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EDITED BY
Shuhong Wang,
Shandong University of Finance and Economics, China

REVIEWED BY
Zhiyi Zhang,
Shanghai Business School, China
Qi Ding,
Yellow Sea Fisheries Research Institute (CAFS), China

*CORRESPONDENCE
Xiu-Mei Fu,
xiumei@ouc.edu.cn
Xiang-Hong Lin,
tianshilezhuzhu@163.com

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Assessing the changes of the monetary value of mangrove ecosystem services in China and its application

Chun-Yu Lin[1], Chen-Yang Fu[1], Ying Liu[1], Meng-Qi Zhang[2], Yang Liu[2], Wan-Yu Wu[1], Li-Xia Wang[1], Xiang-Hong Lin[3]* and Xiu-Mei Fu[1]*

[1]School of Economics, Ocean University of China, Qingdao, China, [2]School of Medicine and Pharmacy, Ocean University of China, Qingdao, China, [3]National Marine Data and Information Service, Tianjin, China

With the development of marine economy and climate changing, the ecological value of mangrove ecosystem has become increasingly prominent. In this study, the ecological values of China's mangrove ecosystem services was evaluated based on the four services and nine functions of mangrove ecosystem. On this basis, the dynamic changing characteristics of the nine mangrove ecological values from 2001 to 2019 were analyzed. The results indicated that the top four service values were that of preventing coastal erosion, raw material supply, regulating water resources, and regulating climate and maintaining air quality. Significant changes were found in China's mangrove areas which increased during 2001–2013 and decreased during 2013–2019, while the unit area value of mangrove ecosystem services generally showed an upward trend. Subsequently, the evaluation results were applied to mangrove asset management with balance sheets, ecological compensation standard determination, and carbon trading in blue carbon sink. Based on the above analysis, the corresponding countermeasures and suggestions were proposed for mangrove protection and value application to guide effective management on mangroves and further to realize a higher ecological value of mangrove ecosystem.

KEYWORDS
mangrove asset management, ecological value evaluation, dynamic change, ecological compensation, blue carbon trading

1 Introduction

Mangroves is a typical tropical and subtropical estuarine wetland ecosystems as well as special salty and fresh overlapping ecological environments. It has a vital ecological regulation function in the coastal area connecting land and sea, which is known for providing many ecosystem services (Marcello et al., 2021). With the rapid development of the marine economy and the dramatic change of global climate, the ecological value of mangroves has attracted more and more attention, and the protection of mangroves thereby has become a global concern (Wang and Sun, 2020). The ecosystem of mangroves is one of the most important ecosystems in the biosphere (Hsieh et al., 2015), mangrove restoration and protection are essential for achieving sustainable goals (Jimenez et al., 2021). However, since the 1980s, the global mangrove area has decreased by 35%, with an average annual decrease of approximately 1% (Hua, 2020). In China, due to excessive reclamation, the area of mangroves in China has also decreased drastically, from approximately 40,000 hm^2 in the 1950s to approximately 27100 hm^2 in 2019 (National Bureau of Statistics of China, 2021) although it has shown a fluctuating trend in recent years. The carbon stock in vegetation, dominated by low-intertidal pioneer species in more than half of the existing mangrove areas, has dramatically decreased from 21.8 Tg C in the 1950s to 10.2 Tg C in 2019 (Wang et al., 2020). Furthermore, mangroves in China face the problem of ecological degradation. The increasing population pressure and the rapid development of offshore fisheries have caused critical environmental pollution, damaging the local mangrove ecosystem (Wang et al., 2018). Mangroves are generally undervalued in both private and public decision-making relating to their use, conservation and restoration (Luke et al., 2012), so motivated by short-term economic gain, the development of land reclamation and marine tourism severely reduced the living space of mangroves in recent years. Correspondingly, the ability of mangrove wetland ecosystems has been severely affected to provide humans with multiple ecological services, resulting in a serious reduction of the ecological value (Wang et al., 2021a). Therefore, it is necessary to evaluate the monetary value of mangrove ecosystem services at different time nodes and furtherly explore the dynamic characteristics of mangrove ecological value as well as the economic reasons behind it for guiding the conservation and restoration of mangroves.

Ecosystem services are the natural utilities formed by ecosystems and ecological processes (Chang et al., 2022). The classification of ecosystem functions is a prerequisite for evaluating the monetary value of ecosystem services (Wang et al., 2021b). Because mangrove ecological functions are multidimensional, there is no unified standard for the ecological service classification so far. For instance, a classification including direct use value, indirect use value, and selection value was used to assess the service value of mangrove ecosystem (He et al., 2015; Malik et al., 2015; Chen et al., 2016). A typical classification of mangrove service functions was recommended by the United Nations Millennium Ecosystem Assessment Classification System, which includes supply, regulation, support, and culture services (Friess, 2016; Owuor et al., 2019; Marlianingrum et al., 2021). This classification system avoids the overlap of the service items, which has been widely adopted in ecological value evaluation for various ecological environments including mangroves.

The evaluation methods used to evaluate the mangrove ecosystem services in the previous reports mainly included the direct market method, alternative market method, and simulated market method (Shen and Mao, 2019; Tuan et al., 2015). The choice experiment method, derived from the simulated market method, was usually used to estimate the willingness to pay of community members based on unpaid labor time to determine the monetary value of mangrove ecosystems (Owuor et al., 2019). The meta-analysis method, also derived from the simulated market method, was used to evaluate the monetary value of mangrove ecosystems based on the literature on mangrove economic valuation (Brander et al., 2012). The above two methods have been found to have disadvantages, such as large uncertainty of results, prone to biases and repeated calculations (Shen and Mao, 2019). It should be noted that due to the complexity of mangrove ecosystem services, the use of a single evaluation method may result in greater errors.

Abundant studies on the evaluation of mangrove ecological values have served as a warning and reference for mangrove ecological protection, such as the mangrove service values of Mida Creek in the Watamu Marine Reserve on the Kenyan coast (Ashournejad et al., 2019), the Nayband National Marine Park in southern Iran, French overseas territories (Trégarot et al., 2021), and the Jiulong River estuary in Fujian province, China (Wang et al., 2018). Previous studies mostly investigated the ecological value of local areas (Ashournejad et al., 2019; Owuor et al., 2019), especially mangrove nature reserves, from a static point of view (Brander et al., 2012; Zhang et al., 2013; Chen et al., 2016; Wang et al., 2018; Yi et al., 2018). With the relatively complete basic data of the nature reserves, the monetary valuation for the mangrove ecosystem services of the protected area could be conducted conveniently, contributing to improving the evaluation technology and providing pilot projects for the establishment of ecological compensation systems (Wang et al., 2018). However, these studies did not incorporate the changes in mangrove ecological values at different time points into an analytical framework, so they failed to reflect the dynamic characteristics of the overall mangrove service values. And they were difficult to grasp the impacts of the changes in natural conditions and socio-economic development on the mangrove ecosystem.

In the context above, this study analyzed the ecological value and its dynamic characteristics of the mangrove ecosystem in China with data from three time nodes, referencing the United Nations Millennium Ecosystem Assessment Classification System and the corresponding methods. On this basis, the evaluation results were applied in mangrove asset management with balance sheets, ecological compensation standard determination, and carbon trading in blue carbon sink to hope to provide a scientific reference for the protective development and utilization of mangrove resources.

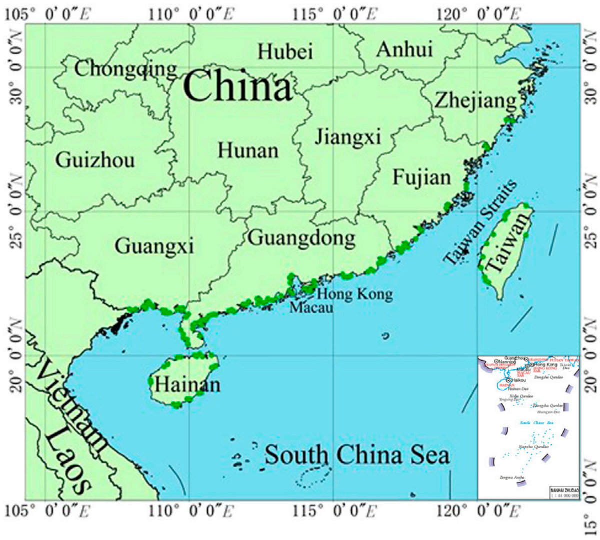

FIGURE 1
Sketch map of mangroves distribution in China. 'Note: ● Mangroves'.

2 Materials and methods

2.1 Study area of mangroves

Chinese mangroves are naturally distributed along the southeast coast of China, mainly in the provinces of Hainan, Guangxi, Guangdong, Fujian, Zhejiang, and Taiwan, and the two special administrative regions of Hong Kong and Macau. The northern boundary of the natural distribution of mangroves in China is located at Shachengwan (27°20′N) in Fuding County of Fujian province, and the northern boundary of artificial introduction is at Yueqing County (28°25′N) in Zhejiang Province (Lin and Fu, 1995). The southern boundary of the distribution is at Yulingang (18°09′N) in Sanya city of Hainan province (Lin and Fu, 1995; Zhang et al., 2006). The research scope of mangroves in this study started from Yueqing County (28°25′N) in the north and ended at Yulingang (18°09′N) in the south of China (Figure 1) (Fu et al., 2021).

2.2 Data sources

Referring to relevant literature (He et al., 2015; Malik et al., 2015; Chen et al., 2016; Yi et al., 2018; Ashournejad et al., 2019), the area data of Chinese mangroves were selected in 2001, 2013, and 2019 for the evaluation of mangrove ecosystem service values. In 2001, the State Forestry Administration of China organized a national mangrove resource survey, which demonstrated that China's mangrove area was 22024.9 hm^2 (Forest Resources Management Division of the State Forestry Administration, 2002). The second national wetland resource survey conducted by Chinese government in 2009–2013 found out the mangrove area in 2013 increased to 34472.14 hm^2 (Dan et al., 2016). According to the third national land survey conducted by Chinese government, the area of China's mangroves in 2019 was 27100 hm^2 (National Bureau of Statistics of China, 2021).

Due to the limitations of data availability, the price parameters selected from the literature for evaluating different service functions were not uniform in their source years and were not comparable in terms of time. Therefore, the social discount rate and the arithmetic average of the producer price index were comprehensively used to convert them into the price parameters of the same period. The conversion method was as follows:

$$R_{it} = \begin{cases} R_{i0}/I^{t_0-t}, t < t_0 \\ R_{i0} \times I^{t-t_0}, t > t_0 \end{cases} \tag{1}$$

where R_{it} represents parameters after conversion; t, the calculated year, which is 2001, 2013 or 2019; R_{i0}, the price parameters selected from relevant literature (Chen et al., 2021); t_0, the base year corresponding to R_{i0}; I, the mean of the average producer price index and social discount rate.

2.3 Classification of service functions of mangrove ecosystem

The mangrove ecosystem service functions were identified by a comprehensive consideration of the universality of wetlands and the particularity of mangroves. Based on the United Nations Millennium Ecosystem Assessment Classification System, four services and nine functions of mangrove ecosystem were confirmed (Figure 2).

Supply services mainly refer to the various products that humans obtain from the ecosystem, including raw materials (such as timber, fiber), and feed (Zhang et al., 2006; Wang et al., 2017). In this study, the monetary value of the supply service mainly included the raw material supply of timber products and the feed supply of mangrove litter which provides abundant bait for offshore fisheries.

Regulating services refer to the various benefits that humans obtain from the regulating function of ecosystems, including regulating climate (carbon fixation), maintaining air quality (oxygen release), regulating water resources (water purification), and preventing coastal erosion (wave reduction and revetment) (Zhang et al., 2007). Mangrove wetlands, like natural filters, have strong adsorption and purification effects on toxic substances, impurities, and other pollutants. Mangroves are extremely important windbreaks in coastal zones. With the ability to reduce waves, known as the green wave-resistant "wall", mangroves can effectively protect the seawall from being destroyed and reduce economic losses along the coast

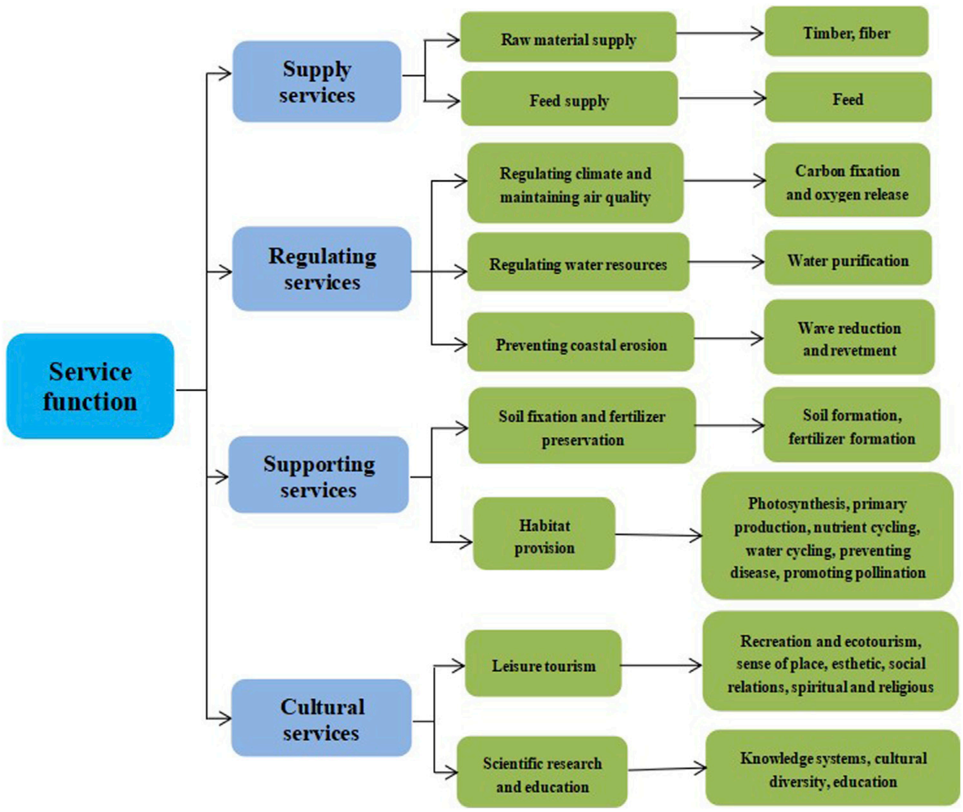

FIGURE 2
Classification of mangrove ecosystem service functions.

(Wang et al., 2009). In this study, the regulating service values were calculated with the values of carbon fixation, oxygen release, water purification, and wave reduction and revetment.

Supporting services are the basic services which are necessary for the ecosystem to provide supply services, regulating services, and cultural services, including the functions of soil fixation, fertilizer preservation, and habitat provision (such as soil formation, nutrient cycling, water cycling, photosynthesis, primary production, preventing diseases, and promoting pollination) (Zhang et al., 2007). Mangrove wetland is one of the most biodiversity-rich ecosystems and is suitable for the habitat of a variety of living beings. In the present study, the values of supporting services were calculated with the functions of soil fixation and fertilizer preservation, and habitat provision.

Cultural services refer to the non-material benefits that people obtain from the eco-system through spiritual satisfaction, cognitive development, thinking, recreation, and esthetic experience, including cultural diversity, spirit and religion, knowledge systems, education, esthetic, sense of place, social relations, recreation and ecotourism (Zhang et al., 2007). The rich animal and plant resources in the mangrove ecosystem provide good conditions for the development of tourism activities. The fauna and flora resources in mangrove wetlands provide abundant materials and research sites for scientific research, and help to raise the public's environmental awareness. In the present study, the cultural service values were assessed in two main parts of leisure tourism value, and scientific research and education value.

2.4 Evaluation methods

In view of the complexity of the classification of mangrove ecosystem services, the evaluation methods for mangrove ecosystem service values used in this study were selected comprehensively (Table 1). The mangrove ecosystem service values in this study were evaluated with reference to the methods for general ecosystem service values, including direct market methods, alternative market methods, and simulated market methods (Shen and Mao, 2019).

The service values of raw material supply, feed supply, soil fixation and fertilizer preservation were evaluated with the market value method, and the value of regulating climate

TABLE 1 Monetary value evaluation methods of China's mangrove ecosystem services.

Classification of service function		Evaluation method
Service	**Function**	
Supply services	Raw material supply	Market price method
	Feed supply	Market price method
Regulating services	Regulating climate and maintaining air quality	Payment for environmental services (PES method)
	Regulating water resources	Expert evaluation method
	Preventing coastal erosion	Shadow price method
Supporting services	Soil fixation and fertilizer preservation	Opportunity cost method; Market price method
	Habitat provision	Shadow price method; Expert evaluation method
Cultural services	Leisure tourism	Expert evaluation method
	Scientific research and education	Practical investigation method

TABLE 2 The parameters selected for monetary valuation of mangroves in China.

Service	Function	2001	2013	2019
Supply services	Raw material supply	R_{11} = \$3822.79	R_{11} = \$8446.69	R_{11} = \$9975.77
	Feed supply	G = 10%; R_{12} = 9.42 t/hm^2		
		P_{12} = 162.15 \$/ton	P_{12} = 358.28 \$/ton	P_{13} = 423.14 \$/ton
Regulating services	Regulating climate and maintaining air quality	C = 11.1 t/(hm^2·a)		
		T = 76.90 \$/ton	T = 169.92 \$/ton	T = 204.10 \$/ton
		K = 68.24 \$/ton	K = 150.77 \$/ton	K = 188.45 \$/ton
	Regulating water resources	Q = 2754.99 \$/(hm^2●a)	Q = 6087.32 \$/(hm^2●a)	Q = 7189.29 \$/(hm^2●a)
	Preventing coastal erosion	S_1 = 13309.64 \$/km	S_1 = 29408.50 \$/km	S_1 = 34732.22 \$/km
		S_2 = 32884.47 \$/km	S_2 = 72660.34 \$/km	S_2 = 95672.97 \$/km
		S_3 = 107641.69 \$/km	S_3 = 237841.20 \$/km	S_3 = 280896.83 \$/km
Supporting services	Soil fixation and fertilizer preservation	D = 0.77 t/m^3; T = 0.31 m; R_{32} = 1.39%		
		P_{31} = 613.90 \$/hm^2	P_{31} = 1356.45 \$/hm^2	P_{31} = 1602.01 \$/hm^2
		P_{32} = 186.27 \$/ton	P_{32} = 411.58 \$/ton	P_{32} = 550.84 \$/ton
	Habitat provision	P_{33} = 452.15 \$/hm^2	P_{33} = 999.06 \$/hm^2	P_{33} = 1179.92 \$/hm^2
Cultural services	Leisure tourism	P_{41} = 1785.18 \$/hm^2	P_{41} = 3944.47 \$/hm^2	P_{41} = 6523.16 \$/hm^2
	Scientific research and education	C_P = \$13385.82		
		N = 131	N = 436	N = 485
Mangrove area (hm^2)	22024.9	34472.14	27100	

and maintaining air quality is evaluated with the payment for environmental service method (PES). The market value method and the PES method could be used to estimate the ecosystem service values based on the actual transaction prices of ecosystem services during transactions and transfers, and the evaluation results of these two methods were considered objective and less controversial (Zhang and Zhang, 2019). The values of preventing coastal erosion, and habitat provision were evaluated with the shadow price method, and the values of soil fixation and fertilizer preservation were evaluated with the opportunity cost method. Both of shadow price method and opportunity cost method were designed as alternative methods to evaluate the service values that are difficult to be directly assessed by the market (Shen and Mao, 2019). The values of regulating water resources and leisure tourism were evaluated with the expert evaluation method. Although the expert evaluation method is subjective, the results obtained by this method still have reference value, which has been frequently used to appraise the ecosystem service values relying on the expert's professional knowledge and evaluation experience (Ding et al., 2016). Additionally, the practical investigation method was used to estimate the value of scientific research and education mainly based on the number of published papers (Yi et al., 2018).

2.5 The monetary value accounting of the mangrove ecosystem services

On the basis of evaluation methods mentioned above, the monetary values of mangrove ecosystem services in China were accounted according to the classification of nine functions with the parameters selected (Table 2).

2.5.1 The monetary value accounting of mangrove supply services

The monetary values of the supply services mainly include the raw material supply value of timber products, and the feed supply value of mangrove litter which provides abundant bait for offshore fisheries.

1) Raw material supply value

The raw material supply value of mangroves was represented and calculated by the value of timber provided by mangroves. The calculation formula was as follows:

$$V_{11} = R_{11} \times S \quad (2)$$

where V_{11} represents the value of the supply of raw materials ($); R_{11}, the annual output value of mangrove timber per hectare ($); S, the area of mangroves (hm^2), the same meaning as in the following formulas.

The annual output values (R_{11}) of mangrove timber per hectare in 2001 and 2013 were from the previous reports as $3822.79 and $8446.69, respectively (Malik et al., 2015) while the annual output value in 2019 was calculated as $9975.77 by price index method based on the value of 2013.

2) Feed supply value

The feed supply value of mangroves was represented and calculated by the value of litter provided by mangroves. The calculation formula was as follows:

$$V_{12} = R_{12} \times G \times S \times P_{12} \quad (3)$$

where V_{12}, the value of feed supply ($); R_{12}, the amount of litter in the mangroves (t/hm^2); G, the yield rate of litter bait (%); P_{12}, the average price of feed ($/ton).

The annual litter of mangroves (R_{12}) was approximately 9.42 t/hm^2, and the yield bait rate (G) was 10% (Han et al., 2000). The average feed prices (P_{12}) in China in 2001, 2013 and 2019 were 162.15 $/ton, 358.28 $/ton (Chen et al., 2016), and 423.14 $/ton (Liu and Chen, 2020), respectively.

2.5.2 The monetary value accounting of mangrove regulating services

The monetary value of the mangrove regulation service is composed of regulating climate and maintaining air quality value, regulating water resources value, and preventing coastal erosion value.

1) Regulating climate and maintaining air quality value.

The regulating climate and maintaining air quality value of mangroves was represented and calculated by the carbon fixation value and oxygen release value provided by mangroves. According to the photosynthesis reaction equation, plants need 1.63 g CO_2 and release 1.19 g O_2 for each 1 g of dry matter production (He et al., 2015). The calculation formula is as follows:

$$V_{21} = 1.63 \times C \times S \times T + 1.19 \times C \times S \times K \quad (4)$$

where V_{21} represents the value of regulating climate and maintaining air quality of mangroves ($); C, the net production of mangroves ($t/[hm^2 \cdot a]$); T, the price of carbon fixation ($/ton); K, the price of oxygen release ($).

The net production of mangroves (C) was 11.1t/($hm^2 \bullet a$) (Zhu et al., 2020); The price of carbon fixation prices (T) in 2001 and 2013 were 76.90 and 169.92 $/ton, respectively, and the price of oxygen release prices (K) were 68.24, 150.77 $/ton, respectively (State Forestry Administration, 2016). The carbon fixation price and oxygen release price in 2019 were 204.10 and 188.45 $/ton, respectively (Hu et al., 2019; Zhang et al., 2020).

2) Regulating water resources value.

The regulating water resources value of mangroves was represented and calculated by the water purification value provided by mangroves. The calculation formula was as follows:

$$V_{22} = Q \times S \quad (5)$$

where V_{22} represents the value of water purification of mangroves ($); Q is the adsorption value of mangroves per unit area to nitrogen, phosphorus, and heavy metals ($/[$hm^2 \cdot a$]).

The adsorption values of nitrogen, phosphorus, and heavy metals per unit area of mangroves in 2001, 2013, and 2019 were 2754.99, 6087.32, and 7189.29 $/($hm^2 \cdot a$), respectively (Trégarot et al., 2021).

3) Preventing coastal erosion value.

The preventing coastal erosion value of mangroves was represented and calculated by the wave reduction and revetment value provided by mangroves. The calculation formula is as follows:

$$V_{23} = (S_1 + S_2 + S_3)d \quad (6)$$

where V_{23} represents the value of mangroves to reduce waves and revetment ($); S_1, the ecological benefits per kilometer of mangrove coastline per year ($/km); S_2, the cost of repairing the seawall ($/km); S_3, the added benefits per kilometer of mangroves to the ecological conservation function of the embankment per year ($/km), and d is the length of the mangrove coastline (km).

The value of S_1 and S_3 were converted into the current year's prices according to the price index with referencing the previous study (Fan 1995). The annual ecological benefits of mangrove distribution along the shoreline (S_1) in 2001, 2013 and 2019 were converted as 13309.64, 29408.50, 34732.22 $/km, respectively; The costs of repairing seawalls (S_2) were saved by 32884.47 and 72660.34 $/km in 2001 and 2013, respectively (Trégarot et al., 2021), and 95672.97 $/km in 2019 (Liu et al., 2018). The added benefits per kilometer of mangroves to the ecological conservation function of the embankment per year (S_3) in 2001, 2013 and 2019 were converted as 107641.69, 237841.20, 280896.83 $/km, respectively; The distribution bandwidth of mangroves along the coast was generally 40–160 m, and the length of the protected shoreline (d) could be obtained by taking the average value of 100 m (Han et al., 2000).

2.5.3 The monetary value accounting of mangrove supporting services

The monetary value of mangrove supporting services comprises two parts. One part is the value generated by mangroves for soil fixation and fertilizer preservation, of which the monetary values were calculated using the opportunity cost method and the market price method. The other part is the value generated by mangroves in habitat provision, which was calculated using an expert evaluation method. The calculation processes were as follows:

1) Soil fixation and fertilizer preservation value.

The soil fixation value of mangroves is reflected in the economic value obtained by reducing soil loss, which was calculated using the opportunity cost method. The calculation formula was as follows:

$$V_{31} = P_{31} \times S \tag{7}$$

where V_{31} represents the value of mangroves in soil consolidation; P_{31}, is the price of unit value of the soil fixation by mangroves ($/hm^2).

The unit values of soil fixation (P_{31}) in 2001, 2013, and 2019 were 613.90, 1356.45, and 1602.01 $/hm^2, respectively (Zhang and Zhang 2019).

The value of fertilizer preservation in mangroves is embodied in the soil nutrient value, that is, the fertilizer value equivalent to the contents of nitrogen, phosphorus, and potassium in the surface soil. The calculation formula was as follows:

$$V_{32} = S \times D \times T \times R_{32} \times P_{32} \tag{8}$$

where V_{32} represents the value of mangroves in fertilizer preservation ($); D is the density of the mangrove surface soil (t/m^3); T is the thickness of the mangrove surface soil (m); R_{32} is the comprehensive content of nitrogen, phosphorus, and potassium in the surface soil of the mangroves (%); P_{32} is the average price of fertilizers ($/ton).

The surface soil density (D) of the mangroves was 0.77 t/m^3; the soil thickness (T) was 0.31 m, and the comprehensive content of nutrition elements (R_{32}) was 1.39% (Ding et al., 2016). The average prices of fertilizers (P_{32}) were 186.27 and 411.58 $/ton in 2001 and 2013, respectively [34], and 550.84 $/ton in 2019 (Liu et al., 2018).

2) Habitat provision value.

The habitat provision value of mangroves was represented and calculated by the animal habitats value provided by mangroves. The unit area values of animal habitats provided by mangroves were 452.15 and 999.06 $/hm^2 in 2001 and 2013, respectively (He et al., 2015; Liu et al., 2018), and 1179.92 $/hm^2 in 2019 calculated using the shadow engineering method. The values of habitat provision were calculated by the following formula:

$$V_{33} = P_{33} \times S \tag{9}$$

where V_{33} represents the value of mangroves in providing wildlife habitat ($); P_{33}, the value of wildlife habitat provided by mangroves per hectare ($/hm^2).

2.5.4 The monetary value accounting of mangrove cultural services

The cultural service values of mangroves comprise two parts. One is the value of leisure tourism, which was calculated with the expert evaluation method; the other one is the value of scientific research and education, which was calculated with the practical investigation method.

1) Leisure tourism value.

The value of leisure tourism was calculated as follows:

$$V_{41} = P_{41} \times S \tag{10}$$

where V_{41} represents the value of leisure tourism ($); P_{41}, represents the value of leisure tourism per hectare ($/hm^2).

The annual ecotourism values per unit area (P_{41}) were 1785.18 and 3944.47 $/hm^2 in 2001 and 2013, respectively (Han and Gao et al., 2009) and 6523.16 $/hm^2 in 2019 (Huang et al., 2020).

2) Scientific research and education value.

The value of scientific research and education of mangroves could be estimated by calculating the total input cost of

TABLE 3 The monetary values of China's mangrove ecosystem services in 2001, 2013, and 2019 (million $).

Service	Function	2001	2013	2019
Supply services	Raw material supply	8419.65	29117.54	27034.32
	Feed supply	336.42	1163.44	1117.56
Regulating services	Regulating climate and maintaining air quality	5049.70	17463.29	16753.27
	Regulating water resources	6067.83	20984.30	19482.98
	Preventing coastal erosion	33882.18	117174.26	111462.85
Supporting services	Soil fixation and fertilizer preservation	1353.47	4680.69	4346.39
	Habitat provision	995.86	3443.99	3197.58
Cultural services	Leisure tourism	3931.84	13597.43	17677.76
	Scientific research and education	175.35	583.62	649.21
Total value	—	60212.31	208208.56	201721.92
unit area value ($/hm^2)	—	27338.29	60399.08	74436.13

publishing papers related to China's mangroves each year. The calculation formula was as follows:

$$V_{42} = N \times C_p \tag{11}$$

where V_{42} represents the value of scientific research and education of mangroves ($), N is the number of published papers related to China's mangroves (piece), C_p, the input cost of each paper ($/piece).

A literature survey of China's mangroves was conducted on China National Knowledge Infrastructure (CNKI) and Web of Science. The publications concerning China's mangroves were retrieved to 131, 436, and 485 papers in 2001, 2013, and 2019, respectively. Based on the 10-years data of general projects (2006–2016) in the annual report data released by the National Natural Science Foundation of China, the input cost of Chinese academic papers was determined as $13,385.82 per article (Liu 2018).

3 Results and discussion of the monetary value evaluation of China's mangrove ecosystem services

The monetary values of mangrove ecosystem services at different time nodes in China were calculated, and the dynamic changes in the monetary values of mangrove ecosystem services were analyzed and discussed.

3.1 The monetary values of China's mangrove ecosystem services

The monetary values of each type of mangrove ecosystem service in 2001, 2013 and 2019 in China were calculated with the methods corresponding to the types of mangrove ecological functions (Table 3).

1) The monetary value of China's mangrove ecosystem services in 2001

In 2001, the calculated monetary value of China's mangrove ecosystem services was $602.12 million, and the unit area value was 27338.29 $/hm^2. The top four functions with high value proportions were preventing coastal erosion, raw material supply, regulating water resources and regulating climate and maintaining air quality among the nine service functions, which were considered as the core functions of mangrove ecosystem services in China in 2001.

2) The monetary value of China's mangrove ecosystem services in 2013

In 2013, the monetary value of China's mangrove ecosystem services was $2082.08 million, and the unit area value was 60399.08 $/hm^2. Compared with 2001, the total monetary value and the unit area value in 2013 were improved greatly. While the proportions of various service values were not much different from those in 2001. The top four functions were preventing coastal erosion, raw material supply, regulating water resources, and regulating climate and maintaining air quality, the same as those in 2001.

3) The monetary value of China's mangrove ecosystem services in 2019

In 2019, the monetary value of China's mangrove ecosystem services was $2017.21 million, and the unit area value was 74436.13 $/hm^2. Compared with 2013, the unit area value increased greatly but the total value decreased. The proportions of various services were not much different from that in 2013 either. The service functions of preventing coastal erosion, raw material supply, regulating water resources, and regulating climate and maintaining air quality, were still accounted for the top four proportions in the nine functions.

4) The credibility of the evaluation results Previous reports showed that the unit area value of Mangroves in China in 2001 was 21982.39 \$/hm^2 (Wang et al., 2009). In 2015, the unit area value of Hainan Province was about 53,402 \$/hm^2, and the mangrove area in Hainan Province accounted for about 33% of the mangrove area in China (He et al., 2015). Therefore, the unit area value could represent the unit area value of mangroves in China to a certain extent. The unit area values of mangroves in China in 2001 and 2013 calculated in the present study were basically consistent with the previous results but relatively larger. The reason is that the conversion of social discount rates and producer price indexes in this study was generally low when dealing with price parameters. There were few studies on the evaluation of the ecosystem service value of mangrove forests in China in 2019, and there was no readily available data for comparison. Based on the comparison of the previous two time nodes, the value evaluation results in 2019 have also certain explanatory power.

3.2 Analysis of the monetary value evaluation results of China's mangrove ecosystem services

By evaluating the monetary value of China's mangrove ecosystem services at three time nodes of 2001, 2013, and 2019, the changing trend of mangrove ecosystem service values was revealed. And the dynamic characteristics of mangrove ecological value were explored for the purpose of revealing the economic reasons behind.

1) During the evaluation period, the area of mangroves in China increased at first and then decreased, but the unit area value of mangrove ecosystem services increased at all these three time nodes. In the first stage, the total area of mangroves in China increased significantly from 2001 to 2013, with an increase of 12,447 hm^2. The main reason was that the Chinese government paid more attention to the protection and restoration of mangroves during this stage. For example, 11 mangrove nature reserves were built covering an area of 41,093.17 hm^2, which effectively improved the area of mangroves (Fu et al., 2021). After 2009, a series of mangrove ecological restoration projects were implemented (Dan et al., 2016). For example, from 2010 to 2013, Fujian province alone increased the area of mangroves by 1,307 hm^2 in Quanzhou Bay, Jiulong River estuary, and Zhangjiang River estuary (Lin et al., 2020).

However, after 2013, improper coastal utilization and environmental pollution led to a decrease of 7372 hm^2 of mangrove area, resulting in a huge loss of mangrove ecosystem service value. During this stage, with the increase in coastal engineering construction, frequent land reclamation led to a sharp decline in the natural shoreline of mangrove distribution (Yu et al., 2019). With the development of the social economy, the functions of mangrove tourism service and ecological aquaculture service became increasingly prominent. However, due to the lack of scientific and long-term planning, the construction and introduction of tourist facilities, such as wooden boardwalks and fast yachts, directly caused the reduction of mangroves. Excessive aquaculture along the coast resulted in the fragmentation of mangrove habitats (Fan and Wang 2017; Wu et al., 2018). Furthermore, the land-based source pollution from the coastal factories with chemicals and heavy metals induced the spread of hostile organisms in mangrove wetlands, which resulted in the death of mature mangroves and a decline in mangrove area (Fan and Wang 2017). Due to the game between economic benefits and ecological benefits, coastal wetland protection behavior was short-term and mutable, which led to the instability of mangrove area in China.

2) According to Table 3, the dynamic characteristics of mangrove ecological value were displayed with the changes of unit area value, total value and the nine service function values at the three time nodes (Figure 3). Although the unit area value of the ecosystem services showed a greatly increasing trend, the total value of Chinese mangroves in 2019 was obviously less than that in 2013 because the area in 2019 decreased severely in recent years. With the development of the social economy, public attention shifted from focusing on the economic benefits to the ecological benefits of mangroves, which greatly increased the nine values of service functions as well as the unit area value. But the monetary value growth in 2019 could not offset the monetary value loss caused by the area decrease, making the total value of China's mangrove ecosystem services in 2019 much lower than that in 2013.
3) The unit area value of regulating services showed an increasing trend in the evaluation period (Table 3; Figure 3). Among them, from 2001 to 2019, the unit area value of regulating climate and maintaining air quality increased greatly. In recent years, the construction of ecological civilization has been placed at an unprecedented high position in China, and more attention has been paid to the vital role of blue carbon in coping with climate change and

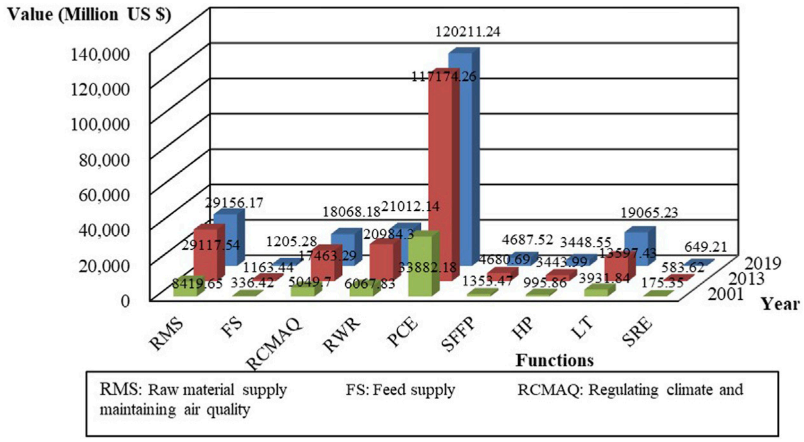

FIGURE 3
Changes of monetary values of mangrove ecosystem services in China in 2001, 2013 and 2019.

improving the marine ecological environment (Zhao and Hu, 2019). Since 2013, China has established several carbon emission exchanges. The construction of carbon emission trading systems has greatly improved the status of carbon sink ecosystems including mangroves (Bai and Hu, 2021). It should be noted that the unit area value of mangroves to prevent coastal erosion has been getting higher and higher. The ability of mangroves to reduce waves has far exceeded that of seawalls, and the costs of building materials and manpower to build seawalls also increased. Ecological seawalls have been widely constructed in the coastal area of China in recent years as an irreplaceable natural means of protection (Zhao et al., 2019). In 2018, the most stringent reclamation control measures were issued in Chinese history, claiming no longer to approve any general projects concerning sea area usage (Wang and Tian, 2019).

4) The unit area value of cultural services showed an increasing trend in the three time nodes (Table 3; Figure 3). With the development of the social economy, the pleasured leisure tourism in mangroves strengthened people's willingness to pay for mangrove ecosystem services (Su and Li, 2016). With the development of tourism, mangrove ecological parks have become one of the favorable destinations to travel (Wu et al., 2021), leading to the increase of the unit area value of mangrove leisure tourism (Spalding and Parrett, 2019). In addition, with the constant enrichment of scientific research achievements and mangrove eco-culture themes, the public cognition of mangrove ecosystem services has been deepening, which brought an inevitable rising trend of the value of mangrove scientific research and education services.
5) The unit area value of supporting services and supply services showed an increasing trend in 2001, 2013, and 2019 (Table 3; Figure 3). Supporting services are essential basic services of mangrove ecosystems to sustain other services. The construction of nature reserves plays an incomparable role in maintaining biodiversity, thus enhancing the unit area value of habitat services. For example, the Shenzhen Futian Mangrove Reserve provides a suitable habitat for a variety of marine living beings, significantly improving the service value of the mangrove ecosystem in the area (Gong et al., 2019). The value proportion of supply services was found to be relatively higher in the four services of the mangrove ecosystem. Specifically, owing to the litter of mangroves could be used as a feed source for offshore fish, the offshore fishing income of local residents could further be increased. Local residents could also directly obtain economic benefits from timber products by raw material supply. Although the direct utilization of timber products should not be encouraged, the value of the supply services was still considerable.

The above analysis would be helpful to deepen the understanding of mangrove ecosystem service functions and awaken people's awareness of the protection and conservation of mangroves. The revelation of mangrove ecological value and its dynamic change characteristics may provide a theoretical basis for promoting and realizing the maximization of mangrove ecological value finally.

4 Application of monetary value evaluation results of China's mangrove ecosystem services

For the purpose of effective protection, management, and development of mangrove resources, the above results of value assessment of China's mangrove ecosystem services were applied to mangrove asset management with balance sheets, ecological compensation standard determination, and carbon trading in the blue carbon sink.

4.1 Application in mangrove asset management with balance sheeting in blue carbon sink

The natural resources balance sheet is an effective tool for the asset management of natural resources (Fu et al., 2018). It is no doubt that the preparation of the balance sheet for China's mangrove resources will be helpful to know the stock of mangrove resources and the dynamic changes of its ecological values.

In this study, the balance sheet of mangrove resources was designed based on the above results of the monetary value evaluation of China's mangrove ecosystem services. Assets tables (Supplementary Tables S1–S3) and resource liability sheets (Supplementary Table S4) were designed and created to reflect the physical inventory and the value inventory of mangrove resources in 2001–2013 and 2013–2019 in China. The final balance sheet of mangrove resources was formed by filling the values of the assets and liability accounts into the accounting accounts (Supplementary Table S5).

The balance sheet of mangrove resources could be used to analyze the status and changes of the final value of mangrove assets, so as to judge the intensity of development and utilization of mangrove resources. The mangrove ecosystem service value may be changed with the utilization, destruction and restoration of mangrove resources. Mangrove area may be increased through natural reproduction, and artificial restoration and afforestation (Li et al., 2021). The newly added mangrove resources may provide new ecological service value, which was defined as a regenerative value on the balance sheet. The values generated by the development and utilization of products and services from mangrove resources were defined as the flow value of mangrove assets during a fixed accounting period. If mangrove resources were over exploited or destroyed by human activities, the assets of mangrove resources may be reduced. The liabilities of assets will occur on the mangrove asset balance sheet if the ending balance of the total mangrove asset value is lower than the beginning balance. On this basis, follow-up management strategies and measures for mangrove resources could be established and implemented. For instance, during an accounting period, if the ending value balance of mangrove resources is lower than the initial value balance, it indicates that the flow value of mangrove resources is greater than the regenerative value, thus the total value of mangrove resources being reduced. This will generate liabilities in the balance sheet of mangrove resources, resulting in a decrease in net assets. In this case, the utilization intensity of mangrove resources should be reduced as much as possible. Meanwhile, the protective strategies and measures should be promoted to cultivate and restore mangrove resources. It is required not only to increase the area of mangrove resources, but also to improve the ecological quality of mangrove resources to increase the service value of mangrove ecosystems. Conversely, if the final value balance of mangrove resources is higher than or equal to the initial value balance, the flow value of using mangrove resources is less than or equal to the regenerative value. Thus, the current status of development and utilization of the mangrove resources could be maintained. It is hoped to control the utilization of mangrove resources within a reasonable threshold, so as to facilitate the coordinated development of the marine environment and marine economy.

4.2 Application in ecological compensation standard determination

Ecological compensation has been considered as an important system for the management of natural resources (Mao et al., 2002). The above results of the mangrove valuation could provide a basis for the ecological compensation of the mangrove ecosystem. There is a game relationship in interest demands between the local government and coastal residents in the process of mangrove wetland usage and mangrove ecosystem compensation. For example, the farmers are the owners of the coastal ponds in the mangrove area who may insist on their rights to use the aquaculture ponds. The government, however, as the main body of mangrove ecosystem management, advocates ecosystem compensation to maintain the rights and interests of the public. From a short-term perspective, regardless of whether the government compensates, farmers will choose not to participate in returning ponds to mangroves for purpose of maximizing their own interests. Similarly, from a short-term perspective, the government will also choose not to compensate the farmers. Apparently, the result of the game (no participation, no compensation) could not maximize the interests of either side. From a long-term perspective, it is necessary for the government to negotiate with farmers on the strategy of government compensation and farmers' participation in returning ponds to mangroves for the purpose of making the interests of both sides to achieve the Pareto optimum so as to well protect the mangrove ecosystem. It could be assumed that after negotiating between the two sides, the policy tool of ecological compensation with added protection cost may be introduced, and after gaming between the two sides, the Nash equilibrium (returning ponds to mangroves, compensating) would be achieved, and the overall optimization could be realized (Table 4).

The willingness of farmers to participate in returning ponds to mangroves is contingent on government subsidies

TABLE 4 The game between the government and farmers.

Subject and strategy			Farmers	
			Returning ponds to mangroves	Not returning ponds to mangroves
Government	No penalty	Compensation	S_1-C_1+C_2, U_1-C_2	S_2+C_2, U_2-C_2
		No compensation	S_1-C_1, U_1	S_2, U_2
	Penalty	Compensation	S_1-C_1+C_2,U_1-C_2	S_2+C_2-θ_1,U_2-C_2
		No compensation	S_1-C_1,U_1-θ_2	S_2-θ_1,U_2-θ_2

S_1 represents the benefits obtained by farmers participating in returning ponds to mangroves, S_2 represents the benefits obtained by farmers not participating, U_1 represents the benefits obtained by the government when farmers participate; U_2 represents the income obtained by the government when farmers do not participate; C_1 represents the cost of fishermen's participation; C_2 represents the cost of the government's implementation of the compensation policy; θ_1 represents the penalty for farmers who do not participate; and θ_2 represents the government's compensation amount when farmers participate.

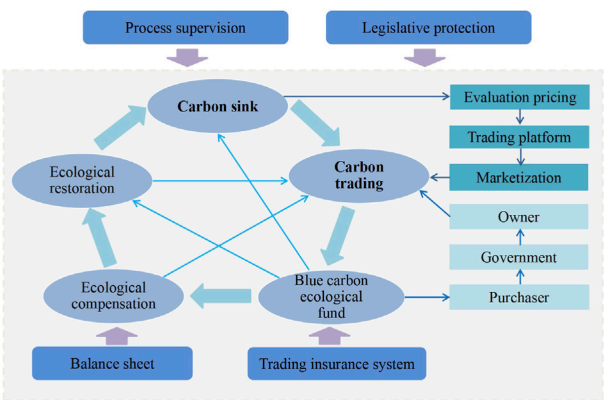

FIGURE 4
Cycle mechanism of mangrove carbon sink and carbon trading.

to compensate for their marginal losses. If the subsidies to farmers cannot make up for the marginal loss, farmers will be unwilling to participate in returning ponds to mangroves, then the subsidies make no sense. Similarly, if the subsidies for farmers exceed the marginal utility of the mangrove ecosystem to the government, the government will be unwilling to pay compensation. Through gaming analysis, the standard amount of ecological compensation should be no less than the marginal loss of farmers and does not exceed the marginal utility of the government as well. Based on the evaluation results in this study, the compensation paid by the government should be lower than 74436.13 $/hm^2, the unit area value of mangrove ecosystem services in 2019. In the future, a reasonable compensation standard and policy should be formulated according to the changes of mangrove ecosystem service value with the development of the social economy and marine ecosystem.

4.3 Application in carbon trading in blue carbon sink

Under the background of global climate change, blue carbon has been considered to be a possibility to make up for the huge gap in carbon sinks. Mangroves have a strong carbon fixation capacity and are of great significance to the carbon sink mechanism (Hong et al., 2017). The evaluation results of mangrove ecosystem service value in this study could offer a reference for the construction of the cycle mechanism of mangrove carbon sink and carbon trading. Based on the function of the mangrove carbon sink, a cycling mechanism of mangrove carbon sink and carbon trading was constructed to facilitate the marketization of the value of mangrove carbon sink (Figure 4).

In this cycle mechanism, a stable carbon sink formed by a healthy mangrove ecosystem is the basis of carbon trading. The historical maximum mangrove area in China was up to about 250,000 hm^2 (Liao and Zhang 2014; Fan and Wang, 2017), nearly 10 times the current area, indicating the considerable potential to recover the mangrove area by returning ponds to mangroves supported by conservation policy such as mangrove ecological compensation.

The mangrove ecosystem with stable carbon fixation ability, formed and consummated by ecological restoration, has ecological and economic values which could become the object of carbon trading in the blue carbon market, which shows great potential in China (Shi et al., 2022). However, blue carbon is usually obtained by free as public goods in China, which causes the loss of its commodity attributes and further hinders the effective construction of the domestic blue carbon trading market (Bai and Hu 2021). Moreover, due to the long transaction cycle and the uncertainty of the transaction process, coupled with the large demand for blue carbon funds, neither the purchasing by a government nor the free supplying by mangrove owners is sustainable. The introduction of the blue carbon ecological fund and blue carbon trading insurance system may provide a feasible way to solve these problems. In order to further improve the ability of mangroves to provide ecosystem services, the funds provided by the blue carbon ecological fund from trading carbon emission reductions could be used not only for ecological compensation, such as returning ponds to mangroves, but also for ecological restoration, mangrove management and conservation, and community public construction. The establishment of blue carbon trading insurance system could transfer the risk to the third party, thus relieving the pressure of the policyholder in the process of blue carbon trading to make the damaged marine ecosystem get recover timely and effectively (Lin et al., 2018).

The current carbon sink trading mechanism develops slowly, owing to a lack of institutional guarantee and process supervision. Problems within the trade must be solved first, such as the unclear definition of property rights, inconsistent measurement standards of carbon fixation (Ahmed et al., 2017), and difficulty in determining the amount of compensation. It is particularly important to reasonably evaluate the values of carbon fixation and other ecosystem services of mangroves. Fortunately, the first blue carbon trading project in China, the Zhanjiang Mangrove Afforestation Project in Zhanjiang, Guangdong Province, was registered successfully in April 2021. This has set a positive example for achieving carbon peaks and carbon neutrality.

5 Conclusion and suggestions

In the present study, the monetary values of the Chinese mangrove ecosystem services in 2001, 2013, and 2019 were estimated and the change characteristics of the values were discussed first. Significant changes were found in the areas and ecological values of mangroves in China at the three time nodes of 2001, 2013 and 2019. Mangrove area increased during 2001–2013 and decreased during 2013–2019. It was demonstrated that the task of protecting mangrove resources in China is still arduous. Although the area of mangroves in 2019 was less than that in 2013, its ecological value was higher than that in 2013, indicating that with the development of the marine economy, the role of mangroves in China is becoming more and more significant. Among the nine mangrove ecosystem service functions, the three functions, namely, preventing coastal erosion, raw material supply, and regulating water resources, accounted for relatively high monetary values, which were considered as the core service functions of China's mangrove ecosystem. Especially, the service function of regulating climate and maintaining air quality of mangroves has become an important part of the blue carbon ecosystem. In order to realize the sustainable development of mangrove ecosystem and maximize its service value, the evaluation results were creatively applied in three aspects: mangrove asset management with balance sheets, ecological compensation standard determination, and carbon in blue carbon sink.

An adequate understanding of the functions and values of the mangrove ecosystem services is a prerequisite for the rational management of the mangroves to realize the sustainable output of ecological value. Based on the above investigation, the following suggestions and measures for the protection and restoration of mangrove ecosystems were proposed:

1) The management of mangrove reserves should be strengthened. Based on the principle of the integrity of mangrove ecosystem, the protected area should not only be limited to mangrove forest lands, but also include beaches, suitable forest lands, and rare and endangered animals and plants around mangroves. Environmental pollution and other destructive activities must be rectified, especially the sewage discharge at the estuary of mangrove wetland, and the pollution of mariculture.
2) A mangrove resources investigation network and monitoring system should be constructed. The data statistics of mangrove resources must also be vigorously promoted to provide original data for the preparation of mangrove resources balance sheet. According to the characteristics and restoration process of mangrove resources, the preparation of mangrove resources balance sheet should be continuously updated. The accounting results of the balance sheet should be applied as soon as possible to the asset management of forest resources and the outgoing audit of leading cadres, so as to realize the orderly and effective management of mangrove resources.
3) The overall restoration of mangrove ecosystem should be actively promoted. In view of the advantages of restoring mangrove ecosystem in China, the implementation of mangrove ecological compensation policy should be accelerated, such as "returning ponds to mangroves". On the premise of comprehensively considering the natural geographical and economic conditions of the restoration area, it is necessary to replace the previous restoration approach dominated by vegetation restoration with the approach dominated by promoting the comprehensive restoration of the ecosystem. At the same time, based on the research on basic theories, technologies, standards, and cases of "returning ponds to mangroves", the sources of compensation should be broadened through multiple channels to solve the problems of a job transfer and employment of farmers by local government.
4) The trading system of mangrove carbon sink market should be continuously improved. It is suggested to take Zhanjiang Mangrove Afforestation Project in Guangdong Province as a pilot to further promote the construction of blue carbon trading market. The mangrove carbon sink cycle mechanism should be continuously improved to help China realize its commitments to "carbon peak" and "carbon neutralization".

It could be expected that the statistical data will be more complete with the continuous advance of the national wetland resources survey and the continuous improvement of technology in the future. The mangrove ecosystem service value assessment could be conducted more accurately according to the ecological conditions and species types of mangrove ecosystems in different regions. And the mangrove ecosystem could create more new values through the application of value evaluation.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

C-YL: idea, design, conceptualization, formal analysis, data curation, writing—original draft; C-YF: methodology, data curation, writing—original draft; YL: formal analysis, visualization, writing—review and editing; M-QZ: methodology, data curation, visualization; YL: methodology, visualization, writing—review and editing; W-YW: formal analysis, visualization, writing—review and editing. L-XW: formal analysis, visualization, writing—review and editing; X-HL: design, conceptualization, writing—review and editing, supervision; X-MF: idea, design, conceptualization, methodology, validation, writing—review and editing, supervision, funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1018801/full#supplementary-material

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