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Multi-year carbon stock study of wetland ecosystem in Hengshui Lake national nature reserve

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ABSTRACT

In order to provide the wetland ecosystem reserve with a scientific basis on which to develop policies to reduce emissions, increase sinks, and improve ecological values, this paper examines the carbon stock and its spatial distribution over the past 42 y in Hengshui Lake National Nature Reserve. It also analyzes alteration patterns and response mechanisms of its ecosystem carbon sequestration. The carbon stock of the wetland at Hengshui Lake was determined using the land use classification data and the InVEST carbon stock model. The difference in value between the carbon stock in the first and last year's reflects changes in the stock and separates the regions of carbon sources and carbon sinks. The land use of a 34.54 km^2 region of the Hengshui Lake wetland ecosystem changed during the course of 42 y (1980–2022), and the carbon stock rose by 16.1°× 10^4 MgC. Wetland carbon stocks were mostly contributed to by cropland, but woodland was primarily responsible for the acceleration of carbon stock growth. The exchange of carbon across different land types and the intimate connection between carbon sequestration potential and land use are the main drivers of changes in carbon stock. This study serves as a pertinent resource for comprehending the level of carbon sequestration in Hengshui Lake wetland and advancing the coordinated growth of wetland economics and ecology.

Keywords: Hengshui Lake; Wetland ecosystem; Carbon storage; Carbon source sink; InVEST model

1. Introduction

Regional carbon stock refers to the accumulated storage of carbon in regional terrestrial ecosystems, which reflects the productivity and climate regulation capacity of terrestrial ecosystems [1,2]. On estimating carbon stocks in various types of terrestrial ecosystems, including forests, grasslands, and agricultural lands, extensive research has been done on a global scale. Prior research has examined a range of subjects, including the estimation of carbon stocks across various ecosystems at different levels [3–6], as well as comparisons of carbon content among soil, vegetation, and litter components within individual terrestrial ecosystems, such as forests. Additionally, investigations have been conducted on the biomass and carbon stock distribution among different organs and components of tree stands at various levels [7,8]. Achieving carbon peak by 2030 and carbon neutrality by 2060 has emerged as a crucial strategic objective for China's long-term development. In this regard, it is imperative to enhance the investigation of carbon stocks in wetland ecosystems to preserve the equilibrium between worldwide carbon emissions and carbon sequestration. The major approaches for estimating carbon stocks now in use are sample field surveys,

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model estimation, and remote sensing simulation, all of which either need a significant quantity of ground survey data to support them or have issues with model-driven data complexity [6,9–11]. The InVEST model, which is an established tool for estimating ecosystem carbon stocks and measuring service values, offers several benefits including ease of use and availability of data [12–15].

The Hengshui Lake wetland is the only natural reserve located in the North China Plain that sustains an intact wetland ecosystem comprising of marshes, waters, mudflats, meadows, and forests. The aforementioned functions are of utmost importance, as they include water retention, preservation of soil quality, and the storage of carbon. The incorporation of Hengshui Lake into the national green ecosphere in 2018 was a strategic move aimed at bolstering the ecological foundation of the Beijing-Tianjin-Hebei synergistic development. Furthermore, the Hengshui Municipal Party Committee and Municipal Government have issued the Regulations on Water Quality Protection of Hengshui Lake and the Special Planning of Hebei Hengshui Lake National Nature Reserve (2018–2035), thereby establishing a legal framework for the conservation of Hengshui Lake. The Hengshui Lake wetland have undergone notable changes in their ecosystem service value and carbon storage as a result of ecological restoration and natural recovery efforts in recent years.

This study uses the InVEST carbon stock model to analyse data on land use classification from remote sensing. The present study centres on the intricate ecosystems of cropland, woodland, grassland, waters, and construction land within Hengshui Lake National Nature Reserve. The study selects five distinct timeframes, including two time periods prior to the establishment of the reserve (1980 and 1990), the year of the reserve's establishment (2000), the time of the first ecological protection progress (2010), and the termination point of this investigation (2022). The present study performed an in-depth analysis of the characteristics and response mechanisms of the carbon stock of the ecosystem of Hengshui Lake wetland, and investigated its spatial and temporal evolution before and during the construction of the reserve. The aim was to explore a scientific management mode for the construction of the reserve and to provide a scientific foundation for the formulation of measures and policies to reduce emissions and increase sinks in wetland reserve ecosystems, thereby enhancing their ecological values.

2. Materials and methods

2.1. Overview of the study area

The Hengshui Lake National Nature Reserve, also known as the "Hengshui Lake wetland" (Fig. 1), is situated in Hengshui City at the confluence of Taocheng and Jizhou counties, between latitudes 115°28′27″-115°41′54″N and 37°31′39″-37°41′16″E. The total expanse of the region is 163.65 km^2, while the present waters retention capacity is 75 km^2. The topography of the area is characterised by a level surface that gradually inclines in a south-west to north-east direction. The altitude of the lakebed is situated within the range of 17 to 19 m. The Hengshui Lake Reserve is situated in a warm-temperate continental monsoon climate zone, characterised by an average annual precipitation of 486.6 mm. Hengshui Lake is home to a total of 323 avian species, among which 56 are classified as national I and II grade key protected birds [16]. The Hengshui Lake Reserve is a freshwater wetland ecosystem nature reserve located in the North China Plain. It serves multiple functions, including water conservation, irrigation of farmland, habitat maintenance, and provision of a habitat for aquatic species.

2.2. Data sources and research methods

2.2.1. Land use classification data

The Resource and Environment Science Data Centre of the Chinese Academy of Sciences provided five distinct categories of land use data, including data pertaining to land use in the years 1980, 1990, 2000, and 2010. These datasets were obtained with a spatial resolution of 30 m. The source of this information can be found at http://www.resdc.cn. The land use data utilized for the year 2022 primarily rely on Gaofen-1 images, as reported by the Land Resources Satellite website. These images possess a spatial resolution of 16 m, which were subsequently resampled to 30 m. The study employed a manual visual interpretation approach in conjunction with field verification to achieve an interpretation accuracy of 90%, thereby satisfying the research requirements. The land use categories in the study area were classified into five categories, namely cropland, woodland, grassland, waters, and construction land, based on the LUCC classification system of the Chinese Academy of Sciences and taking into account the carbon stock characteristics of the respective land types.

2.2.2. InVEST carbon stock model

The InVEST model, which was collaboratively developed by Stanford University, WWF, and The Nature Conservancy, is a no-cost, open-source model primarily utilized for evaluating ecosystem services. The entire regional carbon stock and the properties of its spatial and temporal distribution were calculated using four carbon pools [17]. The InVEST carbon stock estimation model (carbon module) requires two primary input data sets: (1) a land use raster data set

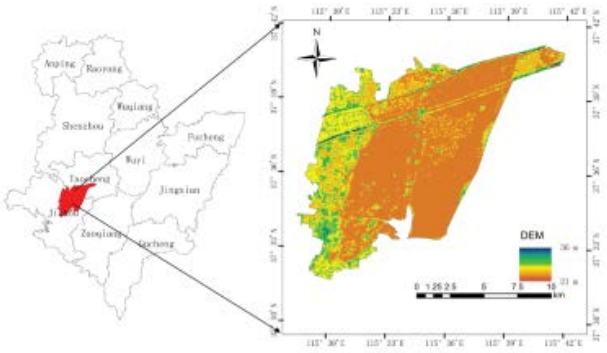

Fig. 1. Location of Hebei Hengshui Lake National Nature Reserve.

and (2) carbon density values for each land use type, which are categorized into four components: aboveground, below-ground root system, soil, and dead organic matter. The carbon stock calculation equation is:

$$C_{tot} = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (1)$$

where C_{tot} is the total regional carbon stock; C_{above} is the above-ground carbon stock; C_{below} is the below-ground root carbon stock; C_{soil} is the soil carbon stock; C_{dead} is the dead organic matter carbon stock.

The construction of the carbon density database primarily relied on referencing measured data from extant literature. A review was conducted on the literature pertaining to carbon stock in ecosystems, sourced from the China Knowledge Network (http://WWW.cnki.net). Following a thorough comparative analysis, the carbon density database utilized in this study was sourced from Hebei Province. This database employed a precipitation relationship model to correct for biomass carbon density and soil carbon density [18], as presented in Table 1.

C_i, above is the aboveground biomass carbon density of land use category i; C_i, below is the underground biomass carbon density of land use category i; C_i, soil is the organic matter carbon density of soil from 0 to 30 cm deep of land use category i; C_i, dead is the organic matter carbon density of dead litter of land use category i. The unit of carbon density MgC/ha.

The cropland of Hengshui Lake wetland is dry land, and the woodland is mainly deciduous broad-leaved forest. According to the actual situation of land use, the relevant data items (Table 2) were selected from the above table as follows:

Table 2
Carbon density of land use categories in Hengshui Lake wetland (Unit: MgC/ha)

Land use type	$C_{i,above}$	$C_{i,below}$	$C_{i,soil}$	$C_{i,dead}$
Cropland	6.60	0.66	92.90	0
Woodland	30.23	9.07	151.40	3.00
Grassland	1.03	2.61	62.90	0.24
Waters	2.29	0	17.16	0
Construction land	7.61	4.51	42.17	0

3. Results and analysis

3.1. Land use alteration patterns of the Hengshui Lake wetland

According to Fig. 2 and Table 3, the land use category in Hengshui Lake wetland from 1980 to 2022 is predominantly cropland that is broadly distributed in the north and west of Hengshui Lake wetland, accounting for approximately 60% of the total study area. More than 30% of the entire area of wetlands is covered by water, and this portion is more consistently sized in the east. The proportion of wetland area that is allocated for construction purposes exceeds 3%. Across the four monitoring periods spanning from 1980 to 2010, the land use category of woodland was observed to be relatively diminutive and overlooked. However, in the most recent monitoring period of 2022, the implementation of successive afforestation and greening initiatives has begun to yield positive outcomes. Following a process of manual discrimination and field verification, the present study has identified the presence of numerous woodlands that are sporadically distributed in the northern and western regions of the Hengshui Lake wetland. These woodlands occupy a total area of approximately 11.73 km^2, which corresponds to 7% of the overall wetland area. The grassland region constitutes a minor proportion, accounting for less than 1% of the entire wetland area.

According to the data presented in Table 3, there were notable fluctuations in the area of different land

Table 1
Carbon density of different land use types in Hebei Province (Unit: MgC/ha)

Land use type		$C_{i,above}$	$C_{i,below}$	$C_{i,soil}$	$C_{i,dead}$
Primary	Secondary				
Woodland	Deciduous broad-leaved forest	30.23	9.07	151.40	3.00
	Evergreen coniferous forest	29.66	9.79	110.75	1.68
	Deciduous coniferous forest	25.03	5.26	154.76	5.99
	Mixed coniferous forest	25.93	5.53	138.99	4.38
	Deciduous broad-leaved scrub	11.71	1.99	94.00	2.47
	Trees and gardens	13.13	3.94	110.60	0.51
Grassland	Grassland/meadow	1.03	2.61	62.90	0.24
	Temperate meadows	1.32	7.06	54.34	0.47
Farmland	Paddy field	8.30	0.83	92.90	0
	Dryland	6.60	0.66	92.90	0
Wetland	Herbaceous wetland	7.40	24.30	247.80	1.24
	Waters	2.29	0	17.16	0
Construction land	Construction land	7.61	4.51	42.17	0
Unused land	Saline/sandy land	9.10	14.20	22.63	0

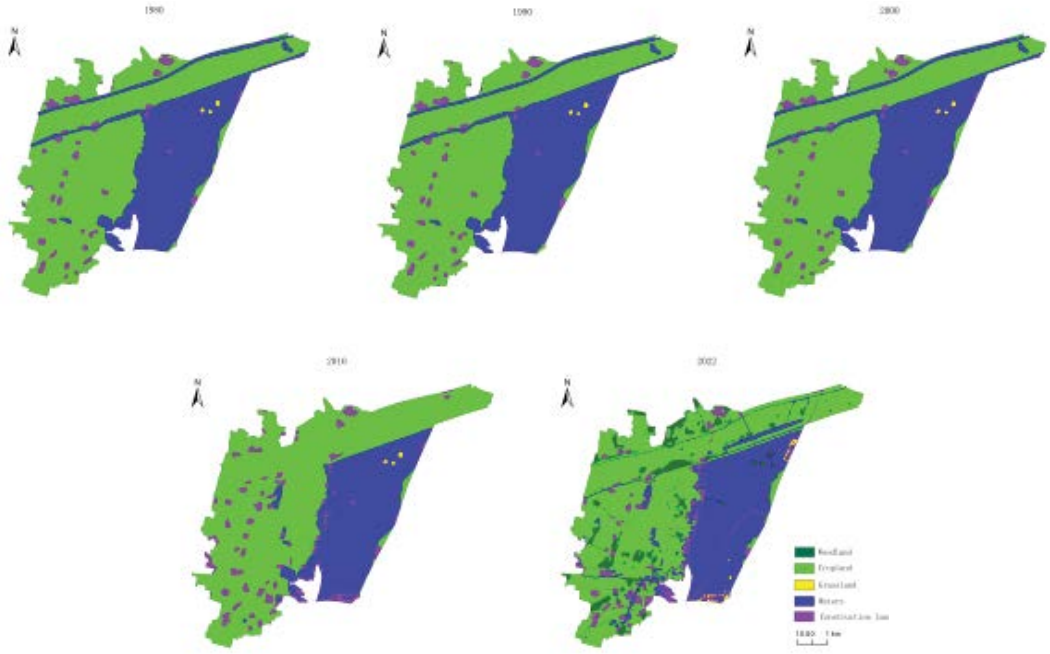

Fig. 2. Spatial distribution of wetland land use in Hengshui Lake wetland from 1980 to 2022.

use categories from 1980 to 2022. Specifically, the area of woodland, grassland, and construction land exhibited an upward trend during this period. Notably, the area of woodland experienced the most significant increase, with a total of 11.73 km^2. The area of construction land also increased, albeit to a lesser extent, with a total of 3.64 km^2. Conversely, the area of grassland remained relatively stable, with a slight increase of 0.43 km^2. The expanse of both waters and cropland has exhibited a decline in their respective surface areas. With regards to alterations in land use transfer (as depicted in Fig. 3), the aggregate area where land use categories were transferred between the years 1980 and 2022 amounted to 34.54 km^2. The most substantial alteration in land use category between 1980 and 2022 was observed in the conversion of cropland to woodland, which amounted to 9.78 km^2. This was followed by the transfer of waters to cropland, which accounted for 8.97 km^2. Since 2018, the Protected Area Farming Back to Forest Project and Large-Scale Greening Action have been implemented with support and promotion from national, provincial, and municipal authorities. As a result, the woodland area surrounding Hengshui Lake has experienced significant growth, while the area of cropland has decreased.

3.2. Space and time characters of carbon stocks changes in the Hengshui Lake wetland

Based on the land use classification data and carbon density data, the InVEST carbon stocks estimation model was used to obtain the spatial distribution of carbon stocks in the Hengshui Lake wetland during different periods (Fig. 4). According to the statistics, the total carbon stocks in the Hengshui Lake wetland in 1980, 1990, 2000, 2010, and 2022 were 1.1466, 1.1466, 1.1463, 1.220, and 1.3076 million tons. As for the growth rate of carbon stock, 1990–2000 (–0.03%) < 1980–1990 (0.00%) < 2000–2010 (4.87%) < 2010–2022 (8.79%).

From 1980 to 2022, the wetland's carbon stocks distribution has not changed very significantly, and the overall distribution pattern is high in the west and low in the east. The wetlands with high carbon stocks mainly concentrate in the northern and western areas, where villages, towns and crop growing regions are located. In these areas, the carbon stocks are higher than 100.2 MgC/ha. Areas with low carbon stocks are mainly located in the southeastern lake area, with the lowest carbon stocks being 19.5 MgC/ha. From 1980 to 2000, the distribution of carbon stocks did not change much; from 2000 to 2010, as some waters were converted to cropland, carbon stocks concentrated more evenly and uniformly in the western and northern areas. Forests sequester carbon by capturing carbon dioxide from the atmosphere and transforming it into biomass through photosynthesis, so they have higher carbon sequestration potential. From 2000 to 2010, woodland appeared between the cropland in the west and that in the north. As a result, the distribution of carbon stocks became sporadic instead of concentrated and continuous. Therefore, land use can cause drastic changes in carbon stock.

Looking at the time dimension, over the past 42 y, the carbon stocks of Hengshui Lake wetland have first reached a steady platform before increasing, with an obvious turning point in 2010. The year 2010 marked the 10-y anniversary since the establishment of the reserve. It was also the time when the ecological protection began to build steam. Looking at the spatial dimension, carbon stocks shifted from concentration to dispersion. This was affected by using land for woodland with stronger capacity for carbon sequestration. In conclusion, under current land using mode, the carbon sequestration capacity of the Hengshui Lake wetland ecosystem is higher than before.

Table 3
Land use category alteration of Hengshui Lake wetland from 1980 to 2022

Land use type	Area (km^2)/Share (%)										Amount of area alteration (km^2)			
	1980		1990		2000		2010		2022		1980–1990	1990–2000	2000–2010	2010–2022	1980–2022
Cropland	100.19	61%	100.19	61%	100.11	61%	105.27	64%	92.98	57%	0.0045	−0.0828	5.1624	−12.2868	−7.2027
Woodland	0.00	0%	0.00	0%	0.00	0%	0.00	0%	11.73	7%	0	0	0	11.7324	11.7324
Grassland	0.21	0%	0.21	0%	0.21	0%	0.22	0%	0.65	0%	0	0	0.0054	0.4275	0.4329
Waters	57.90	35%	57.89	35%	57.89	35%	48.68	30%	49.29	30%	−0.0027	−0.0054	−9.2088	0.6111	−8.6058
Construction land	5.36	3%	5.36	3%	5.45	3%	9.49	6%	9.00	6%	−0.0018	0.0882	4.041	−0.4842	3.6432

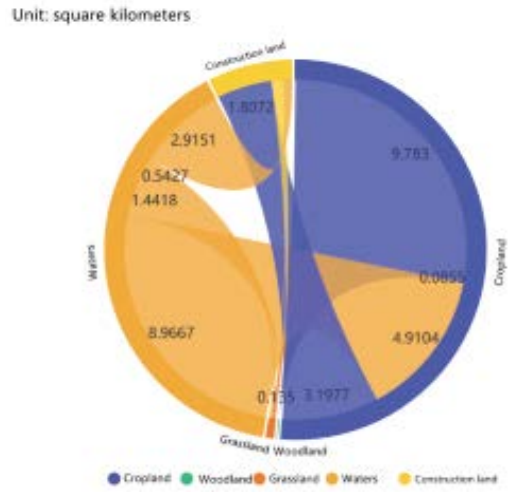

Fig. 3. Land use area transfer chord of Hengshui Lake wetland from 1980 to 2022.

3.3. Influence of land use changes on carbon stocks in the Hengshui Lake wetland

In Hengshui Lake wetland, the carbon stocks per unit area of different land use categories are, in descending order, woodland > cropland > grassland > construction land > waters. However, different land use types contributed different carbon stocks to Hengshui Lake wetland. For example, in 2022, the contributions of different land use categories to the carbon stocks were cropland > woodland > waters > construction land > grassland. The effects of land use change on carbon stock dynamics are analyzed as follows:

3.3.1. Cropland

The cropland in the Hengshui Lake wetland adopts dryland-farming, with major crops being wheat and corn and minor crops being oilseed rape and vegetables. As shown in Tables 3 and 4, during the five monitoring periods (1980, 1990, 2000, 2010 and 2022), cropland was the largest land use category in the study area, and its carbon stocks account for more than 71% of the total. The area of cropland in Hengshui Lake wetland decreased from 100.19 km^2 in 1980 to 92.98 km^2 in 2022, with carbon stocks dropping from 1.035 million tons to 931.3 thousand tons. From 1980 to 2000, the carbon stocks of cropland remained constant; from 2000 to 2010, its carbon sequestration increased by 51.7 thousand tons; from 2010 to 2022, its carbon sequestration decreased by 123.1 thousand tons. In general, carbon stocks in cropland went up first before declining later.

3.3.2. Woodland

During the four monitoring periods from 1980 to 2010, woodland was too small to be identified. Therefore, the area of woodland and carbon stocks were recorded as 0. To apply to be a national 5A tourist attraction, Hengshui Lake Scenic Area has increased efforts in afforestation around the lake since 2020. As a result, a large number

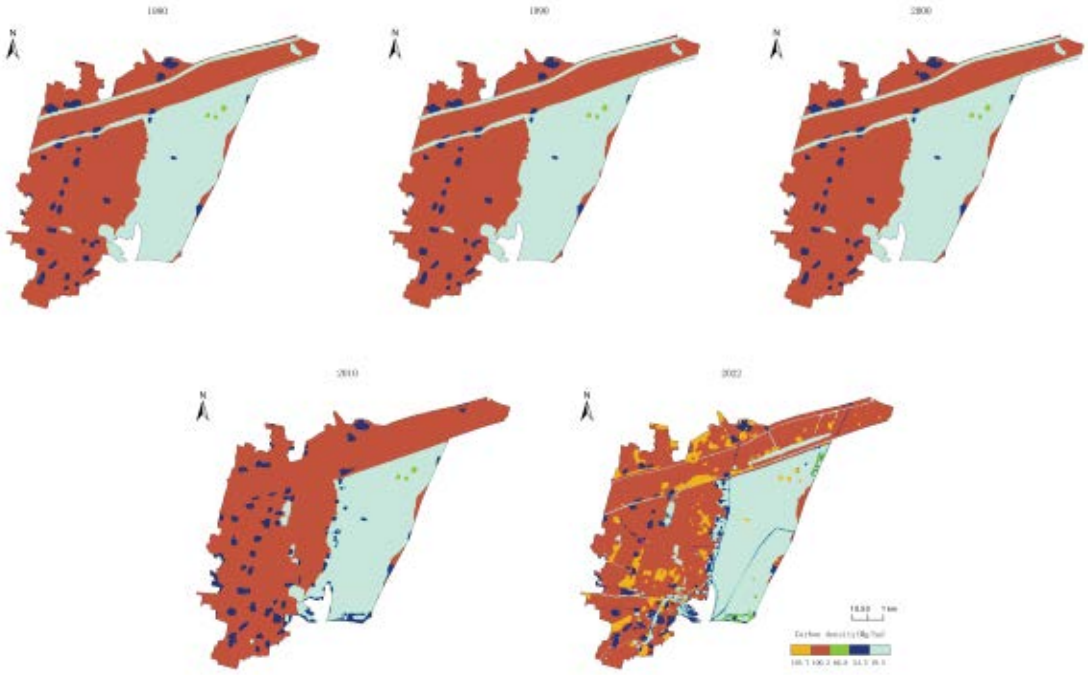

Fig. 4. Spatial distribution of carbon stocks in Hengshui Lake wetland from 1980 to 2022.

of trees and seedlings have been planted in the reserve. In 2022, 227.3 thousand tons of carbon have been sequestered in woodland, accounting for 17% of the total. Forests become the main contributor to the growth of carbon stocks in the study area from 2010 to 2022. Changes in soil carbon stocks over the period can be attributed to changes in woodland, especially during the recent 2 y. In the future, such a growing trend will continue.

3.3.3. Grassland

During the monitoring period, the grassland area of Hengshui Lake wetland accounted for about 0.1%–0.4% of the total area. Its carbon stocks increased from 1.4 thousand tons in 1980 to 4.3 thousand tons in 2022. To be specific, the carbon stocks of the grassland remained unchanged from 1980 to 2010 and increased by 2.9 thousand tons from 2010 to 2022. In general, the carbon stock of grassland remained roughly unchanged, before increasing towards a higher level.

3.3.4. Waters

In Hengshui Lake wetland, the area of waters remained roughly unchanged during the monitoring period from 1980 to 2000. During the monitoring period of 2010, the waters' area significant decreased from 57.90 km^2 in 1980 to 49.29 km^2 in 2022, with carbon stocks decreasing from 112.6 thousand tons to 95.9 thousand tons. From 2000 to 2010, the area and carbon stocks of the waters significantly decreased and carbon sequestration decreased by 17.9 thousand tons; from 2010 to 2022, the data rebounded with carbon sequestration increased by 12 thousand tons. Therefore, in the past 42 y, the carbon stocks of the waters in Hengshui Lake wetland followed significant drops with a small rebound.

3.3.5. Construction land

The carbon stocks of construction land followed an opposite trend to those of waters. The construction land area rose from 5.36 km^2 in 1980 to 9.00 km^2, with carbon stocks rising from 29.1 thousand tons to 48.9 thousand tons. From 1980 to 2000, the area of construction land and its carbon stocks remained unchanged. The turning point occurred in 2010. During 2000 to 2010, the area of construction land increased by 4.04 km^2, with carbon stocks increasing by 21.9 thousand tons and the amount of carbon sequestered increasing by 74%. From 2010 to 2022, the relevant data decreased slightly. In general, the construction land's carbon stocks first significantly increased before slightly decreased. The significant increase in carbon stocks appeared since 2010 when the reserve was established. This was because increasing construction activities around the lake. The later decline of carbon stocks was due to ecological restoration. In recent years, the reserve carried out some ecological relocation projects, in which some villages around the lake were demolished for ecological construction. For example, on the west shore of Hengshui Lake, there was a strip of land that extended out into the waters. This peninsula was former the village of Shunminzhuang. After the villagers were relocated in 2022, the place was planted with ornamental plants. Since 2017, the reserve has implemented the project of "returning farmland to forest" (RFFP). As more construction land are converted to woodland and grassland, the carbon stocks of construction land will keep declining.

Land use changes, such as area changes for cropland, waters and construction land, will impact the overall

Table 4
Carbon stocks of different land use categories in Hengshui Lake wetland from 1980–2022

Land use	Carbon stock (104 MgC) and its percentages (%)										Carbon sequestration volume (104 MgC)				
categories	1980		1990		2000		2010		2022		1980–1990	1990–2000	2000–2010	2010–2022	1980–2022
Cropland	100.35	88%	100.35	88%	100.27	87%	105.44	88%	93.13	71%	0.0045	–0.0829	5.1707	–12.3065	–7.2142
Woodland	0.00	0%	0.00	0%	0.00	0%	0.00	0%	22.73	17%	0.00	0.00	0.00	22.7257	22.7257
Grassland	0.14	0%	0.14	0%	0.14	0%	0.15	0%	0.43	0%	0.0000	0.0000	0.0036	0.2855	0.2891
Waters	11.26	10%	11.26	10%	11.26	10%	9.47	8%	9.59	7%	–0.0005	–0.0011	–1.7911	0.1189	–1.6738
Construction land	2.91	3%	2.91	3%	2.96	3%	5.15	4%	4.89	4%	–0.0010	0.0479	2.1939	–0.2629	1.9779
Total	114.66	–	114.66	–	114.63	–	120.20	–	130.76	–	0.0030	–0.0361	5.5770	10.5607	16.1046

carbon sequestration in Hengshui Lake wetland. Land use categories will keep each other in check and balance, and affects the results of carbon sequestration.

3.4. Division of Hengshui Lake wetland into carbon source areas and carbon sink areas

To measure the carbon balances of Hengshui Lake wetland over the past 42 y and estimate the net change of carbon stocks during a certain period, this study uses the changing pattern of land use categories for calculation. This method calculates the difference in carbon stocks between the first and last years of a certain period based on map units. Based on the value of the carbon stock differences, the areas can be divided into different types. If the result is positive, then the area belongs to the carbon sink area; if the result is zero, the area is the carbon balance area; and if the result is negative, the area is carbon source area. Fig. 5 shows the spatial distribution of the carbon source area and carbon sink area of Hengshui Lake from 1980 to 2022.

In summary, from 1980 to 2022, the total area of carbon sources and carbon sinks in Hengshui Lake wetland was smaller than that of the carbon balance area. Carbon sources and carbon sinks did not concentrate. They were divided by carbon balance areas, which took up most of the land. Most carbon sources were distributed north to the lake and west of the wetland. They were formed by the conversion of cropland into water ponds or canals. Most carbon sinks were scattered west of the wetland and along the rivers north of the wetland. They were formed due to the transformation of cropland into woodland.

4. Discussion and conclusions

In Hengshui Lake wetland, woodland and cropland are land types with higher carbon densities. Areas with high carbon stocks mainly concentrate in the crop planting areas in the west and north. Areas with low carbon stocks mainly concentrate in the waters in the southeast region. From 1980 to 2022, total carbon stocks of Hengshui Lake

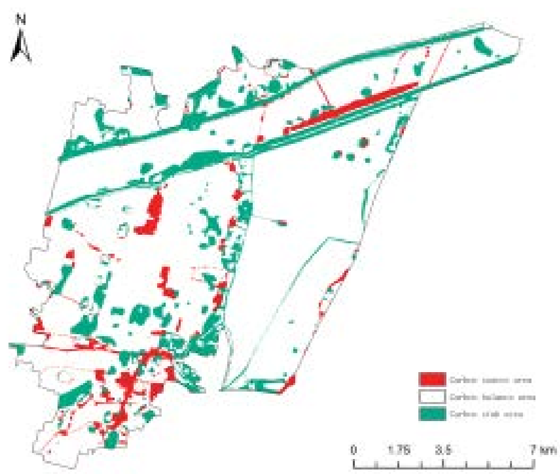

Fig. 5. The division of Hengshui Lake wetland 1980–2022 into carbon sources and carbon sinks.

wetland ecosystem increased by 16.1 × 10^4 MgC, for which the expansion of cropland and woodland was the dominant factor. From 2000 to 2010, the main reason for the increase of carbon stocks was the conversion of some waters into cropland. From 2010 to 2022, the increase of carbon stocks was mainly caused by the conversion of some cropland into woodland. As woodland has a higher carbon sequestration capacity, their expansion can directly increase rates of carbon storage in the wetland. Over the past 42 y, the carbon stocks of Hengshui Lake wetland followed an increasing trend, with significant changes in the spatial distribution. Some regions have better overall carbon sequestration than before. Carbon stock changes are caused by the transfer of land use categories, and the improved carbon sequestration is resulted from more efficient land use.

This study focuses on the Hengshui Lake wetland's carbon sequestration efficiency. The results offer a reference for the coordinated development the wetland's economy and ecology. Previous literature often used the sample plot inventory method to calculate regional carbon stocks [19]. In contrast, this study combines both remote sensing and modeling to rapidly visualize the results. This is one of its advantages. As for the disadvantages, for example, the InVEST model has its own limitations. Although the model assumes a linear variation of carbon stocks during a certain period, the actual carbon stocks are nonlinear, and the calculated carbon stock values may be lower than the actual values. According to the literature review, herbaceous wetlands have better capacity to sequester carbon [20–22]. Although there are aquatic plants in Hengshui Lake wetland, they are incorporated into the waters for calculation. It is because aquatic plants' growing areas change significantly each year, which is hard to measure. In this study, the carbon densities for all land use categories were obtained from previous literature. However, according to related studies, the carbon densities for different land cover types under the same category may not be the same [23–25]. In this study, the land cover types were classified only to the second level. If there is a need to improve accuracy, further classification of land cover types should be done.

Hengshui (Chinese: 衡水) is a prefecture-level city in southern Hebei Province. It is also known as the lake city for its eco-friendly Hengshui Lake. To restore local ecology, it has implemented several policies, such as returning farmland to forests and ecological relocation. During restoration, the land pattern is changing and influencing regional carbon sequestration. The presence of woodland and grassland can reduce carbon emissions and improve carbon sequestration for the ecosystem. For carbon sources, protective measures should be taken to reduce human interference, while for carbon sinks, forests should be planted if soil conditions are favorable. To achieve maximum comprehensive benefits, government departments should consider the economic, ecological and social benefits before adjusting the territorial spatial planning of Hengshui Lake wetland.

5. Results

The carbon stocks in Hengshui Lake wetland during the five monitoring periods (1980, 1990, 2000, 2010 and 2022) were 1.1466, 1.1466, 1.1463, 1.22 and 1.3076 million tons, respectively. The carbon stocks in the wetland ecosystem of Hengshui Lake showed an increasing trend over the past 42 y (1980–2022). In terms of carbon stocks, cropland contributes most to the wetland's ecosystem, accounting for 71% to 88% of the total. Woodland is the largest contributor to the growth rate of carbon stocks.

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