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Ecosystem service valuation of bays in East China Sea and its response to sea reclamation activities

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Abstract: Ecosystem service values (ESVs) of bays and their response to sea reclamation are of great practical importance for forming bay eco-compensation policy and extension of blue economic space. Based on land use information of bays collected during the period of 1990–2015, the spatiotemporal evolution of ESVs of 12 main bays in East China Sea and their response to sea reclamation activities over the past 25 years were quantitatively analyzed. The analysis results indicate that ESVs of bays in East China Sea showed a continuous downward trend and the whole ecosystem was continuously degraded, in which the degradation degree of ESV in the southern bays was higher than that in the northern bays. Spatial zoning of ESVs of bays in East China Sea was remarkable, showing a continuous downward trend from low-value to high-value zone. Spatial variation of ESVs of each bay was also significant, expanding from a city and from inland to the coast, which suggests that human activities, mainly reclamation, have become main agents for ESV evolution of bays in East China Sea. ESVs of bays have a significant response to sea reclamation, manifested as a significant negative correlation between ESV and reclamation intensity. The correlation in the southern bays was stronger than that in the northern bays, which was caused by different effects of sea reclamation modes on ESV evolution of muddy and bedrock bays. A negative effect of sea reclamation activities on bay ecosystem was hysteretic. Therefore, an attention should be paid to dynamic monitoring and early warning of development status in offshore areas, ecosystem-level reclamation control policy, and coastal wetland reserves planning. Moreover, the spatial coupling mechanism study between bay ecosystem service demand and its service supply capacity should be strengthened to realize systematic regulation of bay ecological security pattern.

Keywords: reclamation; ecosystem service value; correlation analysis; bay; East China Sea

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1 Introduction

As a sea area that goes deep in the land to form an obvious water bend, the bay is an important constituent part of ocean (Xia and Liu, 1990). Development and management of bays is a focus of comprehensive management and development of coastal states and regional coastal zones (Komar, 2010). Since the beginning of the 21st century, the rapid industrialization and urbanization in China has produced a sharp contradiction of land use in coastal areas, which is an important factor restricting its sustainable economic development (Zhang, 2012). In order to alleviate the contradiction between supply and demand of land resources and extend the development space, the sea reclamation has become a main form of coastal bay development (Wang *et al.*, 2015) for enormous socio-economic interests; meanwhile, the form has given rise to many ecological impacts (Moromachi *et al.*, 2008; Li *et al.*, 2019). Sea reclamation activities could occupy mudflat, wetlands and sea, usually resulting in a change of the natural property of a bay ecosystem and a decline or even disappearance of ecosystem services. Therefore, relevant investigations on the impact of sea reclamation projects on bay eco-environment have attracted continuous attention from scholars at home and abroad, such as, changing the hydrodynamic conditions in offshore areas, degrading biodiversity in the sea area (Akpinar and Komurcu, 2013), degrading ecosystem service functions like habitat, production and regulation of a bay ecosystem and seriously damaging ecological balance in bays (Jin *et al.*, 2016; Tian *et al.*, 2016; Xu *et al.*, 2018).

Even though China has formulated the policy of compensable use of sea reclamation, the economic outcome of sea reclamation is first evaluated while the ecosystem service value loss is often neglected. A study on a relationship between sea reclamation activities and ESVs in bays enables people to rethink and weigh the pros and cons of sea reclamation, minimizes the loss of ecological service value, strengthens comprehensive bay management based on ecosystem level and maintains regional ecological security of the bays. Currently, scholars in the world have conducted many studies regarding ecosystem service supply and its response to human activities, and thus this has become one of critical research hotspots related to regional ecological security pattern coupling ecological services (Pataki *et al.*, 2011; Zhang *et al.*, 2017), which focus on the evolution of coastal ecosystem and human-environment interaction under the effect of human activities (Li *et al.*, 2017; Li *et al.*, 2018a). Therefore, evaluating the response of ESVs of the bays to sea reclamation activities has become an important method of studying regional ecological security, such as, establishing an evaluation model of ecological value loss caused by sea reclamation (Peng *et al.*, 2005), ecosystem service evaluation based on land use information (Gomes Lopes *et al.*, 2015), and eco-compensation formulation based on ecosystem value evaluation (Bennett *et al.*, 2018). Most of the present studies on the relationship between ecosystem service in bays and sea reclamation concentrate on individual bays (Jiang *et al.*, 2017; Carrilho and de Almeida Sinisgalli, 2018), islands (Zhao *et al.*, 2004; Chee *et al.*, 2017) or costal zones (Luisetti *et al.*, 2014; Cao *et al.*, 2018) but few studies have focused on a macro perspective of sea area, which usually covers a larger natural region. Furthermore, prior research has scarcely combined macro with micro perspectives, so it’s difficult to provide systematic and scientific opinions for reasonable development of large-scale sea area and marine eco-compensation formulation for reference.

East China Sea is the area with rapid economic growth and the fastest urbanization progress and a key area for extension of blue economic space, in which human economic activities are intensive. There are significant differences in bay types, coastal natural properties, socio-economic development status and sea reclamation modes. Therefore, evaluating service values of different bay ecosystems under the effect of sea reclamation can complement relevant research on ecological evaluations in bays. Based on land use information over the 25 years, this study selected main bays in East China Sea, and quantitatively analyzed the spatiotemporal evolution of ESVs of the bays and their response to sea reclamation intensity, expecting to provide a scientific support for reasonable development of bay resources in East China Sea, eco-compensation formulation and decision making for bay protection.

2 Data and methodology

2.1 Study area

The shoreline of the sea area under the jurisdiction of East China Sea is long, and bay types are abundant. East China Sea is the sea area with the largest number of bays in China, having abundant biological, islands and reef sand landscape resources and evident regional advantages. As one of the important sea areas in China's ecological civilization and marine reserve construction (Ding *et al.*, 2008), it is most significantly affected by human activities. The East China Sea area was selected as the study area, which was divided into two regions according to shoreline property (EBCBS, 1993) in combination with administrative division: bays in northern region (northern bays) and bays in southern region (southern bays) in East China Sea. Taking the area >100 km^2 as a criterion, there were 12 main bays selected (Figure 1). There are many silty shorelines in the northern bays with broad area of mudflat, including Hangzhou Bay, Xiangshan Harbor, Sanmen Bay, Taizhou Bay, Yueqing Bay and Wenzhou Bay in Zhejiang Province and Shanghai. In the southern bays there are mostly bedrock shorelines, including Sansha Bay, Luoyuan Bay, Xinghua Bay, Meizhou Bay, Quanzhou Bay and Xiamen Bay in Fujian Province.

2.2 Datasets and preprocessing

Land use data in this study were obtained from national geographical status monitoring cloud platform (http://www.dsac.cn/), namely, 1:100,000 land use maps compiled for the six years – 1990, 1995, 2000, 2005, 2010 and 2015 in Shanghai, Zhejiang and Fujian. The data were clipped for the study area with the extracted bay boundaries. By referring to the remote sensing images, the land use data were interpreted and corrected by visual interpretation. In order to ensure accurate interpretation, checking points were set in each land use map. Based on the verification result created with the checking points, the interpretation accuracy exceeded 85%, which could satisfy the research demand. The data also included DEM data at 30 m spatial resolution (provided by geographical spatial data cloud for free) of shorelines in East China Sea in 2015. The bay range was determined by referring to *Annals of Chinese Estuaries* (EBCBS, 1993), which clearly defines the boundary of the bay to the sea side, the connection between the two corresponding headlands of the bay mouth. Based on the definition coupled with the geographical longitude and latitude coordinates of the bay boundary

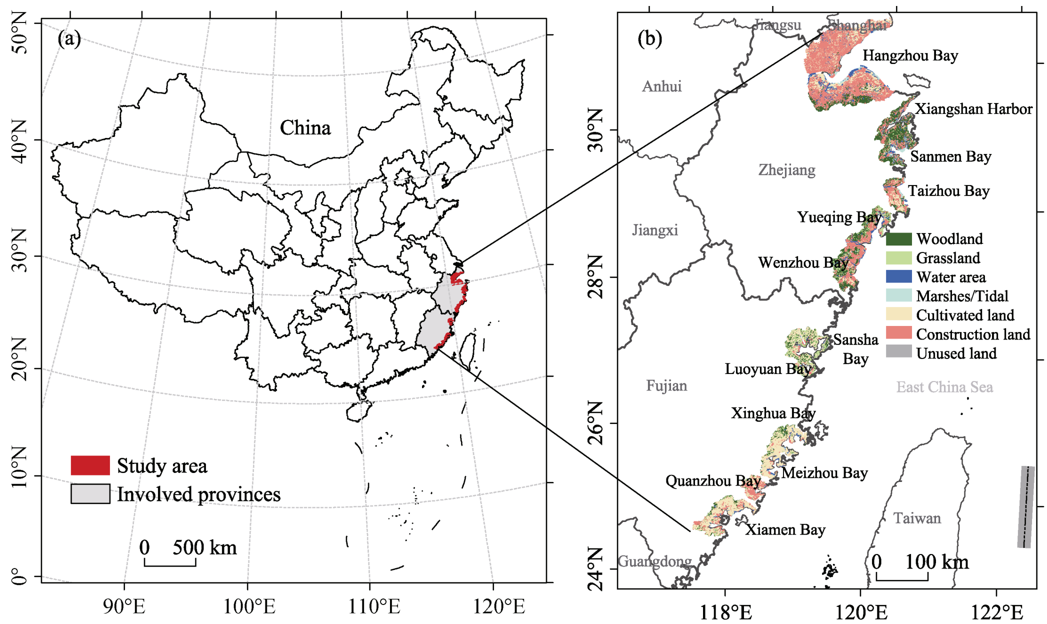

Figure 1 Geographic location of the study area (a) and distribution of land-use types in 2015 (b)

provided from the *Annals of Chinese Estuaries* and the bay literature related to the East China Sea, seaward boundaries of the bays were defined. The boundary of a drainage basin where the land part around a bay was taken as land boundary line at the landward side. Although mean springs high-water lines have been extensively applied to the extraction of natural shorelines (Boak and Turner, 2005), in this study, the extraction of shoreline information was based on Landsat TM/OLI images by using a threshold value method (Li *et al.*, 2009), combined with shoreline interpretation signs (Li *et al.*, 2018b), followed by local correction according to field survey data. Finally, the coastline location and type information in the study area for the six years was obtained. After the study area was clipped based on the defined bay range, the bay landscape data in East China Sea were obtained. Combined with the actual land use status in coastal bays of East China Sea and research requirements, the landscapes in the study area were divided into seven types: cultivated land, construction land, water area, wetland, forest, grassland and unused land (Tian *et al.*, 2019b). Food crop data came from *2016 Zhejiang Statistical Yearbook*, *2016 Fujian Statistical Yearbook*, *2016 Shanghai Statistical Yearbook* and *Cost-Benefit Data Compilation of National Agricultural Products*, which would be used for a correction of unit table of ESVs.

2.3 Ecosystem service classification and value evaluation method

There is still a divergence in the ecosystem service classification, and indicator systems and methods for quantitative evaluation of ESVs are still not unified in China (Xie *et al.*, 2015; Fu *et al.*, 2017). Therefore, this study borrowed the indicator systems and evaluation methods extensively recognized and popularly used in China. Referring to the framework proposed by *Millennium Ecosystem Assessment* (MA) (MEAB, 2005) and combining engineering features of reclamation, four overall indicators – supply service, regulating service, supporting service and cultural service – and nine sub-indicators were screened out by using frequency analysis method to analyze and screen indicators with high frequency of application in relevant studies at home and abroad (Costanza *et al.*, 1997; Xie *et al.*, 2008; Jiang *et al.*, 2017), and thus the evaluation index system of ESV of the bays was constructed.

Equivalent weight factor method was used as the ESV evaluation method based on different land use types in this study area. In order to improve the accuracy of evaluation results, this study used the research results of Costanza *et al.* (1997), Su (2015) and Xie *et al.* (2008, 2015) as references. On the basis of the ESV basic equivalence tables amended by predecessors, the food crop data in Zhejiang, Fujian, and Shanghai were used to amend the standard unit ESV equivalence factors of bays in East China Sea. The amendment method was that average food crop yields in Zhejiang, Fujian and Shanghai in 2015 were taken as a benchmark per unit area, and then according to average yields of food crops like rice and wheat in these provinces and city, economic value of food crops in farmlands in bays in East China Sea was calculated as about RMB 219327.47/km^2 as the economic value of single ESV equivalent weights of ecosystem in this study. Therefore, ESVs per unit area in various land-use types in bays in East China Sea were calculated on this basis (Table 1), and then the calculation model of ESVs in the study area over years was shown as follows:

$$V = \sum_{i=1}^{n} S_i \times V_i \tag{1}$$

where V is the total ESV of bays in East China Sea (RMB); S_i is the area of land type i in the bays in East China Sea (km^2); V_i is the ESV of land type i per unit area of the bays in East China Sea (RMB/km^2).

Table 1 Ecosystem service value coefficient (10^4 RMB/km^2/yr)

Ecosystem classification		Supply service		Regulating service				Supporting service		Cultural service	
Eco-system types	Correspond-ing land types	Food pro-duction	Raw mate-rial pro-duction	Gas regu-lation	Climate regula-tion	Hydro-logical regula-tion	Envi-ronment purifica-tion	Soil conserv ation	Bio-diversity mainte-nance	Aesthetic land-scape	Total
Forest	Woodland	20.40	59.88	14.26	67.99	51.76	39.04	194.33	83.35	39.48	570.48
Grass-land	Grassland	26.98	4.17	6.36	25.00	4.17	35.09	52.86	78.96	7.90	241.48
Waters	Waters	16.89	2.41	1.32	14.91	2697.32	2.19	4.83	19.08	87.07	2846.03
Wetland	Marshes/ Tidal flat/ Mangrove forests	6.58	1.54	39.48	375.05	339.96	398.74	37.51	54.83	121.73	1375.42
Desert/ bare land	Unused land	0.00	0.22	3.73	2.63	0.00	0.22	0.00	1.54	0.44	8.77
Farm-land	Cultivated land	21.93	2.19	2.85	21.93	2.85	3.73	37.29	21.93	1.32	116.02

2.4 Sea reclamation intensity and classification

Sea reclamation intensity index, which is defined as a sea reclamation area per unit length of coastline (Fu *et al.*, 2010), can quantitatively reflect scale and intensity of sea reclamation and be used to investigate the association of sea reclamation activities with ESV. It can be expressed in the following formula:

$$PD = S / L \tag{2}$$

where *PD* is the sea reclamation intensity index; *S* is the cumulative sea reclamation area in the study area (hm^2); *L* is the total length of shorelines within benchmark years in the study area (km). The sea reclamation area refers to the total area of other land-use types that have been transformed from the original natural ecosystems such as the ocean and tidal flat to other artificial construction areas such as reclamation pond, port wharf and protective embankment during the research period. Opinions and research results of multidisciplinary experts were used to classify sea reclamation intensity grades and effects of the corresponding sea reclamation pressure were summarized in Table 2 (Fu *et al.*, 2010). In addition, Pearson correlation coefficient was utilized to analyze the correlation between sea reclamation intensity and ESV (Fu *et al.*, 2010). When the correlation coefficient value is closer to 1, the correlation between the two variables is stronger.

Table 2 Intensity grades of sea reclamation

PD value (hm^2/km)	Strength grade	Meaning
0≤PD<10	Grade 1	Sea reclamation pressure is light and development potential is great.
10≤PD<20	Grade 2	Sea reclamation pressure is low with a certain development potential.
20≤PD<50	Grade 3	Certain sea reclamation pressure exists with a certain effect on the subsequent development.
50≤PD<100	Grade 4	Sea reclamation pressure is strong and attention should be paid to conservation and intensive use of sea reclamation areas.
PD≥100	Grade 5	Sea reclamation pressure is very strong. No new sea reclamation projects should be added, and when necessary, it can be conducted based on the existing sea reclamation projects.

3 Results and Analysis

3.1 Spatiotemporal evolution of ESVs of bays in East China Sea under the effect of sea reclamation

3.1.1 Temporal change of ESVs

In general, ESVs of the bays in East China Sea presented a declining tendency during the period of 1990–2015, cumulatively by RMB 156.20×10^8 with a change rate reaching 12.30%, indicating that the whole ecosystem in East China Sea was continuously degraded over the 25 years. The ESV showed a slight increase before 2000, a total increase of 0.97%, and then, it showed a significant decrease, which embodied instability of bay ecosystem in East China Sea under human interference to a certain degree (Table 3).

From the southern and northern bays in East China Sea, the ESV in the northern bays firstly increased and then declined, it was elevated during the period of 1990–2000 to a great extent, reaching 4.60%, and then the increase slowed down and eventually showed a downward trend (Table 3). The ESV increased at the early phase mainly because water bodies in the northern bays presented a continuous increasing tendency before 2010, and the water bodies existed mainly in two forms: aquaculture water area increased after mudflat reclamation and water area formed within a certain period after sea reclamation; they had the highest service value in the bay ecosystem, and as a result, the ESV in the northern bays in East China Sea continuously increased. However, the ESV of the southern bays in East China Sea continued to decline, and the decrease rate continued to increase, and the overall rate of change was as high as 20.22%, which was much higher than that of the northern bays. This was mainly because the southern bays in East China Sea were mainly distributed on bedrock coasts, and reclamation activities were mainly dominated by the formation of sea reclamation land. This directly caused the bay area to be changed from land types with high ecosystem service function (water body, wetlands) into land types with low ecosystem service function (construction land, cultivated land), and the ESV in the southern bays continuously dropped.

Table 3 Dynamic change of ESV of the northern / southern bays in East China Sea

ESV (10^8 RMB)	1990	1995	2000	2005	2010	2015	1990–2000		2000–2010		1990–2015	
							Variation (10^8 RMB)	Rate of change (%)	Variation (10^8 RMB)	Rate of change (%)	Variation (10^8 RMB)	Rate of change (%)
Northern bays in East China Sea	781.83	790.23	817.79	822.74	834.80	724.35	35.96	4.60	17.01	2.08	–57.49	–7.35
Southern bays in East China Sea	488.21	488.16	464.62	456.44	429.47	389.50	–23.59	–4.83	–35.15	–7.57	–98.71	–20.22
Total	1270.04	1278.38	1282.41	1279.17	1264.27	1113.84	12.37	0.97	–18.14	–1.41	–156.20	–12.30

From the perspective of various bays in East China Sea, during the period of 1990–2015, the ESVs of other bays declined to varying degrees, except for the increase of ESV in Yueqing Bay (Figures 2 and 3). (1) The main cause for increasing ESV in Yueqing Bay was sharp rise of water body ecosystem, and value change rate of the water body reached as high as 288.28% during the 25 years; the increase of water value was mainly derived from mudflat reclamation and sea reclamation activities around Yueqing Bay, and, as a result, aquaculture land area was enlarged by a large margin and regional ESV was increased finally. (2) The largest decrease in value was in Xinghua Bay, with a cumulative decrease of RMB 34.63×10^8 during this period, and change rate was 28.79%. During the period 1995–2000, there were seawall construction and land reclamation in Xinghua Bay. Water and wetland reduction caused by sea reclamation was the main cause for a rapid ESV decrease in Xinghua Bay. (3) The minimum value decrement was in Xiangshan Harbor, a total of RMB 0.36×10^8, with a change rate of only –0.47%, and during the whole period, value change of Xiangshan Harbor was relatively stable, mainly because the internal environment of Xiangshan Harbor was stable, and, meanwhile, Xiangshan Harbor had ecological protection restrictions for development, so that there was almost no change in ESV. (4) The bay with the highest ESV was Hangzhou Bay. Before 2000, the total ESV in Hangzhou Bay presented a rising tendency and then gradually declined, which was related to enhanced bay development and utilization intensity and large increment of sea reclamation scale and intensity in Hangzhou Bay. At the early stage of the study, due to the large demand for urbanization development in Hangzhou Bay, a large number of reclamation activities were implemented, which caused abrupt shrinkage of mudflat wetland area and rapid expansion of water areas like aquaculture land area, but at the late construction phase, wetland and water body were gradually transformed into construction land, which then gave rise to gradual ESV decline of Hangzhou Bay. (5) ESV fluctuation of Taizhou Bay was the maximum, showing a trend of large increase then rapid decrease. At south and north shores of Taizhou Bay there were abundant mudflat resources, and early sea use was dominated by aquaculture. Before 2010, sea reclamation land in Taizhou Bay was mainly used for mudflat aquaculture and harbor construction, resulting in a decrease of wetland value and an increase of water value. At the late stage, sea reclamation mode transformed from sea reclamation aquaculture into industrial sea reclamation, resulting in a rapid reduction of ESV in Hangzhou Bay.

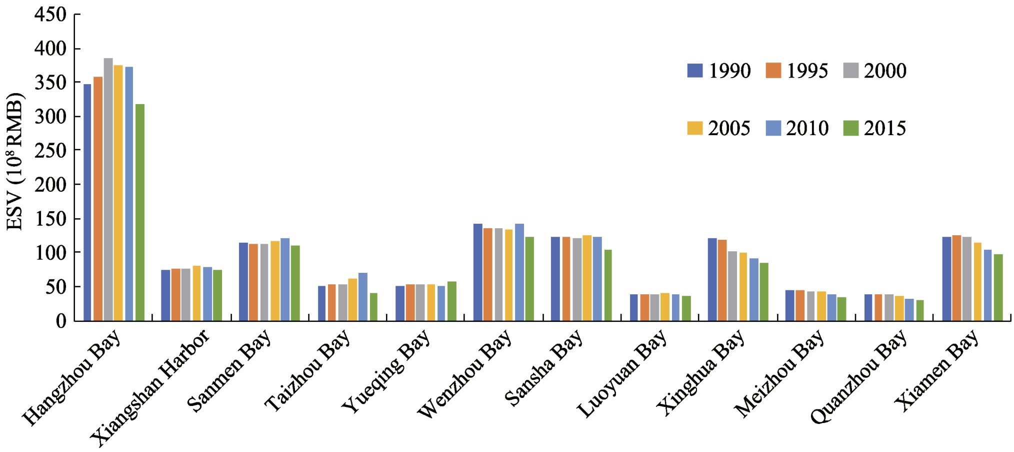

Figure 2 ESVs in the bays in East China Sea during the period 1990–2015

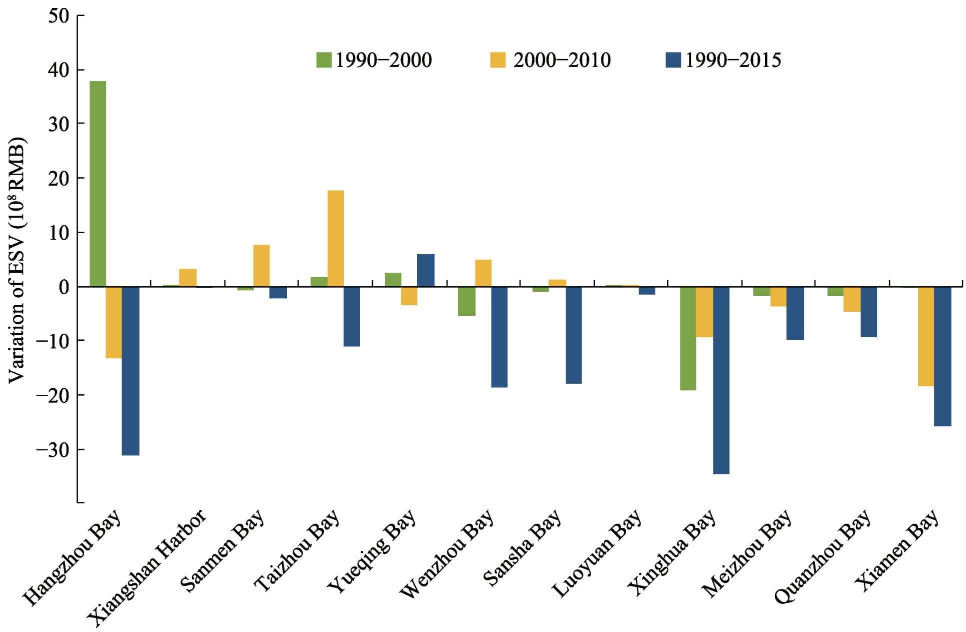

Figure 3 The variation of ESVs in the bays in East China Sea during the period 1990–2015

3.1.2 ESV changes of various ecosystem types

Land use change is the main cause of ESVs changes. During the 25 years, the areas of grassland, wetland, unused land and cultivated land in the bays in East China Sea decreased, among which wetland and cultivated land showed a significant downward trend, decreasing by 1082.84 km^2 and 2609.90 km^2, respectively, while waters increased by 223.96 km^2. The land use change in the northern bays in East China Sea was basically consistent with the study area as a whole. The area of waters and grassland increased by 413.37 km^2 and 21.88 km^2, respectively. Among them, the increased area of waters was the largest. While the area of wetland, cultivated land, forest land and unused land decreased, the wetland decreased the most, reaching 1035.97 km^2. However, the land use change in the southern bays in East China Sea is different from that in the northern. As the areas of waters, wetlands, cultivated land and grassland decreased, the decrease range of waters and wetland was the largest, decreasing by 189.4 km^2 and 46.87 km^2, respectively, followed by cultivated land, while forest land slightly increased.

In bay ecosystems in East China Sea, except for water body and forest land, overall ESV of other ecosystem types showed a downward trend. Among them, service values of water body and wetland fluctuated most remarkably. The maximum ESV increment during the 25 years was water ecosystem, with cumulative increment of RMB 70.87×10^8 and change rate of 19.96%. The maximum ESV decrement was wetland ecosystem, with cumulative loss of RMB 196.09×10^8 and reduction rate of 72.29%, followed by farmland ecosystem, with cumulative loss of RMB 31.36×10^8 (Table 4). Significant ESV changes of wetland and water body were mainly due to large-area mudflat reclamation and sea reclamation in bays in East China Sea during the development and construction processes, which directly led to the continuous and rapid reduction of coastal mudflat wetland resources and reduction of wetland ESV. Some of the newly added water body was transformed into aquaculture land with a

Table 4 Changes of ESV of various ecosystems in the bays in East China Sea

	Ecosystem types	1990	1995	2000	2005	2010	2015	Variation (10^8 RMB)	Rate of change (%)
Northern bays	Forest	270.45	275.50	275.01	273.00	270.10	269.54	–0.91	–0.34
	Grassland	8.94	8.73	9.28	9.18	9.30	9.84	0.90	10.07
	Waters	179.63	206.90	254.04	301.36	375.24	296.27	116.64	64.94
	Wetland	201.55	182.73	162.19	132.72	77.95	49.22	–152.33	–75.58
	Desert/bare land	0.00	0.01	0.00	0.00	0.00	0.00	0.00	–54.53
	Farmland	121.25	116.35	117.27	106.47	102.19	99.47	–21.78	–17.96
	Total	781.83	790.23	817.78	822.74	834.80	724.35	–57.48	–7.35
Southern bays	Forest	182.96	185.68	187.02	186.21	184.78	185.03	2.07	1.13
	Grassland	22.30	21.63	21.78	20.66	20.65	20.64	–1.66	–7.44
	Waters	175.49	182.94	160.74	171.54	159.85	129.72	–45.77	–26.08
	Wetland	69.72	61.46	58.33	45.27	33.19	25.96	–43.76	–62.77
	Desert/bare land	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
	Farmland	37.71	36.44	36.75	32.76	30.99	28.14	–9.57	–25.38
	Total	488.21	488.15	464.61	456.44	429.46	389.48	–98.73	–20.22
Total	Forest	453.41	461.18	462.03	459.21	454.88	454.57	1.16	0.26
	Grassland	31.24	30.36	31.06	29.84	29.95	30.48	–0.76	–2.43
	Waters	355.12	389.84	414.78	472.90	535.09	425.99	70.87	19.96
	Wetland	271.27	244.19	220.52	177.99	111.14	75.18	–196.09	–72.29
	Desert/bare land	0.01	0.02	0.01	0.01	0.01	0.01	0.00	–8.33
	Farmland	158.96	152.79	154.02	139.23	133.18	127.61	–31.35	–19.72
	Total	1270.04	1278.38	1282.39	1279.18	1264.26	1113.83	–156.21	–12.30

greater economic benefit, and the rest existed in the form of reclaimed ponds after sea reclamation within a short time; consequently, water ESV was increased significantly in a certain period, but it was only initial morphology of sea reclamation projects and was further transformed into construction land due to the demand for urban development (Jiang *et al.*, 2017). It may lead to a significant reduction of bay ESVs in East China Sea after the study period.

ESV changes of various ecosystem types in the northern bays were consistent with those in East China Sea, mainly because the northern bays accounted for a large proportion in the study area, and their ESV changes would generate a significant effect on overall ESV in East China Sea. During the 25 years, ESVs of water body and grassland in the northern bays increased somehow, while those of wetland, farmland and forest land were reduced. The ESV increment of water body was the maximum, with a change rate of 64.94%. In the northern bays in East China Sea there were mostly silty shorelines with broad mudflat area, so the main sea reclamation mode was mudflat reclamation. During the study period, sea reclamation activities were in full swing in the northern bays, so as to form large-area reclaimed pond water, leading to a large increment of ESV of water body. During the sea reclamation process, mudflat wetland was reclaimed in quantity as the most available land resource, resulting in that wetland area was rapidly reduced and thus ESV was markedly reduced.

ESV change features of various ecosystem types in the southern bays in East China Sea were different from those in the northern bays, manifested by reduction of ESVs of water body, wetland, farmland and grassland as well as small increment of forest land ESV. During the period of 1990–2015, water body presented a significant fluctuating tendency with alternation of increase and decrease, but wetland was displayed as a continuous declining tendency. In the southern bays in East China Sea were mostly bedrock coasts, and mudflat siltation existed only on partial silty coasts, so the main sea reclamation form in the southern bays in East China Sea was sea reclamation, accompanied by reclamation of a small quantity of mudflats, which led to a large number of wetlands and water bodies converted into construction land, and consequently this was a main cause for reduction of water and wetland values.

3.1.3 Spatial variation and evolution of ESVs

Interpolation and simulation were carried out via Kringing method by constructing a 1.5 km ×1.5 km fishing net. ESVs were uniformly divided (unit: RMB 10^4/km^2) into five levels: low (ESV<200), relatively low (200≤ESV<400), medium (400≤ESV<800), relatively high (800≤ESV<1300) and high (ESV>1300), and ESV spatial variation graphs in East China Sea during different periods of 1990-2015 were obtained (Figures 4 and 5).

Spatial zoning of ESVs of the bays in East China Sea was remarkable, which clearly indicates spatial variation of ESV in various bays. Low-ESV area was expanded, showing the expansion from low-value area to high-value area and outward from cities and from inland towards coastal areas. High-ESV areas were mainly distributed in offshore areas in the bays while low-value areas were mainly distributed in areas with extensive distribution of construction land and cultivated land (Figures 4 and 5). During the 25 years, the areas where ESVs experienced significant changes were generally centralized at sea-land borders, and these areas were usually replaced by low-ESV areas from high-ESV areas and relatively high-ESV areas. The high-ESV areas were mainly distributed in areas with surface features like water bodies and wetlands. Due to the regional development needs of coastal areas, coastal water bodies and wetlands were occupied in quantity and they were gradually transformed into construction land, aquaculture land and cultivated land, and this was the primary cause for ESV reduction in high-value areas. This common phenomenon further indicated that since 1990, sea reclamation-centered human activities had been the main agents for ESV evolution in the bays in East China Sea, and their influence degree was much higher than the effect of natural agents on bay ecosystems.

Among the northern bays in East China Sea, ESV spatial variation and evolution in Hangzhou Bay and Taizhou Bay went through significant changes, followed by Wenzhou Bay, while the ESV of Xiangshan Harbor had the lowest change and the smallest overall difference (Figure 4). This was because terrain in Hangzhou Bay and Taizhou Bay was flat, with many cultivated lands but few mountainous areas, and there were a large number of silty coasts. These bays were developed very early and belonged to the most developed areas among the northern bays in East China Sea with a stronger disturbance degree from human activities, where large-area sea reclamation activities existed. This was the main reason for the significant spatial evolution of ESV in Hangzhou Bay and Taizhou Bay. However, Xiangshan Harbor had zigzag coasts, scarce back silting and large relief amplitude; regional economic development was restricted by ecological protection; reclamation almost didn't take place. This was the reason why overall ESV was kept relatively stable in Xiangshan Harbor.

In the southern bays in East China Sea, ESV of Xinghua Bay presented a most significant declining tendency, followed by Meizhou Bay, Quanzhou Bay and Xiamen Bay, but ESVs of Sansha Bay and Luoyuan Bay were stable only with a small decrease amplitude (Figure 5). There were many water bodies in the northeast of Xinghua Bay in 1990, mainly being high-ESV values. Jiangyin Island and land were connected into Jiangjin Peninsula during the 25 years with a large reduction amplitude of water area, and sea reclamation intensity of the peninsula was enlarged, and as a result, high-ESV value areas were gradually transformed into low-value and relatively low-value areas. Meizhou Bay, Quanzhou Bay and

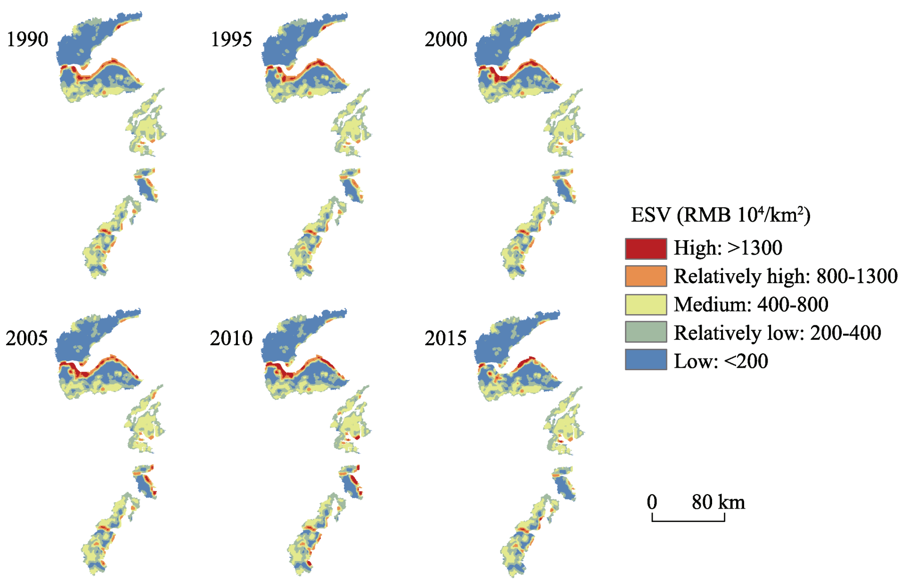

Figure 4 The spatial differentiation of ESV in the northern bays in East China Sea

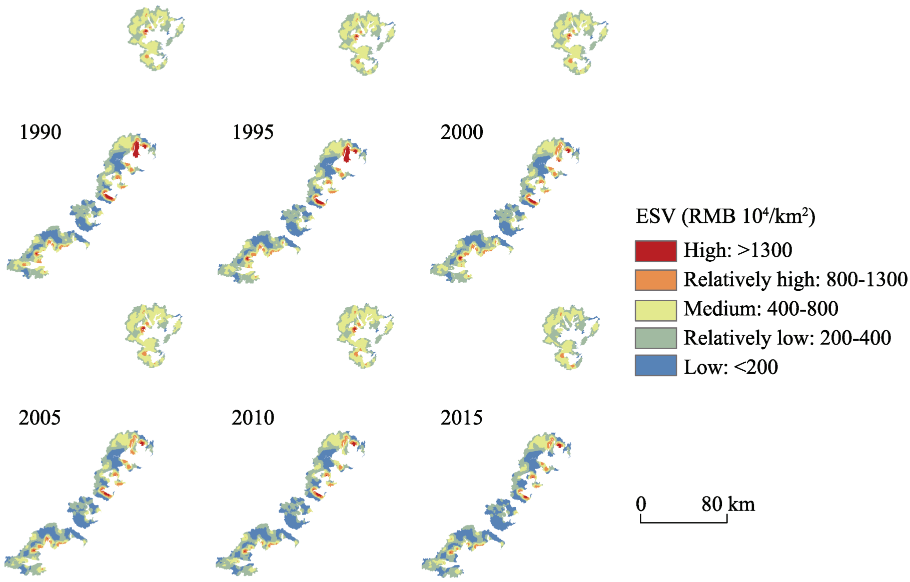

Figure 5 The spatial differentiation of ESV in the southern bays in East China Sea

Xiamen Bay were more economically developed and more affected by human interference. Most of these bays were bedrock coasts with regional development demand-oriented sea reclamation activities, there was a mudflat reclamation phenomenon in minority areas. Excessive human development activities constituted the decline of ESVs in these areas.

3.2 Correlation analysis between ESVs of the bays and sea reclamation intensity

3.2.1 Intensity change of sea reclamation activities in the bays

By analyzing changes in sea reclamation intensity index of bays in East China Sea, it is found that during the period of 1995-2015, sea reclamation intensity indicators of the bays in East China Sea were manifested as a continuous increasing tendency, meaning that with the rapid urbanization, sea reclamation intensity kept rising in all bays in East China Sea, and the area covered by sea reclamation activities was continuously expanded, which resulted in the overall sea reclamation scale in East China Sea (Table 5 and Figure 6). Among them, sea reclamation intensity in the northern bays in East China Sea was higher than that in the southern bays, and, meanwhile, the variable quantity of sea reclamation intensity was larger than that in the southern bays, indicating that, compared with the southern bays in East China Sea, both expansion scale and development intensity of sea reclamation activities were larger and higher in the northern bays.

Among the northern bays in East China Sea, except Xiangshan Harbor that was always beyond grade 2 sea reclamation intensity, the increment of sea reclamation intensity in Hangzhou Bay, Sanmen Bay, Taizhou Bay, Yueqing Bay and Wenzhou Bay was all greater than 20 hm^2/km. Those in Hangzhou Bay and Taizhou Bay even exceeded 140 hm^2/km, and sea reclamation intensity rose to grade 5, indicating that sea reclamation activities in the northern bays in East China Sea have caused a deep impact on the bay ecosystem, especially due to the pressure on resources and environment in the sea reclamation area. And sea reclamation intensity in Hangzhou Bay and Taizhou Bay already exceeded the maximum sea reclamation area which could be borne by the bay ecosystem, which would produce a severe impact on ecological health, and thus the implementation of sea reclamation projects should be strictly controlled.

Sea reclamation intensity in the southern bays in East China Sea presented a steady growth tendency, but the overall variable quantity of sea reclamation intensity was relatively small, in which the sea reclamation intensity in Quangzhou Bay was the minimum, stabilized within grade 1 interval of sea reclamation intensity with low sea reclamation pressure and large development potential. Sea reclamation intensity in Sansha Bay, Luoyuan Bay, Xinghua Bay, Meizhou Bay and Xiamen Bay was elevated to grade 3, indicating that these bays were already under a certain sea reclamation pressure, but the effect on the bay ecosystem was still within their bearing capacity. The coordination between ecological protection and development and construction in the bays should be kept so as to realize steady development in the bay ecosystem.

Table 5 The intensity grade of reclamation in the bays in East China Sea

Northern bays	Grade of reclamation intensity at early stage of study	Grade of reclamation intensity at late stage of study	Southern bays	Grade of reclamation intensity at early stage of study	Grade of reclamation intensity at late stage of study
Hangzhou Bay	Grade 3	Grade 5	Sansha Bay	Grade 2	Grade 3
Xiangshan Harbor	Grade 1	Grade 2	Luoyuan Bay	Grade 1	Grade 3
Sanmen Bay	Grade 1	Grade 3	Xinghua Bay	Grade 1	Grade 3
Taizhou Bay	Grade 1	Grade 5	Meizhou Bay	Grade 1	Grade 3
Yueqing Bay	Grade 1	Grade 3	Quanzhou Bay	Grade 1	Grade 1
Wenzhou Bay	Grade 1	Grade 4	Xiamen Bay	Grade 1	Grade 3

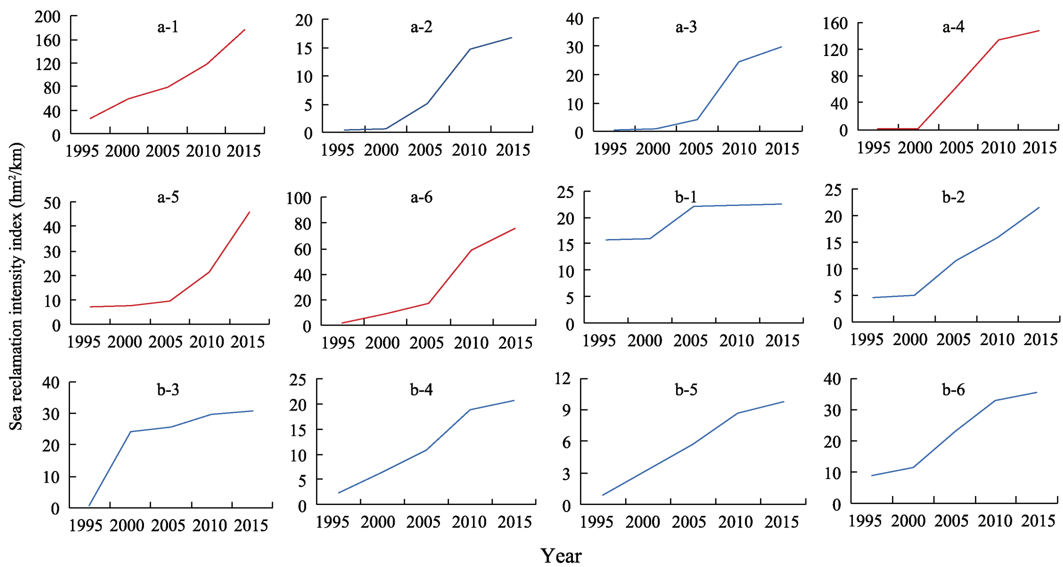

Figure 6 The change of the reclamation intensity in the bays in East China Sea (Note: a - Northern bays in East China Sea, and a – 1 to 6 are Hangzhou Bay, Xiangshan Harbor, Sanmen Bay, Taizhou Bay, Yueqing Bay and Wenzhou Bay in turn. b – Southern Bay in East China Sea, and b – 1 to 6 are Sansha Bay, Luoyuan Bay, Xinghua Bay, Meizhou Bay, Quanzhou Bay and Xiamen Bay in turn. The curves of the bays where sea reclamation intensity exceeded 40 hm^2/km were marked in red.)

In addition, following the year 2000, the sea reclamation intensity of most bays significantly elevated, and during this period, sea reclamation activities were more common in the bays. After 2015, sea reclamation activity intensity largely presented a gentle changing tendency, indicating that national and regional sea reclamation management and control measures had already taken place, and sea reclamation activities were effectively controlled and reduced in the bay areas. Sea reclamation activities were continuously expanded in bays in East China Sea, and sea reclamation intensity presented a rising tendency. In the meantime, during the whole study period, overall ESV in East China Sea was continuously reduced. According to our research findings, ESV and sea reclamation intensity presented a "wane and wax" tendency in East China Sea.

3.2.2 Response of ESVs of the bays to sea reclamation activities

For a further quantitative analysis of the response degree of ESVs of the bays to sea reclamation activities, scatter diagram of a relationship between sea reclamation intensity and ESV was drawn based on sea reclamation intensities in the bays in East China Sea during different time periods, and linear function curves were fitted using the least squares fitting method (Figures 7 and 8). R^2 is the Pearson correlation coefficient that is used to quantify the correlation between sea reclamation intensity and ESV. It could be seen from the fitting results that sea reclamation intensity largely showed a significant negative correlation with ESVs of the bays, namely the stronger the sea reclamation intensity, the lower the ESVs of the bays. The correlation between sea reclamation intensity and ESV was strong for the fitting results of the southern bays in East China Sea. Except the correlation coefficients for Sansha Bay and Luoyuan Bay that were partially low, those for other bays were all about 0.9, indicating that there existed an extremely significant linear correlation between the two variables. Compared with the southern bays, the correlation between sea reclamation intensity and ESV of the northern bays in East China Sea was weak, and only those for Xiangshan Harbor and Yueqing Bay were high.

The sea reclamation intensity showed a significant correlation with ESVs of the southern bays in East China Sea, which was related to the form of sea reclamation activities. In the southern bays were mostly bedrock shorelines; local sea reclamation activities were mainly land reclamation, and mudflat reclamation only occurred in small areas. Coastal water bodies or some mudflats were directly transformed into construction land through sea reclamation activities, which resulted in continuous drop of ESVs. However, due to high-intensity development and utilization in Fujian Province, the regional land use was in short supply. Therefore, regional development tended to demand land from the sea, which further promoted continuous implementation of sea reclamation activities. Thus, with the elevation of sea reclamation intensity, ESVs of the southern bays in East China Sea tended to continuously decline, which led to a significant correlation between the two variables. The correlation coefficient was partially low in Sansha Bay and Luoyuan Bay because topographic relief in the two bays was large, mainly being forest land, and regional ESV reduction was the main cause for transformation of forest land into construction land. Meanwhile, human development and construction in this area are relatively late, and the reclamation activities were not yet strong. Therefore, the correlation between ESV change and sea reclamation intensity was not significant in Sansha Bay and Luoyuan Bay.

The correlation between sea reclamation intensity and ESVs of the northern bays in East China Sea was generally low because there were mostly silty coasts. The main sea reclamation form was mudflat reclamation, namely converting coastal water bodies or wetlands into construction land, cultivated land or water body in reclaimed ponds, in which the last one was the existing form at the intermediate stage of sea reclamation process, and the service value of water body in the bay ecosystem was the highest, which directly led to elevated ESV within a certain period in the sea reclamation process. Afterwards, the sea reclamation area would be completely transformed into construction land, which would then cause declining tendency of ESV in this period. Therefore, the mudflat reclamation-centered sea reclamation form in the northern bays in East China Sea would result in alternate increasing and declining tendencies of ESVs of the bays, and this was the primary cause for weak correlation between sea reclamation intensity and ESVs of the northern bays in East China Sea.

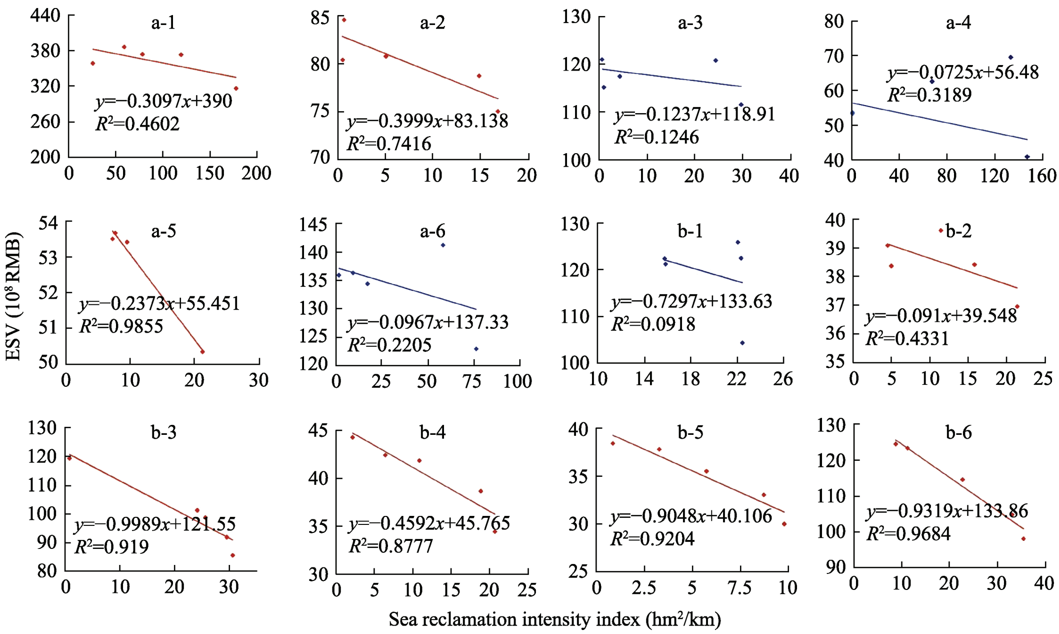

Figure 7 Relationship between sea reclamation intensity and ESV of the bays in East China Sea (Note: a - Northern bays in East China Sea, and a - 1 to 6 is Hangzhou Bay, Xiangshan Harbor, Sanmen Bay, Taizhou Bay, Yueqing Bay and Wenzhou Bay in turn. b - Southern bays of East China Sea, and b – 1 to 6 is Sansha Bay, Luoyuan Bay, Xinghua Bay, Meizhou Bay, Quanzhou Bay and Xiamen Bay in turn. Marked in red indicates high correlation.)

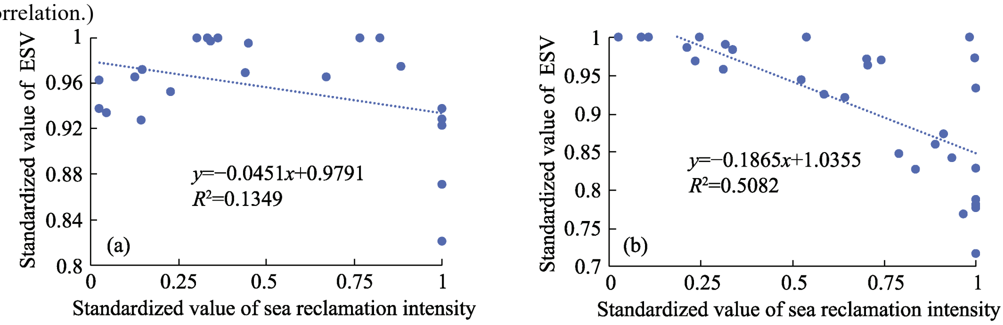

Figure 8 Correlations between sea reclamation intensity and ESV of the bays in East China Sea
(Note: a - Northern bays in East China Sea, b - Southern bays in East China Sea)

4 Discussion

4.1 Evolution differences of ESVs of the bays in East China Sea

During the study period, ESVs of the bay ecosystems in East China Sea went through obvious differential evolutions, which was closely related to different economic development patterns and land use modes in the bays. Increasing ESVs in Yueqing Bay was mainly ascribed to mudflat reclamation and land reclamation activities around the Bay so that the area of water bodies in aquaculture ponds was enlarged by a large margin. ESV reduction and the reduction rate were the maximum in Xinghua Bay because Fujian Jiangyin Island in Xinghua Bay was connected with the land to form Jiangyin Peninsula, which directly led to reducing ESVs of water bodies. In the study period, ESVs of Xiangshan Harbor changed little, mainly because Xiangshan Harbor was a long and narrow semi-closed bay with a stable internal environment, and thus the impact of natural forces on coast was small. Restricted by related planning and legal regulations like *Conservation Regulations on Marine Environment and Fishery Resources of Xiangshan Harbor in Ningbo* (Liu *et al.*, 2019), the development in Xiangshan Harbor was limited due to ecological protection. The urbanization development demand-oriented implementation with large-scale sea reclamation activities in Hangzhou Bay caused abrupt shrinkage of mudflat and grassland-centered wetland area and rapid expansion of water bodies like aquaculture land, and, finally, wetlands and water bodies were gradually transformed into construction land, which gave rise to gradual decline of service value of Hangzhou Bay. In addition, value of Taizhou Bay fluctuated by the largest margin. Along the south and north shores of Taizhou Bay there were abundant mudflat resources, and early-stage sea land utilization was mainly large-scale sea reclamation for aquaculture. Before 2010, sea reclamation area in Taizhou Bay was significantly enlarged and mainly used for mudflat aquaculture and harbor construction. After 2006, the construction of port industrial zone and port transportation developed rapidly at Jiaojiang estuary (Cai, 2011), gradually transformed from sea reclamation for aquaculture into industrial sea reclamation, and, as a result, water area formed by sea reclamation was gradually developed into construction land and ESV of Taizhou Bay was rapidly lowered.

4.2 Effects of different sea reclamation modes on ESV evolutions in silty and bedrock bays

In the study period, both the northern bays and southern bays in East China Sea were obviously different in ESV evolution features, which was caused by natural properties like coast type and hydrodynamic conditions (Li *et al.*, 2016; Chen *et al.*, 2017) and regional socio-economic development status in bays in East China Sea. Due to river sediment transportation and sedimentation in the northern bays, there were mostly silty shorelines with a broad mudflat area, high economic level and rapid urbanization development (Xu *et al.*, 2016). The disturbance caused by human activities especially sea reclamation activities to the area had far exceeded natural agents in recent years (Yu *et al.*, 2016). Interactive influence of multiple natural and social factors in the bays resulted in large-scale expansion of local land resources in the mudflat reclamation-centered sea reclamation mode in recent decades, and natural mudflat wetlands and shorelines were rapidly reduced. Mudflat reclamation in the northern bays included several different phases like reclamation area formation through diking, transformation into salt pan or aquaculture fishpond and transformation into construction lands like industrial, mining and transportation lands due to the latter land demand for urban construction (Jiang *et al.*, 2017). Different land utilization modes formed at different reclamation phases brought about rapid and staged evolution from protogenetic wetland and marine natural ecosystems into artificial ecosystem types like aquaculture pond and city, and, consequently, ESVs of the northern bays evolved accordingly. Shorelines stretched and zigzagged in the southern bays in East China Sea, most of which were bedrock shorelines with superior bay environment and developed bay economy, and their development speed and degree were both higher than those in inland. Based on natural factors like bay environment, sea reclamation mode in the southern bays in East China Sea was mainly sea reclamation, the reclamation for aquaculture existing at the initial phase to a certain degree, and after 2000, the main sea reclamation mode was commercial sea land utilization, namely coastal areas that were reclaimed and transformed into construction lands like ort and pier, industrial, mining and logistics lands (Chen *et al.*, 2018). Therefore, the transformation of land use mode caused by this sea reclamation form resulted in transformation of marine and wetland ecosystems into urban ecosystems in the southern bays (Hua *et al.*, 2018) and bays' ESVs were also evolved.

4.3 Hysteretic effect of sea reclamation activities on the bay ecosystems

From 1990 to 2015, sea reclamation intensity in the bays in East China Sea continued to increase, and their ESVs continued to decrease. The urbanization progress in the bays in East China Sea was abruptly accelerated, accompanied by continuous expansion of sea reclamation activities. Due to the lack of ecosystem level-based comprehensive development planning, urban and town, traffic construction and salt pan aquaculture lands were rapidly expanded, and coastal natural mudflat wetlands, offshore areas and cultivated lands were occupied in a large area (Wu *et al.*, 2011). Natural wetlands and sea ecosystems have extremely high ecological service values, such as, regulating service and supporting service, which are not only directly embodied in the present development process of human society but also constitute the foundation for improving human well-being (Tian *et al.*, 2019b). Due to the direct change of land use mode, ESVs of the bays suffered from nearly irreversible reduction, and some ecological service functions were even permanently lost. In addition, water is the most valuable ecosystem type in bays in this study, and the main "member" of water is the sea, which is the marine ecosystem. Marine ecosystems are of great value in many aspects, such as, food supply, waste disposal, hydrological regulation, and gas regulation (Wang and Tang, 2009). During reclamation, due to insufficient understanding of the economic value and ecological value of marine resources and environment, unreasonable development of the reclamation results in the reduction of the service function of marine ecosystem. This is a key issue that how to combine protection and development to maintain the function of marine ecosystems (Tian *et al.*, 2019b). Therefore, we first need to realize the importance of the value of marine ecosystem services, which is the purpose of this study to assign high value to water. The research on the service value of marine ecosystem can provide theoretical support for decision makers of marine planning and management and gradually improve the marine eco-compensation mechanism.

The effect of sea reclamation activities on the bay ecosystem was both enduring and hysteretic, causing the short-term economic benefit of sea reclamation activities to be much higher than benefits of ESVs loss in the bays, and this was an important reason why sea reclamation activities extensively existed in the bay areas at present. Cumulative negative effects caused by sea reclamation activities on the bay ecosystems like environmental degradation, resource exhaustion and reduction of biodiversity have gradually appeared (Huang *et al.*, 2017), which resulted in continuous degradation of bearing capacity of the bay ecosystems and went against sustainable development and utilization of the bay areas. Therefore, ecosystem and economic construction benefits should be comprehensively considered in the land utilization planning of local governments (Chen *et al.*, 2018). On a precondition that the regional ecological security is maintained, the local governments should establish comprehensive regional development plan based on ecosystem sevices (Wang *et al.*, 2010) to carry out urban development and production in a planned and organized way and realize coordinated and sustainable economic development and regional ecological protection.

4.4 Application value of ESVs of the bays to ecosystem protection

The response of ESVs of the bays to human sea reclamation activities is extremely significant. Their ESVs present a significant negative correlation with sea reclamation intensity, fully certifying the consistent existence of the contradiction between economic development demand of human society and ecosystem service supply, and this is basically identical with ecosystem service evolution features and patterns caused by extensive land use under the background of rapid urbanization in numerous developing countries (Dewan *et al.*, 2012). However, bays in East China Sea are interactively influenced by sea and land and they are located in the coastal areas with rapid economic growth and fastest urbanization progress in China with intensive socio-economic activities and more diversified driving and influencing factors of ESVs of the bays, so that the evolution mechanism is more complicated.

As a sea-land interface, a bay ecosystem is a typical ecologically sensitive area. In recent years, people have gradually realized the importance of bay protection. The national and local governments have formulated sea reclamation management and control policies and methods in succession to realize strict management and control of sea reclamation projects (Wang *et al.*, 2014), moreover, there have been increasing protective measures for bay areas. Based on the ESV evaluation of the bays, we can provide ecological protection in the bays with more pertinent and applicable policies and countermeasures, so that ESVs of the bays will be of direct and highly efficient application values to ecological protection in the bays. Specifically, in consideration of the hysteretic effect of sea reclamation activities on ESVs of the bays, the government should reinforce dynamic monitoring and early warning of future development status in offshore areas. In policy formulation of sea reclamation activities and bay planning, the government should not only consider socio-economic benefits of sea reclamation activities but also formulate more reasonable ecosystem level-based sea reclamation management and control policies and ecological compensation plans from the angle of balancing ecosystem services (Peng *et al.*, 2011). In addition, government departments can implement coastal environmental management (Matsuda and Kokubu, 2016) based on new concept which promotes land-ocean interaction, relying on the environmental regulation and restoration capabilities of marine and wetland ecosystems to fully restore the ecosystem services of the coastal zone. For the existing coastal wetlands, irreplaceability of their ESVs should be considered. Coastal wetland conservation area planning should be added into related governmental planning (Tian *et al.*, 2019a). Management departments should promote the implementation of the coastal wetland ecological compensation strategy combining theory (mainly out-of-kind offsets) and practice (mainly in-kind offsets) (Yu *et al.*, 2019). The regions where wetlands are located can accurately implement zoning and grading compensation and set up wetland protection zones, buffers zones and moderate development zones. ESV high-value zones are protection zones, and development is strictly prohibited; buffers zones are set up in ESV fluctuating areas to complete ecological restoration and environmental buffering; development zones are areas where wetlands have been damaged, and eco-type projects can be constructed appropriately so as to coordinate the utilization mode of wetland resources and maintain the balance in the protection and utilization of coastal wetlands.

4.5 Limitations of ESV evaluation pattern

The land use information-based evaluation pattern was used to investigate the response relationship between bay ESVs and sea reclamation activities. In the recent decades, land utilization/land cover change has generated an enormous effect on the global bay ecosystem and it is the most direct embodiment of the effect of the current human activities on natural environment of the bays (Gomes Lopes *et al.*, 2015). Therefore, land use information, when applied to ESV evaluation, can intuitively reflect ESV evolutional features in the bays under the effect of human activities and it is convenient for discussing their responding mechanism to human activities. Therefore, this method can be used to evaluate ESVs of other bays. However, this method has some limitations which should be considered in a subsequent study. The proposed evaluation method in this study is applicable to the ESV evaluation of all types. The method was corrected using socio-economic data of the bays, but it didn't build a more applicable evaluation system for bay ecosystems according to specific regions or specific processes, e.g., formulating an evaluation system in view of sea-land dual attributes of the bay ecosystem and refining ESVs at different sea reclamation and development phases. Development activities like sea reclamation will form an impact on hydrodynamic environment of the bays, including offshore tide dynamic process and water exchange of the bays (Yu *et al.*, 2016), so as to influence ecosystem service functions and values of the bays. Therefore, ecological effect of sea reclamation can be comprehensively considered by combining ecosystem structural functions and hydrodynamic environmental conditions in the bays. In addition, ESV evaluation is based on an experience-based judgment (Xie *et al.*, 2008). Parameter weight determination of the proposed evaluation system is mainly based on empirical judgment of Chinese experts, and thus this method is not objective enough. However, in general, this method is still of applicability and practicability and can reflect main differences of different sub-ecosystem services of the bays. Importance should be attached to weight allocation of evaluation indicators and uncertainty of evaluation results in the future in order to improve effectiveness and scientificity of the evaluation system.

5 Conclusions

In this study, a total of 12 main bays in East China Sea were selected. Spatiotemporal evolution features of ESV gain and loss of bay ecosystems in East China Sea under the effect of sea reclamations over the 25 years (1990–2015) were analyzed based on land use data of the bays, and the response degree of ESVs of the bays to sea reclamation intensity was discussed. The conclusions were drawn from analysis results as follows:

(1) ESVs of bays in East China Sea presented a continuous declining tendency, with a decrease of RMB 15.621 billion, reaching 12.30%, indicating that the overall bay ecosystem in

East China Sea was continuously degraded during the 25 years. The reduction amplitude of ESVs of southern bays was greater than that of northern bays, and the change difference was related to two sea reclamation activities – inning and land reclamations – of southern and northern bays. Per various bays, their ESVs declined to different degrees. The reduction of ESV of Xinghua Bay was the maximum, with a decrease of RMB 34.63×10^8, and the rate of change reached 28.79%. The smallest reduction was in Xiangshan Harbor, with a rate of only –0.47%. The ecological service value of Taizhou Bay fluctuated the most. Per ecosystem type, the wetland decreased the most, with a loss of RMB 196.09×10^8, reaching 72.29%, followed by farmland at RMB 31.36×10^8.

(2) Spatial zoning of ESVs of bays in East China Sea was significant. A low-ESV area was expanded and the ESVs presented a continuous expanding tendency from low-value area to high-value area. Spatial variation of ESVs of the bays was also remarkable, spatially manifested as expansion outward from cities and expansion from inland to coastal areas. The areas experiencing significant ESV change were centralized at sea-land borders, indicating that, since 1990, coastal human activities centering on sea reclamation had become the main agents for the evolution of ESVs of the bays in East China Sea.

(3) The response of ESVs of the bays in East China Sea to sea reclamation activities was significant. During the 25 years, sea reclamation intensity in the bays in East China Sea continued to enhance and the overall sea reclamation scale was continuously expanded. After 2015, sea reclamation intensity tended to be gentle, manifesting that sea reclamation activities in bay areas in recent years were effectively controlled. The sea reclamation intensity presented a significant negative correlation with ESVs of the bays in East China Sea. The correlation in the southern bays was stronger than that in the northern bays, in which the correlation coefficients of most bays were about 0.9, and this was caused by the different effects of sea reclamation modes on ESV evolution of silty and bedrock bays.

(4) The negative effect of sea reclamation activities on bay ecosystems was hysteretic, and dynamic monitoring and early warning of future development status in offshore areas should be enhanced. By taking a full consideration of socio-economic benefits of sea reclamation, cumulative ecological effect and effect of non-sea reclamation factors in the sea reclamation policy formulation and bay development planning, the government should formulate proper ecosystem level-based sea reclamation management and control policies. For existing coastal wetlands, the irreplaceability of their ESVs should be taken into consideration, and coastal wetland conservation area planning should be added into related governmental planning. The proposed ESV evaluation method has some limitations. The follow-up study should refine the ESV evaluation system of the bays, discussing spatial coupling mechanism of ecological service demand of the bays and their ecological service supply capacity and providing more scientific and reasonable decision-making schemes for regulation of ecological security patterns in the bays.

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