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Assessment of the impact of wetland changes on carbon storage in coastal urban agglomerations from 1990 to 2035 in support of SDG15.1

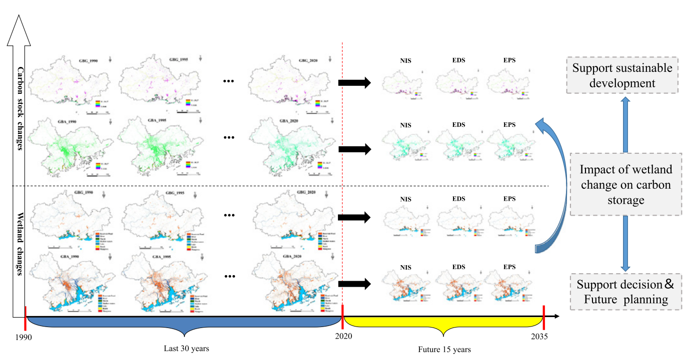
Ze Zhang [a,b], Weiguo Jiang [a,b,*], Kaifeng Peng [c], Zhifeng Wu [d], Ziyan Ling [a,b,e], Zhuo Li [a,b]

[a] State Key Laboratory of Remote Sensing Science, Faculty of Geographical Sciences, Beijing Normal University, Beijing 100875, China
[b] Beijing Key Laboratory for Remote Sensing of Environment and Digital Cities, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[c] College of Geographic and Environmental Sciences, Tianjin Normal University, Tianjin 300387, China
[d] School of Geography and Remote Sensing, Guangzhou University, Guangzhou 510006, China
[e] Key Laboratory of Environmental Change and Resource Use in Beibu Gulf, Ministry of Education, School of Geography and Planning, Nanning Normal University, Nanning 530001, China

HIGHLIGHTS

- Proposed a long time series refined wetland carbon stock assessment model
- Coupling RF-CLUE-S and InVEST models for wetland carbon stock assessment
- Quantitative assessment of two coastal urban clusters SDG15.1
- Changes in wetland carbon stocks are linked to urban agglomeration development and ecological policies.

GRAPHICAL ABSTRACT



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ABSTRACT

The quantitative assessment and spatial representation of wetland carbon storage, which play a critical role in the global carbon cycle and human production, can provide useful data and knowledge for decision-making in achieving sustainable development goals (SDGs). Currently, human activities and climate change impacts pose a challenge for the assessment of wetland carbon storage in coastal urban clusters. We proposed a "past-present-future" long time series refined wetland carbon storage assessment model using Guangxi Beibu Gulf (GBG) and Guangdong, Hong Kong, Macao and the Greater Bay Area (GBA) as the study area. The CLUE-S and InVEST models were coupled to conduct a comparative analysis of the spatial and temporal changes in wetland carbon storage and the spatial identification of damages from 1990 to 2035 and finally explore the sensitivity of wetland changes to carbon storage and quantitatively assess the SDG15.1 target. The results showed that (1) both urban clusters are characterized by many reservoirs/farming ponds, large river areas and few lakes. 1990–2035 rivers, shallow waters and mudflats have a decreasing trend to be distributed in the middle of their respective regions, mangroves are on an increasing trend, GBG is mainly distributed in the Maowei Sea and GBA is mainly distributed in Shenzhen Bay. (2) Wetland carbon storage of the two urban clusters show an overall fluctuating downward trend, with rivers, lakes and beaches all showing a downward trend. The multiyear average carbon storage of the GBG are 3.2 times higher than those of the GBA. In ecological protection scenario (EPS) policy planning, it is reasonable to help wetland carbon sequestration in coastal urban clusters. (3) The trend of wetland change from 1990 to 2020 was positive for carbon storage. The rate of recovery of wetland carbon stocks is lower in GBA than in GBG under the natural increase scenario (NIS) and the ecological protection scenario

* Corresponding author at: State Key Laboratory of Remote Sensing Science, Faculty of Geographical Sciences, Beijing Normal University, Beijing 100875, China.
E-mail address: jiangweiguo@bnu.edu.cn (W. Jiang).

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(EPS). The economic development scenario (*EDS*) contributes least to the realisation of SDG15.1 for the coastal urban agglomeration. The ecological protection scenario (*EPS*) contributes the most to the realisation of SDG15.1 for the coastal urban agglomeration.

1. Introduction

Wetlands are highly productive ecosystems with abundant carbon storage, and wetland carbon storage play a critical role in the global carbon cycle (Xiao et al., 2019; Jiang et al., 2017a). Wetlands cover approximately 6–9 % of the Earth's land surface but store an estimated 35 % of global terrestrial carbon (Deng et al., 2022). Since 1970, 35 % of the world's natural wetlands have been damaged (Niu et al., 2012), and the loss of carbon storage in wetland ecosystems can lead to an increase in atmospheric CO_2 concentrations, resulting in global warming (Liu et al., 2019). As the importance of wetland carbon storage has come to the fore, there is growing international and Chinese interest in wetland conservation and carbon storage assessment. Both the Wetlands Convention and the United Nations Sustainable Development Goals (SDGs) propose protecting and restoring water-related ecosystems and their services (Fitoka et al., 2020). SDG15.1 states "By 2020, protect, restore and sustainably use terrestrial and inland freshwater ecosystems and their services, especially forests, wetlands, foothills and dry lands, in accordance with obligations under international agreements." China has also issued a series of wetland conservation and restoration programs and notifications since this century (Smith et al., 2019) and started to implement the Wetland Protection Law in June 2022. This has become one of the hot spots of concern for many international organizations and the Chinese government. Therefore, it is important to explore the spatial and temporal changes in wetland carbon storage to improve the quantitative assessment of wetland ecosystem services and sustainable development in coastal urban clusters.

Wetland types are diverse, and accurate, fine-grained data on wetland types are an important basis for exploring ecosystem service functions. Related researchers have produced a series of data products at different scales, laying a rich foundation for sample selection and data application analysis. (Sagar et al., 2017; Zhao and Qin, 2020; Zhang et al., 2021). Existing wetland classification data are mainly based on single wetland type data and land use data from historical periods (Liu et al., 2018; Chen et al., 2014), which suffer from difficulties in obtaining fine wetland types, especially the incomplete mapping scope of coastal wetlands. Similarly, most of the future spatial prediction data focus on scenario prediction of broad land use categories, and the prediction of fine types of wetlands in urban clusters has not been fully studied (Aburas et al., 2019; Liang et al., 2021). There are problems such as unclear discussion of different scenarios applicable to coastal urban clusters and in applicability of constructing spatial prediction models, which make it difficult to serve coastal urban clusters with long time series accuracy. It is difficult to serve the wetland conservation and restoration and ecological function assessment of coastal urban clusters in a long time series. Therefore, we produced a set of long time-series refined wetland type data for coastal city groups to provide good data support for carbon storage assessments of wetland resource conservation and ecological functions.

Wetland changes have an impact on carbon storage, which are difficult to recover once damage occurs, such as urban expansion and climate change. This has a great impact on human life and other ecosystems. The existing methods used to assess the carbon storage of wetland ecosystems mainly include field surveys, remote sensing inversions and model simulations. The traditional methods of field surveys can obtain wetland carbon storage with high precision, but they are expensive in terms of financial, material, and human resources, are limited to studies at the site scale at the time, and cannot perform past and future studies (Sun and Li, 2017). Currently, the rapid development of remote sensing technology provides favorable and convenient tools for carbon storage estimation, resulting in model simulation-based carbon storage estimation methods. The InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model, which is based on remote sensing models, can be used to calculate the dynamic assessment of carbon storage in wetland ecosystems with simple inputs, flexible parameter settings, accurate results, and wide application (Liu et al., 2019; Babbar et al., 2021). Some researchers have conducted studies on carbon storage in some regions of China, mainly focusing on carbon storage estimation, the impact of land use change on carbon storage, and the simulation of future spatial changes in carbon storage based on future projections (Jiang et al., 2017b; He et al., 2016). For example, Zhu et al. (2022) used CA-Markov and InVEST models to explore the impact of land use on carbon storage in coastal provinces of China. (Zhang et al., 2016) used a base-dynamic land-ecosystem model to simulate soil organic carbon storage and vegetation carbon storage in the southern United States during the period 1945–2007. However, most of these studies mainly emphasize land use types to estimate carbon storage, and there is a lack of detailed types of carbon storage for past and future wetland habitat systems. Therefore, it is necessary to explore the carbon storage changes and their impacts based on a long time series refined wetland classification dataset and the InVEST model.

As a transition zone between land and sea ecosystems, coastal areas are sensitive to climate change and have fragile ecological environments (He et al., 2016). Both Guangxi Beibu Gulf (GBG) and Guangdong, Hong Kong and Macao Greater Bay Area (GBA) are coastal city clusters in southern China, which also have a complex river network in the Pearl River Basin and rich coastal wetland resources of diverse types, such as mangroves, mudflats, and shallow marine waters. Since the reform and opening up, the two regions have entered a rapid development stage, with rapid urbanization and industrialization and increasingly frequent coastal development activities, which have led to significant changes in land use patterns and unreasonable use of national land resources, such as encroachment on agricultural land and large-scale reclamation, resulting in the massive disappearance of wetlands. These factors have led to a continuous decline in ecosystem service functions and sustainable use, posing a great threat to the carbon storage of wetlands in the region. Additionally, in the context of the new era, the two study areas have an important national strategic position and are given new missions. The GBG is an important gateway for the organic connection of "One Belt, One Road", an international corridor for ASEAN, and a new land and sea corridor in the west. The GBA is one of the four major bay areas in the world and is a space for the cross-strait economy to seek greater development and a fresh blood for national development. Therefore, the impact of wetland changes on the carbon storage of ecosystem services in both regions should be explored simultaneously to support the sustainable development of wetland carbon storage.

The main aim of this study is to investigate the assessment of the impact of wetland change on carbon storage in the coastal urban agglomeration from 1990 to 2035 in support of SDG15.1. Specifically, (1) we analysed the changes in wetland area and spatial changes in the natural increase scenario (NIS), economic development scenario (EDS) and ecological protection scenario (EPS) for 1990–2020 and 2020–2035 in the GBG and the GBA based on the RF-CLUE-S model. (2) We explored the spatial and temporal changes in refined wetland carbon storage from 1990 to 2035 based on the InVEST model, and conducted a spatial identification analysis of impaired wetland carbon stocks for three scenarios, 1990–2020 and 2020–2035, respectively. (3) We correlated SDG with carbon storage and used sensitivity analysis to reveal the impact of wetland change on carbon storage, assessing changes in SDG15.1 under multiple scenarios for 1990–2020 and 2020–2035.

2. Materials and methods

2.1. Study area

The Guangxi Beibu Gulf (GBG) is located in southern Guangxi, China, and the overall topography gradually decreases from northwest to southeast. The climate has a subtropical monsoon climate, with high temperature and rain in summer, mild and little rain in winter, abundant heat and sometimes extreme weather, precipitation between 1745.6–3111.9 mm, abundant rainfall and rich wetland resources. There are many rivers, and the mainland coastline is approximately 1595 km. By 2020, the study area includes 6 prefecture-level cities and 38 counties (districts), covering a land area of approximately 42,500 km^2, the population is approximately 24.56 million, and the GDP per capita generally shows a rapid upward trend.

The Guangdong-Hong Kong-Macao Greater Bay Area (GBA) is located in the southern part of Guangdong, China, and is known as one of the world's four major bay areas along with the New York Bay Area, San Francisco Bay Area, and Tokyo Bay Area. The GBA consists of nine cities in Guangdong and two special administrative regions, Hong Kong and Macao, with a total area of 56,000 km^2. The topography of the study area is high in the northwest and low in the southeast, with a dense network of inland rivers, abundant water, rich wetland resources, and a predominantly subtropical and tropical monsoon climate with good hydrothermal conditions. by 2020, the population of the GBA exceeded 70 million, and the total GDP reached 11.6 trillion yuan (Fig. 1).

2.2. Data source and data preprocessing

The data from 1990 to 2035 were extracted from a study conducted by our coauthor (Peng, 2022), which was based on Landsat data, combined with random forest and hierarchical decision tree to build a "meta-object-knowledge" classification algorithm and extracted the coastal urban cluster for seven periods from 1990 to 2020. The overall accuracy was above 0.88. Based on the policy constraints, coupled with random forest and CLUE-S models, the classification dataset of wet coastal urban agglomerations for 2020–2035 was predicted with an overall accuracy of 0.86 or more. Based on the needs of this study, the wetland types were readjusted and classified into marshes, rivers, lakes, beaches, mangroves, reservoirs/ponds, and shallow waters.

The natural increase scenario (NIS) is that future spatial and temporal changes in wetlands are not affected by major natural disasters and national macro policy regulation, and that each land use type continues to change according to the trend of change in the historical period respectively. The economic development scenario (EDS) refers to the future development of the coastal urban agglomeration focusing on economic development and the pursuit of maximum economic benefits. In this scenario, the area demand structure of future wetlands should be designed to serve socioeconomic development, with economic benefits as a priority. The ecological protection scenario (EPS) refers to the future development of the coastal urban agglomeration focusing on the conservation of the ecological environment and resources and the pursuit of maximum ecological benefits. In this scenario, the area demand structure of future wetlands should be designed so that their ecosystem service value is maximised, with ecological benefits as a priority.

2.3. Research methods

In the context of the Sustainable Development Goals, this study collects wetland classification data and projection data to obtain carbon intensity data. We conducted a spatial and temporal analysis for the period 1990–2035 and calculated refined wetland carbon stocks based on the InVEST model. Finally the impact of wetland change on carbon stocks was analysed in detail and quantitatively assessed for SDG15.1. (Fig. 2).

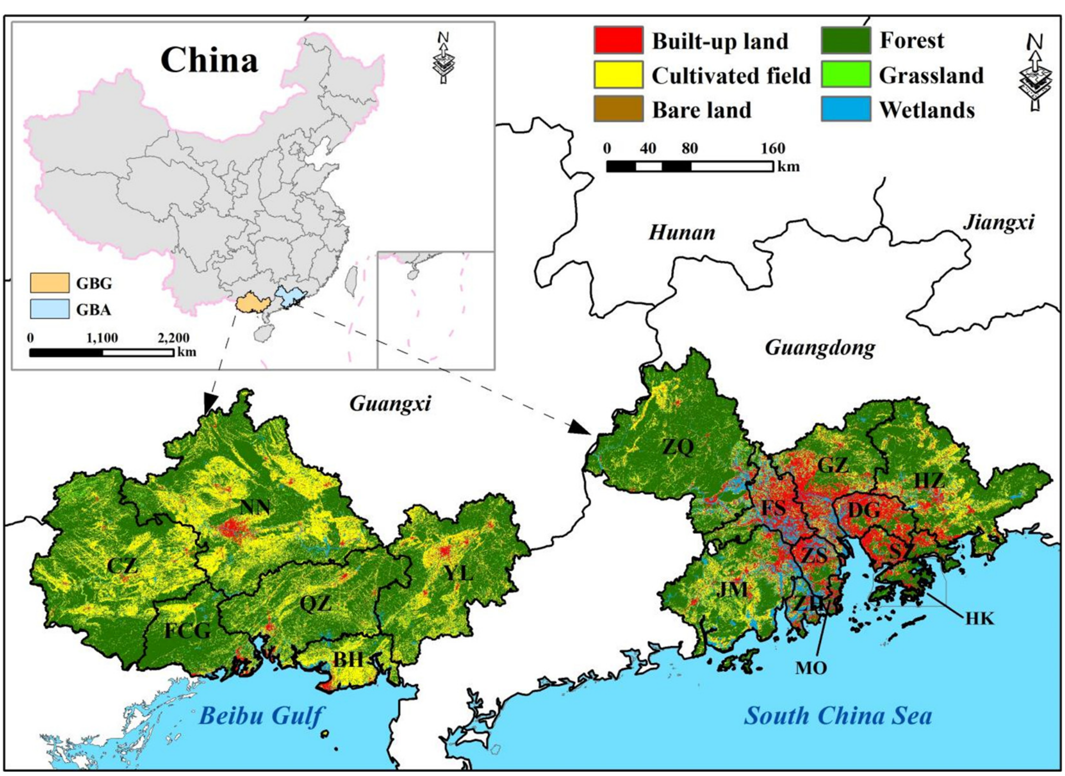

Fig. 1. Schematic diagram of the study area (GBG: Guangxi Beibu Gulf; GBA: Guangdong, Hong Kong, Macao and the Greater Bay Area; NN: Nanning; CZ: Chouzuo; YL: Yulin; QZ: Qinzhou; FCG: Fangchenggang; BH: Beihai; ZQ: Zhaoqing; FS: Foshan; GZ: Guangzhou; JM: Jiangmen; ZS: Zhongshan; DG: Dongguan; SZ: Shenzhen; HZ: Huizhou; ZH: Zhuhai; MO: Macao; HK: Hong Kong).

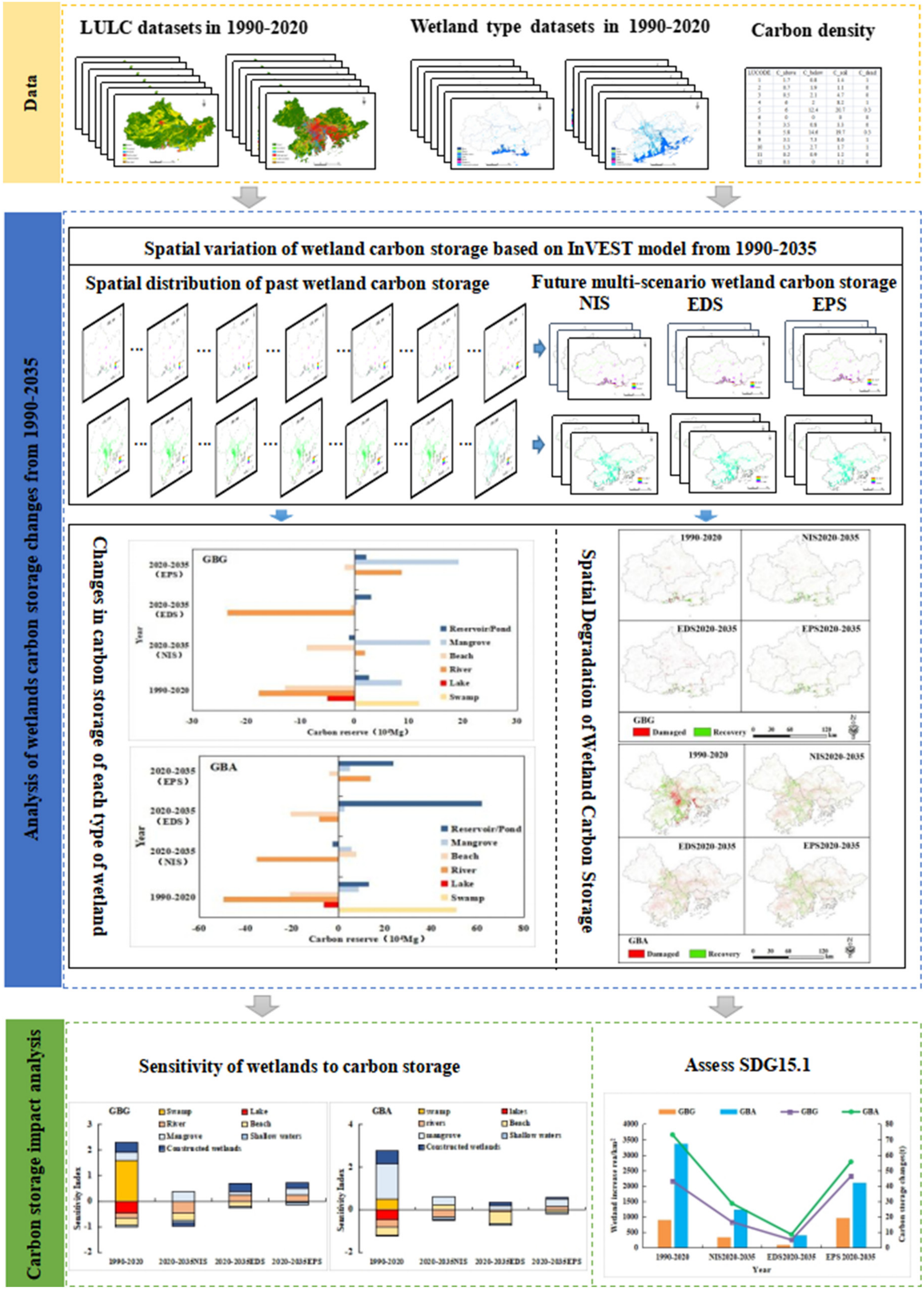

Fig. 2. Flow chart of the study.

2.3.1. Carbon storage estimation method based on InVEST model

The model divides carbon storage into four basic carbon pools for each wetland type: above-ground biomass (C_above), below-ground biomass (C_below), soil organic matter (C_soil), and dead organic matter (C_dead) (Sharp et al., 2015). Therefore, this study estimates the spatial distribution of carbon storage based on wetland type

Table 1
Carbon density of different wetland types (kg/m^2).

Wetland type	C_above		C_below		C_soil		C_dead	
	GBG	GBA	GBG	GBA	GBG	GBA	GBG	GBA
Swamp	1.9	1.7	1.9	1.8	18.3	14.0	1.0	1.0
Lake	0.5	0.7	2.0	1.9	1.2	1.1	0.0	0.0
River	0.7	0.5	4.3	2.1	9.6	4.7	0.0	0.0
Beach	1.8	6.0	1.9	2.0	4.2	8.2	1.0	1.0
Mangrove	4.3	5.4	12.8	8.4	23.5	17.7	0.3	0.3
Reservoir/pond	0.1	3.5	0.5	0.8	0.1	3.3	0.0	0.0

data and corresponding carbon pool data. The expression is as follows:

$$C_i = C_{i\_above} + C_{i\_below} + C_{i\_soil} + C_{i\_dead} \tag{1}$$

where C_i is the carbon density of the i-th wetland type, C_{i_above} is the above ground biomass carbon density of the i-th wetland type, C_{i_below} is the below ground biomass carbon density of the i-th wetland type, C_{i_soil} is the soil carbon density of the i-th wetland type, and C_{i_dead} is the dead organic carbon density of the i-th wetland type.

The carbon density data were obtained from the National Ecosystem Science Data Center (https://www.cern.ac.cn) carbon density dataset for terrestrial ecosystems in China. This dataset was created by combining carbon density in Chinese terrestrial ecosystems with relevant experimental data (Xu et al., 2018). The dataset covers forest, grassland, cropland, shrub and wetland ecosystems in China and contains carbon density data for the major components. Based on the above dataset and combining the results of previous studies in the same region (Ma et al., 2018; Deng et al., 2022; Li et al., 2022; Qiu, 2017; Lin, 2021; Huang, 2021; Jiang, 2021), we finally determined the carbon density dataset for different wetland types in this study area. The carbon density dataset in this study area is shown in Table 1.

2.3.2. Sensitivity index analysis method

In this study, the sensitivity index (SI) was used to determine the effect of wetlands on carbon storage. The index reflects the degree of response to the change in carbon storage when the wetland area changes by 1 % (Qiu et al., 2021; Peng et al., 2021). The higher the SI value was, the more sensitive the wetland change is to the carbon storage. When SI > 0, wetland change has a positive effect on carbon storage change; in contrast, wetland change has a negative effect on carbon storage. The expression is as follows:

$$SI = \frac{(C_{i\_end} - C_{i\_start})/C_{i\_start} \times 100\%}{D_h} \tag{2}$$

$$D_h = \frac{|V_h|}{U_{ha}} \times \frac{1}{T} \times 100\% \tag{3}$$

where SI is the sensitivity index and C_{i_start} and C_{i_end} are the carbon storage in the beginning and end years of the study period, respectively. D_h is the degree of wetland dynamics. Where h is the wetland type; D_h is the dynamic attitude of the h-th wetland type; V_h is the amount of change of the h-th wetland type during the study period; U_{ha} is the area of the i-th wetland type at the beginning of the study; and T is the length of the study period.

2.3.3. Evaluation of SDG15.1 methodology

SDG15.1 states "By 2020, protect, restore and sustainably use terrestrial and inland freshwater ecosystems and their services, especially forests, wetlands, foothills and dry lands, in accordance with obligations under international agreements." To refine the assessment to obtain more relevant findings for the study area, this study optimized the SDG15.1 indicator. As carbon is an important service function of wetland ecosystems, it is necessary to assess whether the conservation and restoration of wetlands has enhanced carbon storage. This indicator was calculated using a spatial overlay and raster calculator.

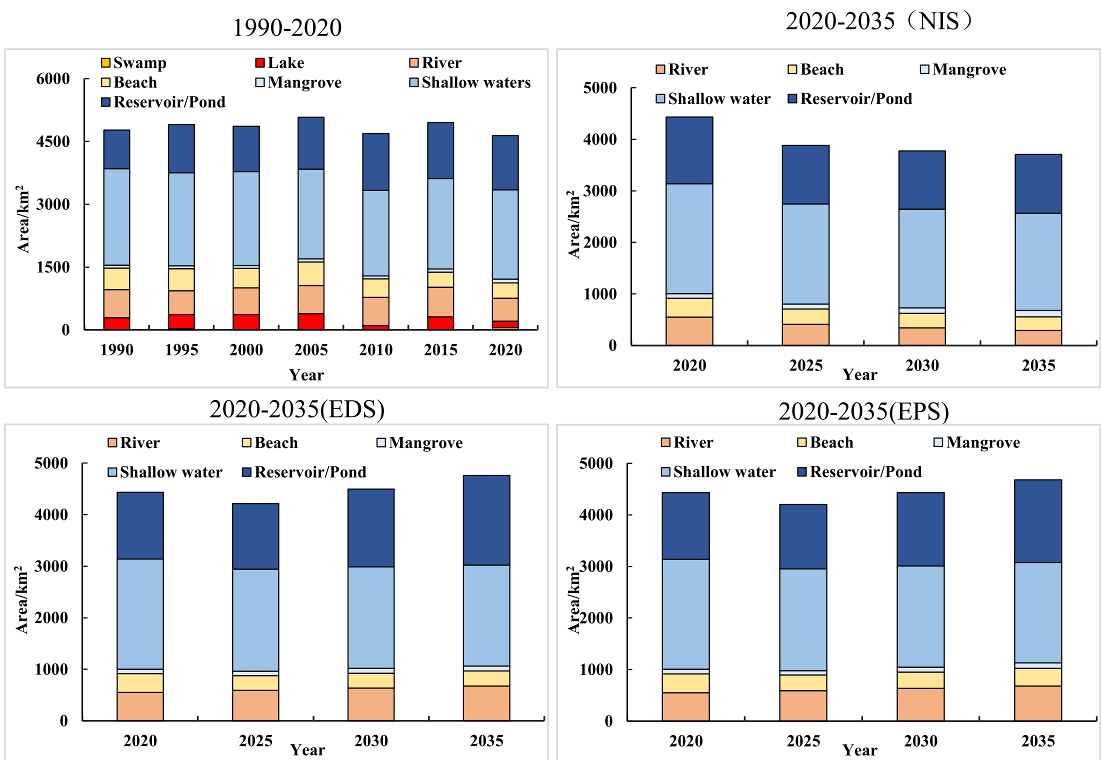

Fig. 3. Map of change in area of GBG wetland types 1990–2035.

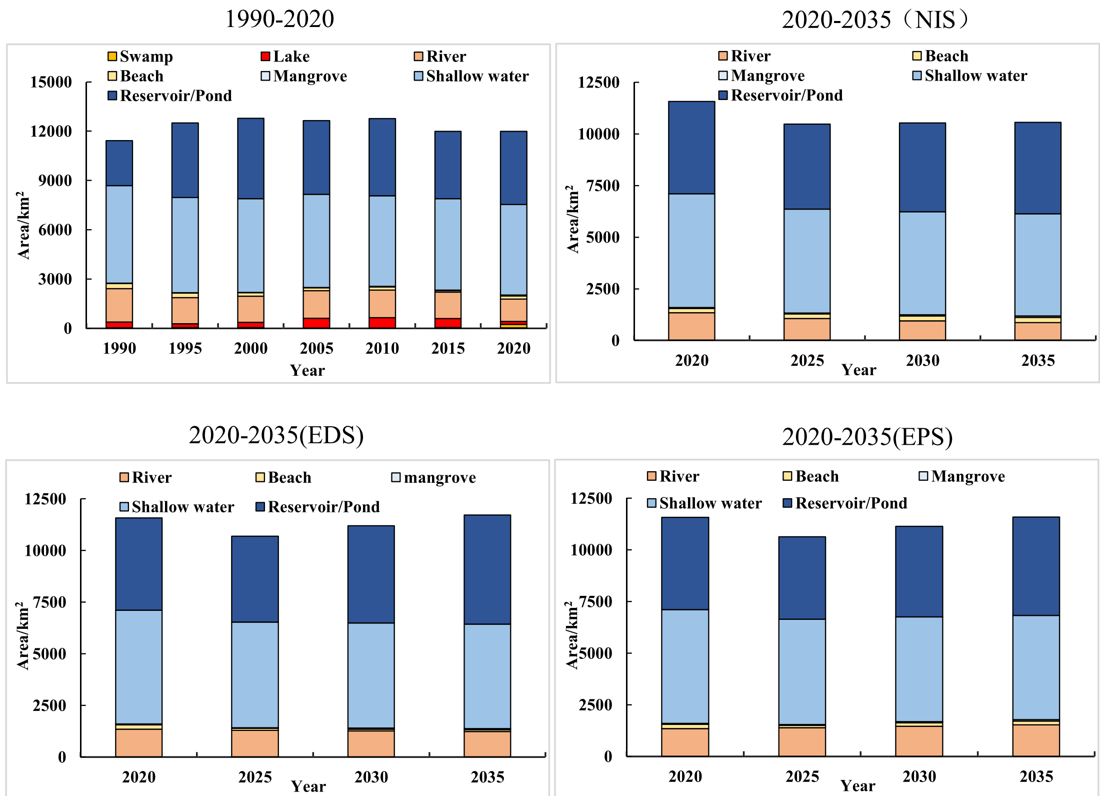

Fig. 4. Map of change in area of GBA wetland types 1990–2035.

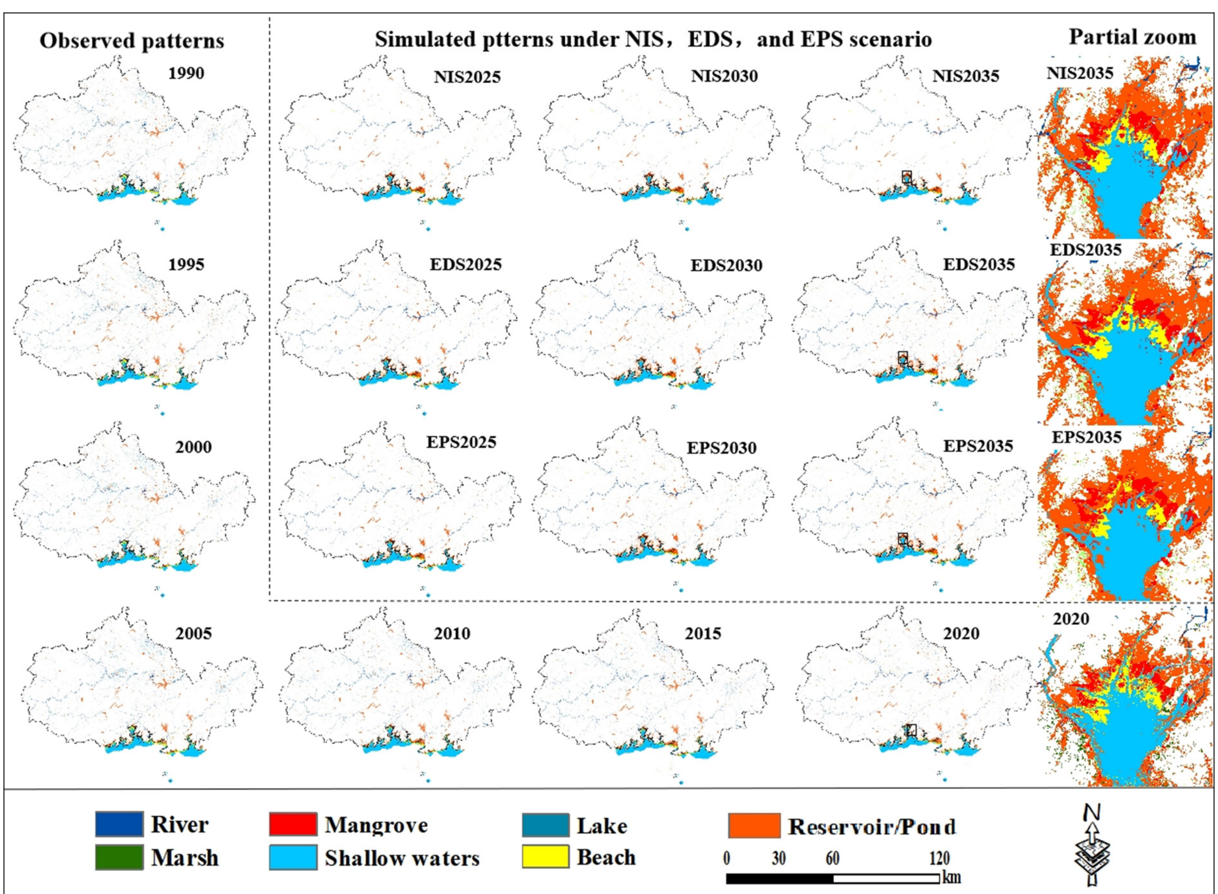

Fig. 5. Spatial distribution of wetland types in the GBG 1990–2035.

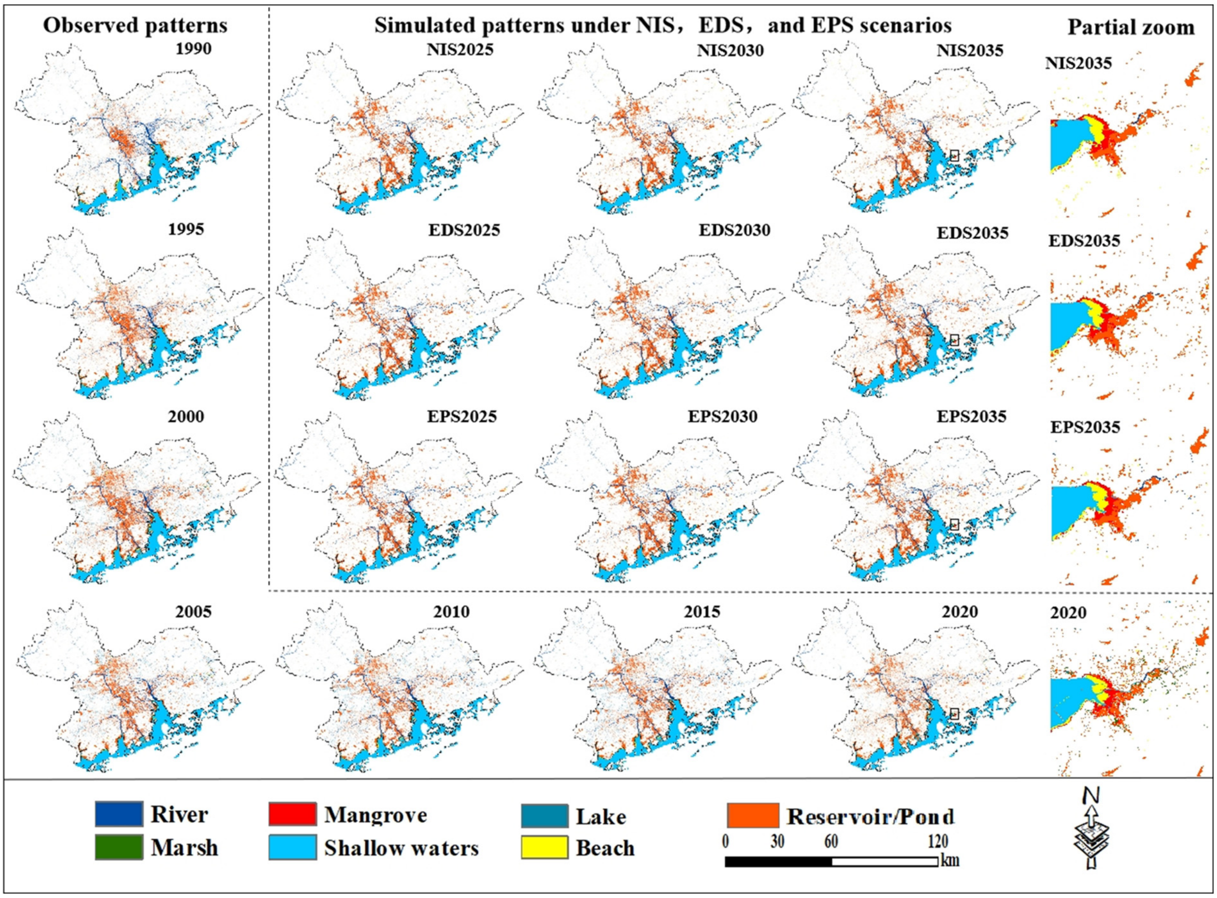

Fig. 6. Spatial distribution of wetland types in the GBA 1990–2035.

3. Result analysis

3.1. Analysis of spatial and temporal changes in wetlands from 1990 to 2035

3.1.1. Analysis of temporal changes in wetlands

Comparing the wetland areas in Figs. 3 and 4 reveals that both urban agglomerations show a fluctuating increasing trend, showing more reservoirs/farm ponds, larger river areas and fewer lakes. From 1990 to 2020, rivers, mudflats and shallow waters showed a decreasing trend, and mangroves showed an increasing trend. The trend in the NIS for 2020–2035 is essentially the same as in past periods, with an increasing trend in rivers, mangroves and reservoirs/farm ponds under EDS and EPS and a decrease in shallow marine waters. The mangrove area increased by 0.16 and 1.78 percentage points from 1990 to 2035, respectively, mainly due to the local government's increasing attention to mangroves and the introduction of a series of protection policies and restoration projects. By 2020, the total area of the GBG was 1.3 times larger than that of the GBA, but the area of wetlands in the latter was 2.6 times larger than that of the former, mainly because the main wetland types in both regions are rivers, shallow waters, and reservoirs/farm ponds, while the GBA has a larger share of these wetland types, which are 2–5 times larger than the corresponding types in the GBA.

3.1.2. Spatial change analysis of wetlands

Comparing the spatial distribution of wetlands in Figs. 5 and 6 reveals that the wetland types in the observed and simulated maps of the two urban clusters are spatially similar. The reduction of rivers, mudflats and shallow waters in the two urban clusters from 1990 to 2020 is mainly due

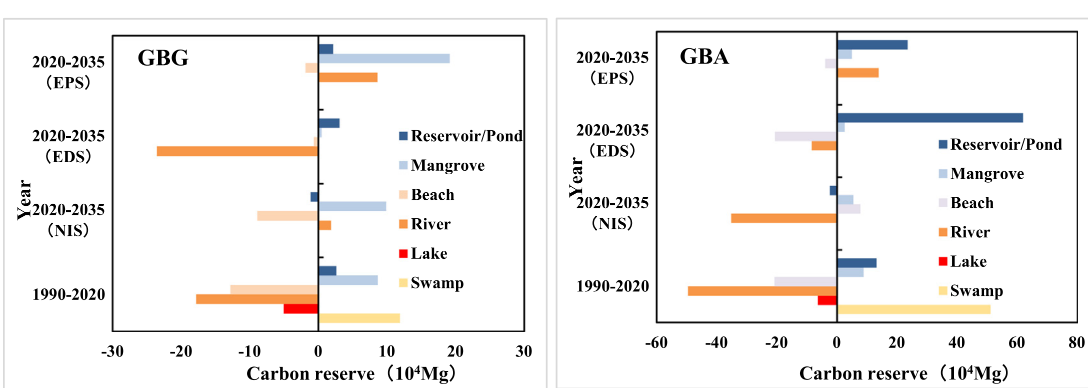

Fig. 7. Change in carbon stocks by wetland type 1990–2035.

to the encroachment of reservoirs/farming ponds and construction land; the reduction of mudflats is influenced by tides, and the conversion of reservoirs/farming ponds and mangroves on the other; the reduction of shallow waters is mainly distributed in the central part of the respective regions, and the reasons for the reduction are the same as those of rivers. The mangrove distribution of the GBA is not as widely distributed as that of the GBG, but the rate of increase is faster, mainly in reservoirs/farming ponds, shallow waters and mudflat conversions, with the GBG mainly in the Mao Wei Sea and the GBA mainly in Shenzhen Bay. The fragmentation of reservoirs/farming ponds is becoming increasingly serious. Other wetland types are basically unchanged in space. In 2020–2035, the overall trend of beach and shallow waters still shows different degrees of decline under different scenarios, with the same type of encroachment as in the history, but with a slower rate of decline; shallow waters show a significant decline under NIS and a slowdown under EPS. Rivers show an increase in EPS, mainly due to the containment of encroachment of construction land. Mangroves show the fastest increase in NIS, and it is obvious that a large number of mudflats have been converted, which shows that the relevant protection and restoration policies enacted in the past two years are more effective. Reservoirs/farm ponds are affected by economic policies, and the increase is more obvious, with some of them converted into cultivated land.

3.2. Analysis of spatial and temporal changes in carbon storage from 1990 to 2035

3.2.1. Analysis of temporal changes in wetland carbon storage

According to Fig. 7, comparing the two urban groups, we find that the overall trend of carbon storage in wetlands fluctuates and decreases, with rivers, lakes and mudflats all showing a decreasing trend, with rivers decreasing the most and marshes increasing the most, and the situation was not optimistic. From 1990 to 2020, the multiyear average carbon storage of the GBG was 3.2 times that of the GBA, and the carbon storage of the GBG wetlands fluctuated, with a maximum increase of 2.4×10^7 t; the carbon storage of the GBA wetlands showed an increase and then a decrease, with a maximum increase of 1.29×10^7 t. In the three scenarios from 2020 to 2035, NIS is basically the same as the past trend, EDS except for mangroves and reservoirs/farming ponds show a continuous decreasing trend, indicating that if the two urban clusters pay attention to economic construction and development in the future, the impact on wetland carbon storage will be greater and the damage will be serious and there is a high possibility that it will be difficult to repair the situation.

3.2.2. Spatial variation analysis of wetland carbon storage

Comparing the spatial distribution of wetland carbon storage in Figs. 8 and 9, it is found that the carbon storage of lakes, shallow marine waters and reservoirs/farming ponds in the two urban clusters from 1990 to 2020 were very low, especially the subsurface biomass. Mangroves, marshes and mudflats have high carbon storage, especially soil organic matter. Because of the small area of these three wetland types, they enhance the overall carbon storage less but perform ecological functions that cannot be ignored. The areas with low carbon storage in both urban clusters showed a significant expansion of construction land and a serious encroachment on wetlands. From 2020 to 2035, the distribution pattern of GBG under different scenarios is basically consistent with the historical period, and the mangrove carbon storage increases, mainly in the Maowei Sea and Dafengkou. The EDS carbon storage reduction area of the GBA expands significantly to the north, and the ecological protection policy of the EPS has some influence and constraints on coastal wetlands. The results show that in the EPS, reasonable policy planning helps wetland carbon sequestration in coastal urban clusters.

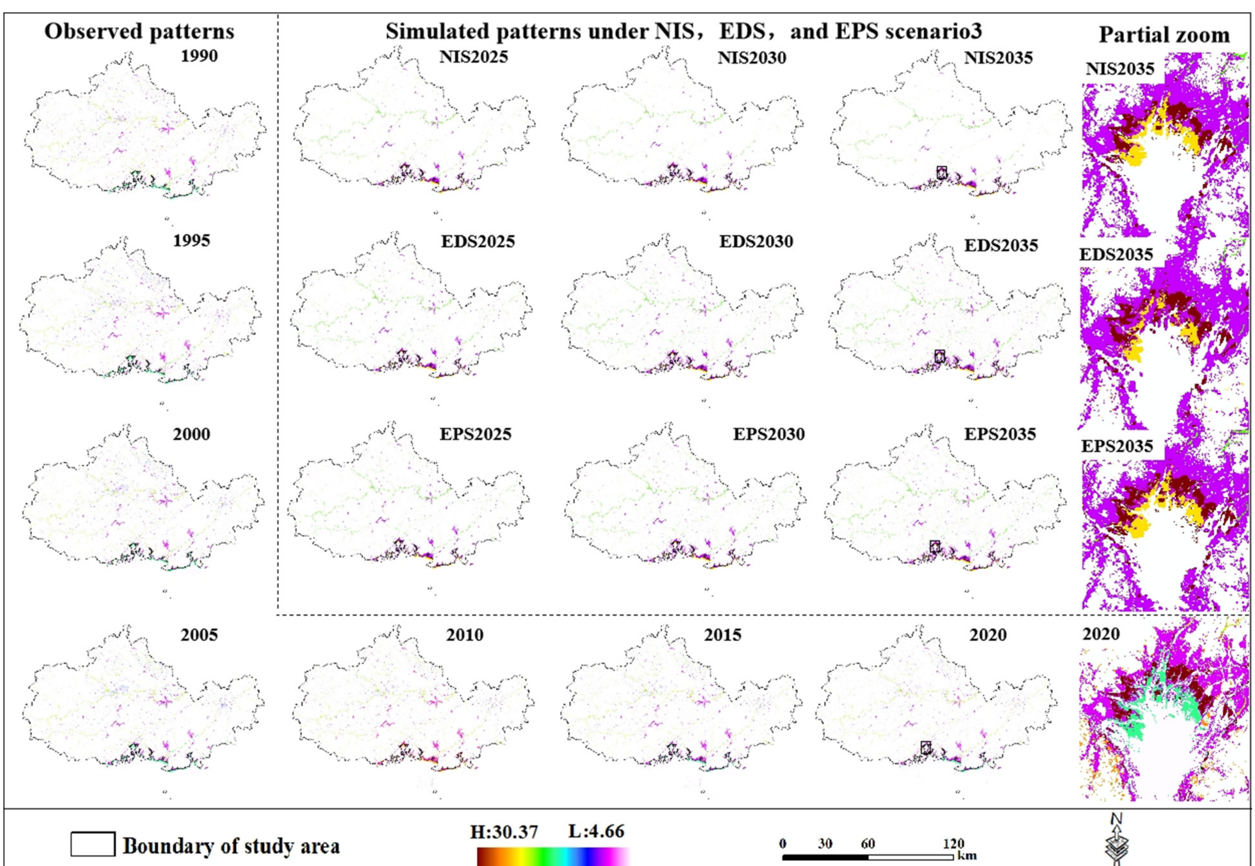

Fig. 8. Spatial distribution of wetland carbon storage in the GBG 1990–2035.

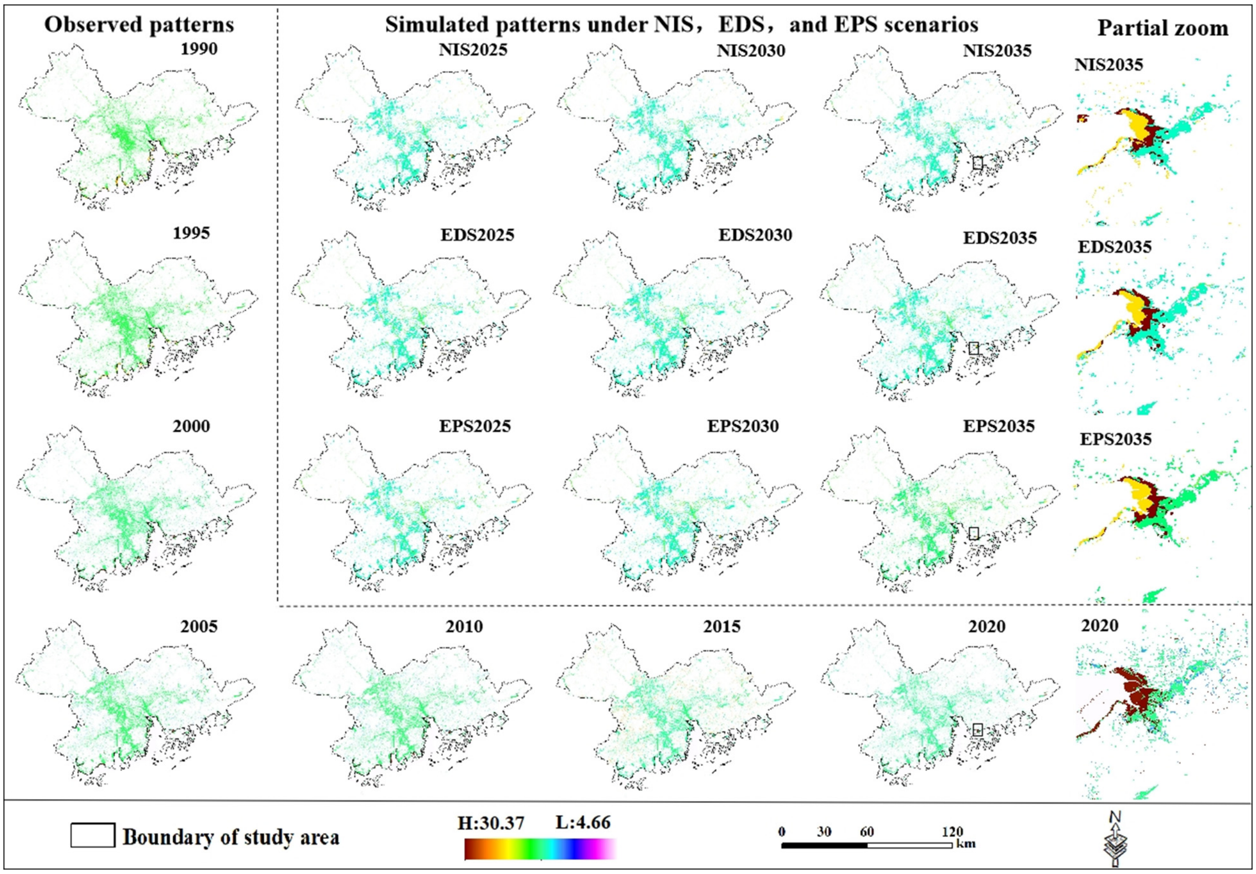

Fig. 9. Spatial distribution of wetland carbon storage in the GBA 1990–2035.

3.2.3. Spatial analysis of impaired wetland carbon storage

Comparing the spatial distribution of damaged wetland carbon storage in Figs. 10 and 11, it was found that the more seriously damaged areas are concentrated in the expansion area of construction land, which has encroached on all wetland types to different degrees. This results in a large amount of damaged wetland carbon storage. The damaged area of the GBA from 1990 to 2020 was three times larger than that of the GBG, which was directly related to the rapid development of the GBA relative to the economic development of the GBG as long as 10 years earlier. The GBG wetland carbon storage damage is mainly concentrated in the urban area of Nanning and the built-up areas of the three coastal cities; the GBA was mainly concentrated in Shenzhen, Zhongshan and Foshan. Compared to the damage, the recovery area was not very good, and GBG was mainly distributed in coastal areas, such as mangroves and mudflats. The GBA was mainly distributed in Zhaoqing, Jiangmen and a small part of coastal areas. 2020–2035, there were some differences in the damage of the three scenarios. The GBG damage under NIS had improved, and EPS has shown a recovery higher than the damage, again showing that EPS helps wetlands sequester carbon and EDS damaged areas are distributed near rivers. The GBA damage under NIS has not improved significantly, the damaged areas were scattered and the recovery area is decreasing, EPS had improved compared to the historical and NIS damage, the recovery area was elevated, but it does not reach the recovery effect of GBG.

3.3. Impact of wetland change on carbon storage

3.3.1. Sensitivity of wetlands to changes in carbon storage

To further explore the sensitivity of wetland changes to carbon storage, the sensitivity of wetland changes to carbon storage was calculated for three scenarios from 1990 to 2020 and 2020–2035, as shown in Fig. 12. The results showed that the SI of 1.296 and 1.521 for the GBG and GBA from 1990 to 2020, respectively, indicate that the trend of wetland change has a positive influence on the carbon storage, the GBG marsh has a value of 1.5 and the GBA mangrove has a slight increase with a value of 1.6, and the change in rivers, lakes, mudflats and shallow waters of the two urban groups have a negative influence on the carbon storage. From 2020 to 2035, wetlands have different impacts on carbon storage under different scenarios. The two urban agglomerations have a positive impact of wetland changes on carbon storage under EPS, and only rivers and shallow waters have a slight negative impact; the NIS of GBG shows a negative impact, and only mangroves have a positive impact, which can be the current development situation is an unreasonable situation and does not fully apply to the development of local wetland carbon storage. EDS shows a positive impact because of the impact of coastal development on mudflats, which has a slightly less positive effect compared to EPS. The trend of the impact of GBA wetlands on carbon storage was opposite to that of GBG, which shows that the current comprehensive development of GBA is relatively good, especially for mudflats and mangroves; DES is not applicable to local wetland carbon storage.

3.3.2. SDG15.1 quantitative assessment

We quantitatively assessed SDG15.1 based on the results of the wetland carbon storage assessment from 1990 to 2035, which we refined and mined according to the definition of SDGs (Fig. 13). The results show that the restoration of wetland areas in both urban agglomerations showed different degrees of carbon storage enhancement, which shows that the restoration and conservation policies and urban development in both urban agglomerations positively promote carbon storage. 2–3 times the restored wetland area GBG in GBA, with essentially the same rate of increase. From 1990 to 2035, GBA carbon storage were 0.5 times, 1.5 times, and 2 times 0.4 times that of GBG, respectively, none of which reached the wetland area restoration ratio, and the rate of increase of GBA under NIS and EPS was lower than that of GBG. The GBA should not pursue only area

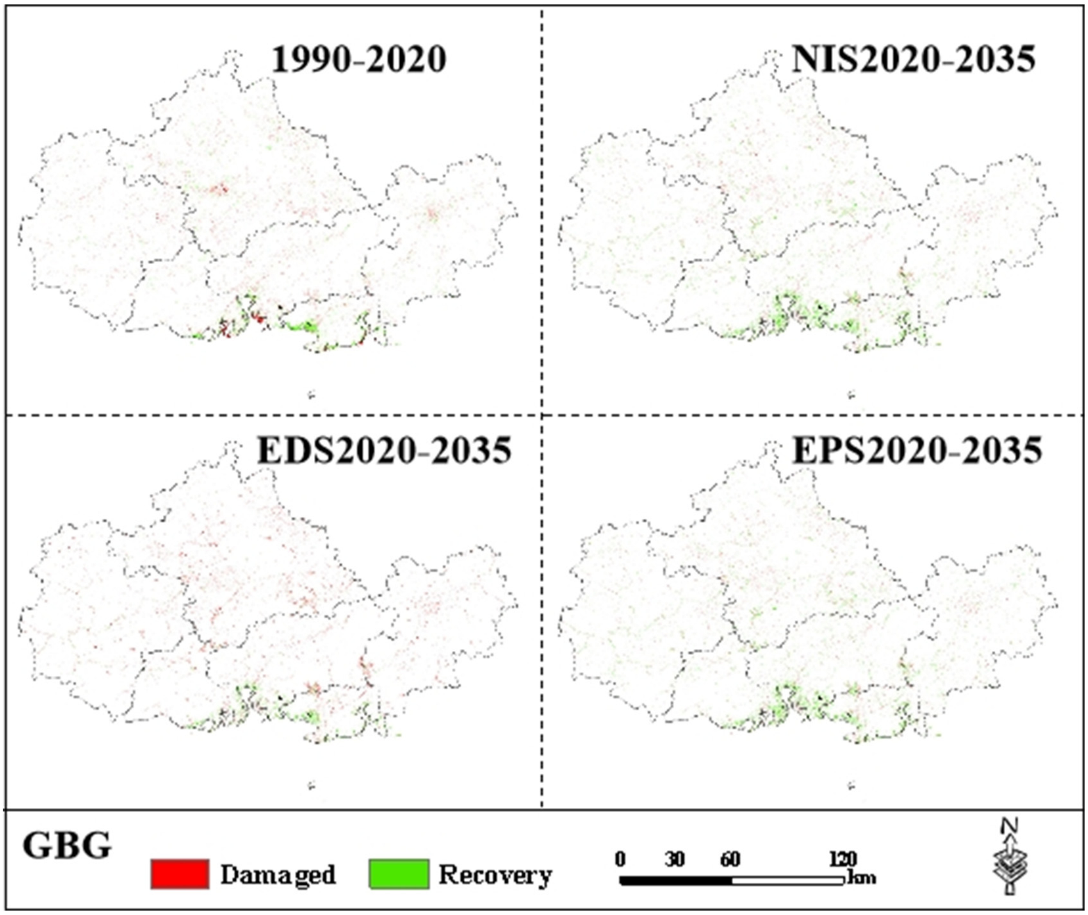

Fig. 10. Spatial distribution of impaired carbon stocks in GBG wetlands 1990–2035.

enhancement, especially for aquaculture ponds/ponds, ignoring other ponds with higher ecological function restoration efficiency, which needs to be considered. The two urban clusters have the largest contribution to SDG15.1 under the EPS, which indicates that the wetland restoration and protection policies in China and the region have a certain amount of feasibility and provides data support and a reference basis for the quantitative assessment of SDGs.

4. Discussions

4.1. Comparison of research content and methods with existing studies

We proposed a new wetland carbon storage assessment model using two coastal city clusters in southern China as the study area. It realizes dynamic remote sensing monitoring of wetlands and fine assessment of carbon storage, which is important for wetland resource conservation and restoration and sustainable development. Comparing the existing studies, we found that the classification algorithm of our wetland type data is more universal in terms of wetland type data, and the prediction model solves the problem of unmet area demand and unreasonable spatial allocation, which is a great advantage over the existing dataset. (Tiné et al., 2019; Mozumder and Tripathi, 2014), providing a detailed database for our carbon storage. Our results exhibit large differences in wetland carbon storage between scenarios, and this uncertainty is consistent with the extensive literature on predictive simulations (Liu et al., 2019), but the limitation of this scenario is that it ignores the uncertainty in possible changes in key input parameters that were propagated through the CA modelling process and requires more intensive computer simulations to resolve, which currently is unattainable and a challenge for future accurate simulation prediction model construction. In terms of wetland carbon storage assessment, our wetland carbon storage estimates have longer time series, more refined wetland types, and more targeted assessment results (Liang et al., 2017), therefore more comprehensively reflecting the spatial and temporal changes in wetland carbon storage in the two coastal urban clusters. In addition, our proposed wetland carbon storage model is innovative and easily applicable to other ecosystem areas, which is lacking in previous studies (Deng et al., 2022). Even though there is still some uncertainty in such estimation results, the model and mechanism behind them are still reasonable and can provide a convenient and efficient means and technical reference for obtaining long time series carbon storage in wetlands. In addition, our proposed methodological framework and model for wetland carbon storage assessment can be applied to the monitoring and conservation of ecological functions of wetlands in other parts of the world.

4.2. More contributions of this study to the SDG assessment

Now that global ecological problems and climate change are intensifying, it is necessary for the local ecological situation to refer to the international situation, and there is an urgent need to assess and analyze local ecosystems in conjunction with SDGs. Based on the findings of this study, it is good news that carbon storage increases with the increase in wetlands in the two urban clusters, and we must continue to evaluate whether the increase in wetland area and other ecosystem service functions increases to prevent the appearance that some areas pursue quantitative indicators without considering functional restoration. Of course, we can also discuss more perspectives, such as the effectiveness of restoration of each ecosystem, supply and demand of ecosystem services, and ecosystem service flows, to enrich the assessment of the functional aspects of SDG15.1 ecosystem services. Based on the research data and results of this study, it can also support the assessment of other objectives of SDG, and this section takes

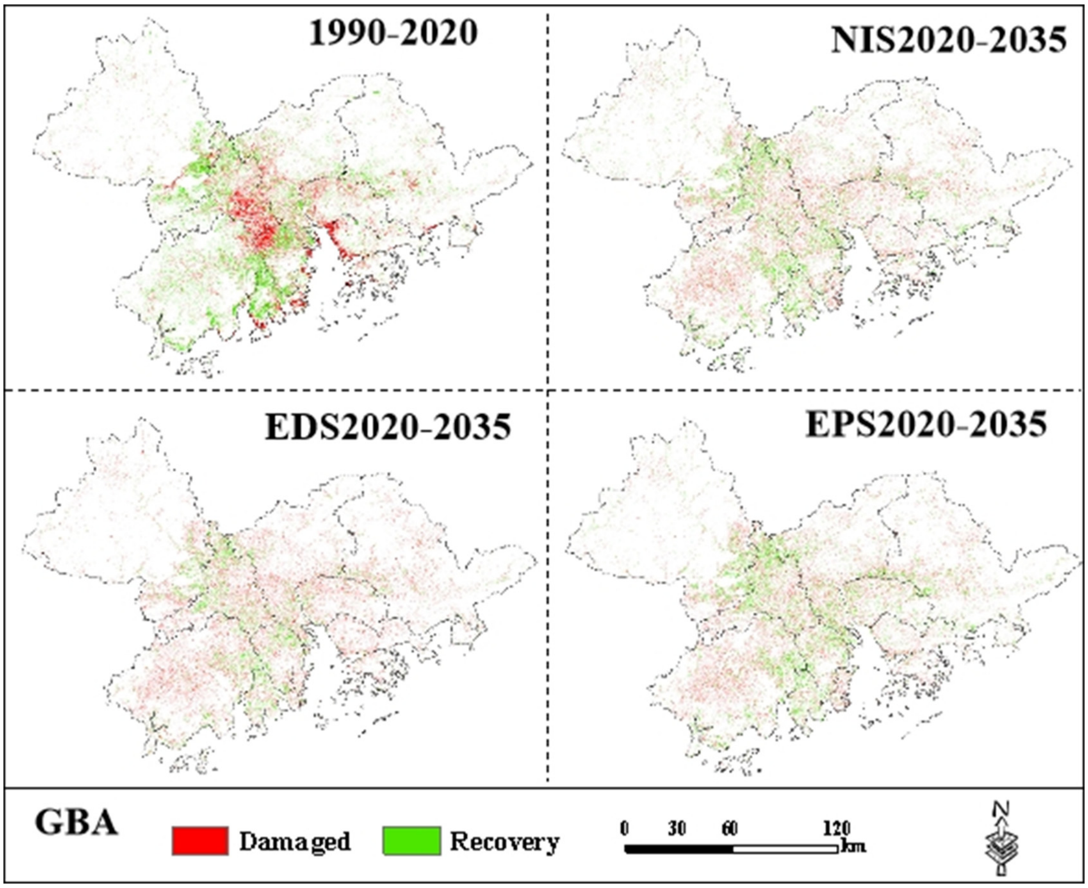

Fig. 11. Spatial distribution of impaired carbon stocks in GBA wetlands 1990–2035.

SDG14.2 and SDG14.5 as examples, and we hope our research can enrich this area.

In accordance with UN Sustainable Development Goal 14.2, "By 2020, sustainably manage and protect marine and coastal ecosystems from significant adverse impacts, including by strengthening resilience to hazards, and take action to help restore them to their original state so that the oceans remain healthy and productive", due to the lack of data on our oceans, we assessed whether coastal wetland ecosystems have declined in size in the past and in the future and whether they are helping to return to their original state in terms of conservation programs and action plans at multiple national, provincial, and municipal levels. China has introduced a series of policies, such as the Special Action Plan for Mangrove Protection and Restoration (2020–2025) issued in 2019 and the National Major Project Construction Plan for Important Ecological Protection and Restoration (2021–2035) issued in 2020, and both urban clusters in this study are key areas for protection and restoration. Based on this, we analysed the changes in wetland area in coastal counties of the two urban clusters according to the definition of coastal ecosystems in the China Marine Statistical Yearbook (Fig. 14). The results showed that the change in wetland area in the two regions from 1990 to 2020 is smooth, and there is no serious decline under the NIS from 1990 to 2035. The wetland ecosystem in the two regions basically achieves no negative impact and some recovery, and if the two urban agglomerations focus on economic construction in the future, the wetland ecosystem will be seriously affected by necessity.

For SDG 14.5, "By 2020, protect at least 10% of coastal and marine areas in accordance with national and international law and based on the best available scientific information". China's national plan recommends a significant expansion of coastal protected areas. The Chinese government

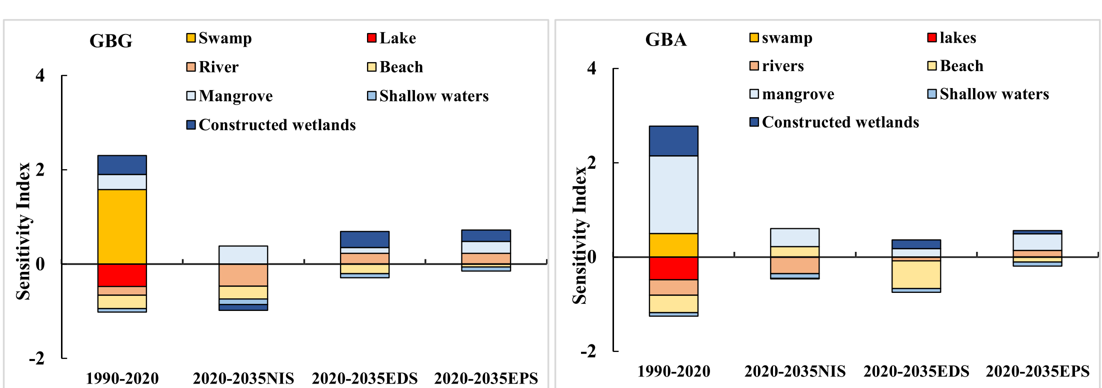

Fig. 12. Sensitivity analysis of wetland changes to carbon stocks in the study area 1990–2035.

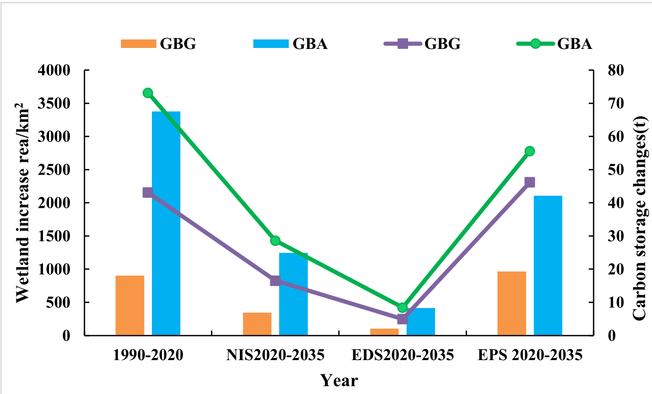

Fig. 13. Comparison of wetland and carbon stock area changes in the study area 1990–2035.

has strengthened the protection of coastal wetlands through the establishment of nature reserves, selected at the national and provincial levels based on the National Nature Reserve List published in 2015, and we use the “ratio of the area of coastal protected areas to the area of coastal areas and the area of wetland protected areas in coastal areas to the area of coastal protected areas” to quantitatively assess the progress toward target 14.5 (Fig. 15). The results show that the ratio of the area of coastal protected areas to the area of coastal areas in both regions did not meet the target requirements. In the establishment of protected areas, the identification of nature reserves is still the next step, and the area of wetland reserves in both urban clusters exceeded 10 %, indicating that the management of this area has reached the target requirements.

4.3. The role of past and future policies in the conservation of wetland carbon storage

We shed light on the management of wetland carbon storage in two urban agglomerations, with the hope that it can inform the management of wetland carbon sequestration benefits. In addition to human activities and climate change, wetland changes in China cannot be ignored in relation to conservation policies and economic plans. China's accession to the Convention on Wetlands in 1992 and the “China Wetlands Conservation Action Plan” in 2000 have led to a slow increase in carbon storage in two urban clusters. We combed GBG and found that in 2003, China proposed the strategy of western development, GBG socioeconomic development was slow, despite the few wetland protection policies, and by virtue of superior natural climatic conditions and less human interference, wetland carbon storage were not affected. In 2008, the State Council approved the Outline of the Development Plan of Guangxi Beibu Gulf Economic Zone, and wetland carbon storage showed a decreasing trend from 2008 to 2010. In 2014, the Guangxi Wetland Protection Regulations were promulgated, and wetland carbon storage showed an increasing trend from 2014 to 2015. We combed through the GBA and found that the “Guangdong Wetland Protection Regulations” were promulgated in 2006, but only the rivers had a certain effect. With the introduction of the Guangdong Marine Economic Development Plan in 2007 and the issuance of the Quality Discovery Program in 2012, wetland carbon storage were on a decreasing trend. China proposed an action plan for mangrove protection and restoration, and this policy has caused a good response, and mangrove wetland carbon storage are on an increasing trend in the next three scenarios. Outline of the 14th Five-Year Plan (2021–2025) for National Economy, all three scenarios have different degrees of decline in the next 5 years. The year 2030 is the SDG assessment year and an important nodal year for China's proposed dual carbon strategy, with increasing trends in wetland carbon storage under NIS and EPS for GBG and increasing trends in wetland carbon storage under EPS for GBA.

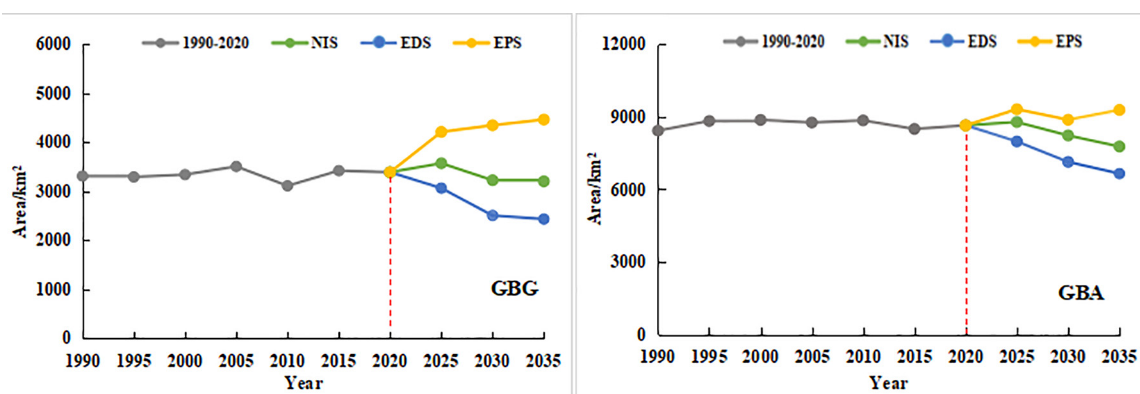

Fig. 14. Map of wetland area changes in the coastal zone of the study area, 1990–2035.

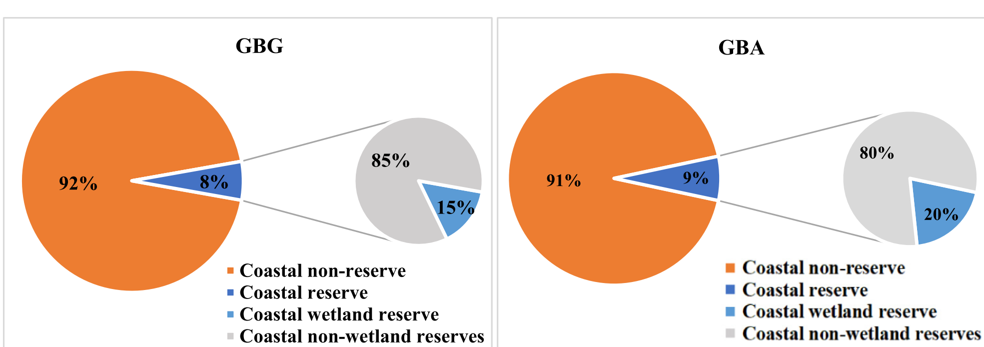

Fig. 15. Map showing the proportion of protected area in the study area 1990–2035.

China proposed the Outline of Vision 2035, and both urban clusters show a decreasing trend of wetland carbon storage under NIS and EDS. As the National Major Project Construction Plan for Ecological Protection and Restoration (2020–2035) is also to be realized in the same year, wetland carbon storage under the EPS show an increasing trend.

We found that both city groups have implemented various socioeconomic policies and wetland conservation policies. The "New Western Land and Sea Corridor", the "New Jin Free Trade Zone", and the "Outline for the Development of the Guangdong-Hong Kong-Macao Greater Bay Area" have been developed to promote economic and social development. These built-up land policies have expanded significantly, causing significant encroachment on wetlands (Fig. 11), and policy-driven wetland changes have further led to significant carbon storage degradation (Fig. 16). However, many policies have been developed to protect and restore wetland ecosystems. These policy-supported ecological projects have largely contributed to the increase in wetlands, and many nature reserves have been established in China to protect wetland ecosystems in two urban agglomerations. Therefore, it is worthwhile for us to think about how to achieve a policy balance to promote the enhancement of wetland carbon storage in the two urban agglomerations and promote their sustainable development. We need to thoroughly implement the new urbanization strategy, and we should not only focus on the expansion of large urban areas but also on the improvement of the ecological quality of urbanization. In the process of urbanization, large areas of ecological and production space are destroyed, bringing great pressure on water resources, carbon sequestration and the idea that "green mountains and clear water are golden mountains", as President Xi Jinping said, should be put into practice. We need to improve the effectiveness of the implementation of ecological engineering and protected areas. Although policies of returning ponds to wetlands and strictly prohibiting reclamation are underway, the declining trend of wetland carbon storage has not been significantly reversed, so improving the effectiveness of ecological engineering and protected area implementation is a matter of urgent need. These were the focus of our subsequent research.

4.4. Contributions and limitations

This study compared two coastal urban clusters, couples the RF-CLUE-S-InVEST model, and proposes a "past-present-future" long time series refined wetland carbon storage assessment model, which is good for assessing wetland carbon storage and SDG15.1 of multiple scenarios, and such a method and model are feasible for wetland carbon storage assessment. is feasible. Our wetland carbon storage estimation has the advantage of long time series refinement, which can provide theoretical contributions and technical support for other coastal wetland ecosystems and enrich the data and content in this field. There are still some limitations and uncertainties in this study. The calculation of wetland carbon storage using the InVEST model was based on the spatial and temporal assessment of carbon storage based on the type of wetland change and did not consider other factors, such as photosynthetic rate and soil microbial activity, which have important effects on carbon sinks. The absence of interannual variation in carbon density in this study also suggests that changes in carbon stocks are caused by changes in wetland type, but this does not affect the final assessment, and some results suggest that the effect of wetland change on carbon stock change can be well assessed even if changes in carbon density are ignored (Li et al., 2022). Although our wetland type classification is based on remote sensing technology, which cannot avoid the influence of cloud shadows and subjective errors caused by processes such as visual interpretation, there are still some systematic or random errors in wetland classification accuracy. In future research, we will continue to strengthen the continuous monitoring of carbon density in situ for different wetland types and seek more efficient and accurate methods to improve the accuracy and spatial resolution of wetlands.

5. Conclusions

We demonstrated the dynamic monitoring and refined carbon storage assessment of wetlands in coastal city clusters and uncover the impact of wetland changes on carbon storage and SDG15.1 assessments under multiple scenarios. The following conclusions were obtained.

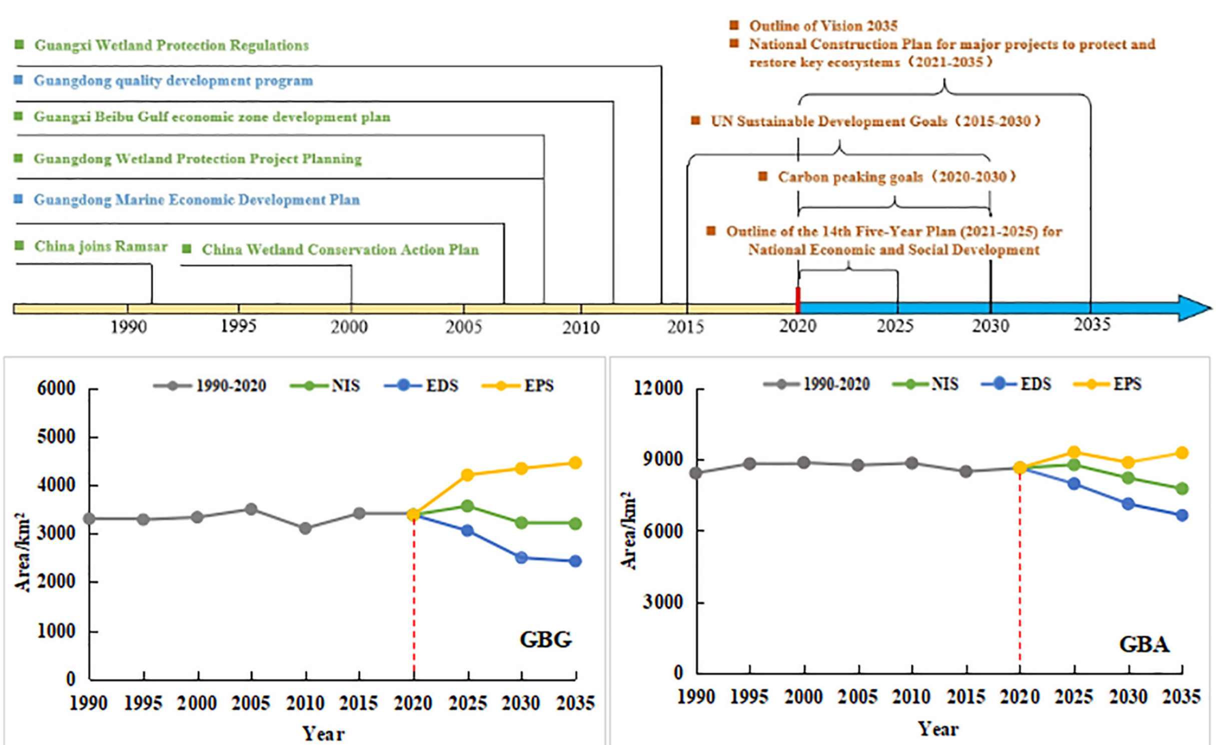

Fig. 16. Relationship between the development history of urban agglomerations and wetland conservation policies and carbon storage.

(1) The two urban clusters in this study are characterized by many outflow reservoirs/farming ponds, large river areas and few lakes. The total area of the GBG was 1.3 times larger than that of the GBA, yet the wetland area of the latter is 2.6 times larger than that of the former, and the annual rivers, shallow waters and mudflats have a decreasing trend from 1990 to 2035 to be distributed in the middle of their respective regions, and mangroves are on the rise. GBG is mainly distributed in the Mao Wei Sea, and GBA is mainly distributed in Shenzhen Bay. The GBA is mainly distributed in Shenzhen Bay.
(2) The carbon storage of wetlands in the two urban clusters show an overall fluctuating downward trend, with rivers, lakes and mudflats all showing a downward trend. The areas with lower carbon storage all show obvious expansion of construction land and serious encroachment on wetlands, and the multiyear average carbon storage of the GBG was 3.2 times that of the GBA. EPS, as long as policy planning is reasonable, helps wetland carbon sequestration in coastal urban clusters.
(3) The trend of wetland change from 1990 to 2020 was positive for the carbon storage, and from 2020 to 2035, under the EPS, wetland change has a positive effect on the carbon storage. The NIS of GBG showed a negative effect, the EDS shows a positive effect, and the change in GBA was opposite to that of GBG. The area of wetland restoration of the GBA is 2–3 times that of the GBG, but the carbon storage of the GBA was only 0.5–2 times that of the GBG. The increase rate of GBA under NIS and EPS was lower than that of GBG. The largest push for SDG15.1 under EPS.

CRediT authorship contribution statement

Ze Zhang: Methodology, Software, Data curation, Writing-original draft. **Weiguo Jiang:** Conceptualization, Writing-review & editing. Project administration. **Kaifeng Peng:** Methodology, Data curation. **Zhifeng Wu:** Writing-review, Project administration. **Ziyan Ling:** Writing-review, Project administration. **Zhuo Li:** Resources.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Declaration of competing interest

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

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References

Aburas, M.M., Ahamad, M.S.S., Omar, N.Q., 2019. Spatio-temporal simulation and prediction of land-use change using conventional and machine learning models: a review. Environ. Monit. Assess. 191 (4), 1–28. https://doi.org/10.1007/s10661-019-7330-6.

Babbar, D., Areendran, G., Sahana, M., Sarma, K., Raj, K., Sivadas, A., 2021. Assessment and prediction of carbon sequestration using markov chain and InVEST model in sariska Tiger Reserve India. J. Clean. Prod., 278 https://doi.org/10.1016/j.jclepro.2020.123333.

Chen, J., Ban, Y., Li, S., 2014. Open access to earth land-cover map. Nature 514 (7523), 434. https://doi.org/10.1038/514434c.

Deng, Y.W., Jiang, W.G., Wu, Z.F., Peng, K.F., Ling, Z.Y., Wang, X.Y., 2022. Assessing and characterizing carbon storage in wetlands of the Guangdong-Hong Kong–Macau Greater Bay Area, China, During 1995–2020. IEEE J Sel. Top. Appl. Earth Observ. Remote Sens. 15, 6110–6120. https://doi.org/10.1109/JSTARS.2022.3192267.

Fitoka, E., Tompoulidou, M., Hatziiordanou, L., et al., 2020. Water-related ecosystems' mapping and assessment based on remote sensing techniques and geospatial analysis: the SWOS national service case of the greek Ramsar sites and their catchments. Remote Sens. Environ. 245, 111795. https://doi.org/10.1016/j.rse.2020.111795.

He, C.Y., Zhang, D., Huang, Q.X., Zhao, Y.Y., 2016. Assessing the potential impacts of urban expansion on regional carbon storage by linking the LUSD-urban and InVEST models. Environ. Model. Softw. 75, 44–58. https://doi.org/10.1016/j.envsoft.2015.09.015.

Huang, X.Y., 2021. A Study on Land Use Change and Its Ecosystem Service Trade-offs in the Karst-coastal Zone of Southwest Guizhou. Nanning Normal University, Nanning.

Jiang, W.G., Deng, Y., Tang, Z.H., Lei, X., Chen, Z., 2017a. Modelling the potential impacts of urban ecosystem changes on carbon storage under different scenarios by linking the CLUE-S and the InVEST models. Ecol. Model. 345, 30–40. https://doi.org/10.1016/j.ecolmodel.2016.12.002.

Jiang, W.G., Deng, Y., Tang, Z.H., Lei, X., Chen, Z., 2017b. Modelling the potential impacts of urban ecosystem changes on carbon storage under different scenarios by linking the CLUE-S and the InVEST models. Ecological Modelling 345, 30–40. https://doi.org/10.1016/j.ecolmodel.2016.12.002.

Jiang, W.K., 2021. Study on Ecosystem Service Assessment in Guangdong-Hong Kong-Macao Greater Bay Area Based on CA-Markov and InVEST Models. South China University of Technology, Guangzhou.

Li, J.T., Yan, D.D., Yao, X.Y., Xie, S.Y., Liu, Y., Shang, Y.F., Luan, Z.Q., 2022. Carbon Storage Estimation of Coastal Wetlands in China. Acta Pedol. Sin., 1–18 https://doi.org/10.11766/trxb202106290335.

Liang, X., Guan, Q.F., Clarke, K.C., Liu, S.S., 2021. Understanding the drivers of sustainable land expansion using a patch-generating land use simulation (PLUS) model: a case study in Wuhan, China. Comput. Environ. Urban. Syst. 85, 101569. https://doi.org/10.1016/j.compenvurbsys.2020.101569.

Liang, Y.J., Liu, L.J., Huang, J.J., 2017. Integrating the SD-CLUE-S and InVEST models into assessment of oasis carbon storage in Northwestern China. PLoS One 12 (2), e0172494. https://doi.org/10.1371/journal.pone.0172494.

Lin, X., 2021. Research on the Trade-offs and Synergistic Relationships of Ecosystem Services in the Nanliu River Basin Based on the InVEST Model. Nanning Normal University, Nanning.

Liu, M.Y., Dehua Mao, D.H., Wang, Z.M., Li, L., Man, W.D., Jia, M.M., Ren, C.Y., Zhang, Y.Z., 2018. Rapid invasion of Spartina alterniflora in the coastal zone of mainland China: new observations from Landsat OLI images. Remote Sens. 10 (12), 1933. https://doi.org/10.3390/rs10121933.

Liu, X.P., Wang, S.J., Wu, P.J., Feng, K.S., Hubacek, Klaus, Li, X., Sun, L.X., 2019. Impacts of urban expansion on terrestrial carbon storage in China. Environ. Sci. Technol. 53 (12), 6834–6844. https://doi.org/10.1021/acs.est.9b00103.

Ma, T.T., Li, X.W., Bai, J.H., Jing, S.Y., 2018. Four Decades' Dynamics of Coastal Blue Carbon Storage Driven by Land Use/Land Cover Transformation Under Natural and Anthropogenic Processes in the Yellow River Delta, China. 655, p. 4. https://doi.org/10.1016/j.scitotenv.2018.11.287.

Mozumder, C., Tripathi, N.K., 2014. Geospatial scenario based modelling of urban and agricultural intrusions in Ramsar wetland deepor beel in Northeast India using a multi-layer perceptron neural network. Int. J. Appl. Earth Obs. Geoinf. 32, 92–104. https://doi.org/10.1016/j.jag.2014.03.002.

Niu, Z.G., Zhang, H.Y., Wang, X.W., et al., 2012. Mapping wetland changes in China between 1978 and 2008. Chin. Sci. Bull. 57 (22), 2813–2823. https://doi.org/10.1007/s11434-012-5093-3.

Peng, K.F., 2022. Remote Sensing Classification of Wetlands in Coastal Urban Agglomerations and Simulation of Future Spatial Changes: A Case Study of Guangdong-Hong Kong-Macao Greater Bay Area and Guangxi Beibu Gulf. Beijing Normal University, Beijing.

Peng, K.F., Jiang, W.G., Ling, Z.Y., et al., 2021. Evaluating the Potential Impacts of Land Use Changes on Ecosystem Service Value Under Multiple Scenarios in Support of SDG Reporting: A Case Study of the Wuhan Urban Agglomeration. 307, p. 127321. https://doi.org/10.1016/j.jclepro.2021.127321.

Qiu, J.H., 2017. Study on the Impact of Reclamation Activities on the Carbon Storage of Coastal Wetlands in China. Xiamen University, Xiamen.

Qiu, H.H., Hu, B.Q., Zhang, Z., 2021. Impacts of land use change on ecosystem service value based on SDGs report–Taking Guangxi as an example. Ecol. Indic. 133, 108366. https://doi.org/10.1016/j.ecolind.2021.108366.

Sagar, S., Roberts, D., Bala, B., Leo, Lymburnera, 2017. Extracting the intertidal extent and topography of the Australian coastline from a 28 year time series of Landsat observations. Remote Sens. Environ. 195, 153–169. https://doi.org/10.1016/j.rse.2017.04.009.

Sharp, R., Tallis, H.T., Ricketts, T., et al., 2015. InVEST 3.2.0 User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Smith, P., Adams, J., Beerling, D.J., et al., 2019. Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. Annu. Rev. Environ. Resour. 44, 255–286. https://doi.org/10.1146/annurev-environ-101718-033129.

Sun, X., Li, F., 2017. Spatiotemporal assessment and trade-offs of multiple ecosystem services based on land use changes in Zengcheng China. Sci. Total Environ. 609, 1569–1581. https://doi.org/10.1016/j.scitotenv.2017.07.221.

Tiné, M., Perez, L., Molowny-Horas, R., Marcel, D., 2019. Hybrid spatiotemporal simulation of future changes in open wetlands: a study of the Abitibi-Témiscamingue region, Québec, Canada. Int. J. Appl. Earth Obs. Geoinf. 74, 302–313. https://doi.org/10.1016/j.jag.2018.10.001.

Xiao, D., Deng, L., Kim, D.G., Huang, C., Tian, K., 2019. Carbon budgets of wetland ecosystems in China. Glob. Chang. Biol. 25 (6), 2061–2076. https://doi.org/10.1111/gcb.14621.

Xu, L., He, N.P., Yu, G.R., 2018. A dataset of carbon density of China's terrestrial ecosystem in 2010s. Science Data Bank https://doi.org/10.11922/sciencedb.603.

Zhang, C., Tian, H., Chen, G., Chappelka, A., Xu, X., Ren, W., Hui, D., Liu, M., Lu, C., Pan, S., Lockaby, G., 2016. Impacts of urbanization on carbon balance in terrestrial ecosystems of the southern United States. Environ. Pollut. 164, 89–101. https://doi.org/10.1016/j.envpol.2012.01.020.

Zhang, Z., Hu, B.Q., Jiang, W.G., Qiu, H.H., 2021. Identification and scenario prediction of degree of wetland damage in Guangxi based on the CA-Markov model. Ecol. Indic. 127, 107764. https://doi.org/10.1016/j.ecolind.2021.107764.

Zhao, C., Qin, C., 2020. 10-m-resolution mangrove maps of China derived from multi-source and multi-temporal satellite observations. ISPRS Journal of Photogrammetry and Remote Sensing 169, 389–405. https://doi.org/10.1016/j.isprsjprs.2020.10.001.

Zhu, L.Y., Song, R.X., Sun, S., Li, Y., Hu, K., 2022. Land use/land cover change and its impact on ecosystem carbon storage in coastal areas of China from 1980 to 2050. Ecol. Indic. 142, 109178. https://doi.org/10.1016/j.ecolind.2022.109178.