential.

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Conflicts of Interest

The authors declare no conflict of interest

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