Anthropocene Coasts

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Spatiotemporal Changes and Driving Factors of China's Coastal Marsh during 2000–2020 based on Open Datasets

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Abstract

Coastal wetlands face dual threats from climate change and human disturbances, while they provide important ecosystem functions and deliver essential ecosystem services. Exploring the drivers behind coastal wetland changes will benefit sustainable coastal ecosystem management. Based on GlobaLand30 data, this study systematically assessed the spatiotemporal changes and drivers of China's coastal marsh changes during 2000–2020 by incorporating land-use transformation process and various anthropogenic and environmental factors from public datasets. Our findings revealed a net increase of 865.8 km^2 in coastal marsh area during 2000–2020, with distinct regional variations. Coastal marsh changes were more evident north of 30°N, particularly in the Bohai Rim region (37–41°N) and the Yangtze River Delta (30–33°N). Over 75% of major coastal marsh gains (> 1,250 ha) and losses (> 1,000 ha) based on 25 km^2 hexagonal grids occurred in these two regions during 2000–2020. The increase in the proportion of major coastal marsh loss grids (> 1,000 km^2) from 80.0% to 89.8% in these two regions during 2010–2020 suggests that some areas continued to deteriorate, highlighting that total area changes may mask important local dynamics. While driving factors varied across latitudes, land reclamation remained the dominant reason for coastal wetland loss. Reclamation induced coastal marsh loss accounting for over 60% of the total losses across all sea regions during different periods. In the Bohai Rim, the latitudinal distribution of marsh losses aligned with aquaculture changes patterns, while marsh gains primarily resulted from ecological recovery. In the East China Sea region where the Yangtze Delta is located, accretion contributed over 65% of total gains during both 2000–2010 and 2010–2020 periods. The areas of significant coastal marsh changes in the East China Sea region spatially overlapped with the distribution range of *Spartina alterniflora*. Based on the analysis of driving forces and ecological issues, this study proposed region-specific adaptive management strategies. Future research should strengthen the quantitative analysis of multiple driving forces' interactions to provide a scientific basis for developing more targeted land-sea management strategies.

Keywords Gains and losses, Land-use transformation, Human activities, *Spartina alterniflora*, Management strategies

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1 Introduction

Coastal wetland ecosystems bridge terrestrial and marine environments, delivering various ecosystem services, including coastal erosion control, nutrients regulation, water quality regulation, carbon sequestration, and biodiversity maintenance (Barbier 2015; Barbier et al. 2011; Costanza et al. 2021; Spalding et al. 2014). This ecosystem plays a vital role in the life cycles of both aquatic and terrestrial animals, serving as essential feeding and breeding grounds for waterbirds, fish, shrimp, and other species (Li et al. 2018; Wu et al. 2020). Moreover, abundant fishery resources from coastal wetlands provide economic benefits and job opportunities for millions of coastal residents worldwide, making significant contributions to societal well-being (Barbier et al. 2011; Jänes et al. 2020; Lefcheck et al. 2019).

Although coastal wetlands are known to respond to environmental changes at local scales and expand through sediment accumulation, inland migration, redistribution, ecological restoration, and artificial wetland construction, their widespread loss and degradation over time has become an undeniable fact (Murray et al. 2022). It has been confirmed that more than 50% of salt marsh, 35% of mangrove, 30% of coral reef, and 29% of seagrass worldwide have been degraded or even lost over the past decades (Barbier et al. 2011). This decline stems from multiple interacting factors, including intensive human activities in coastal zones, continuous land reclamation, coastal squeeze from hardened engineering structures, environmental pollution and eutrophication, and hydrological changes caused by climate change (Deegan et al. 2012; Li et al. 2018). To better understand and address these threats to coastal wetlands, long-term monitoring of their spatiotemporal changes and exploration of underlying drivers is essential.

Historically, limited data acquisition capabilities and technical constraints have hindered large-scale, long-term monitoring of coastal wetlands, making it difficult to accurately assess wetland changes. This data scarcity hampers the understanding of spatiotemporal dynamics of coastal wetlands and the identification of key driving mechanisms, thereby limiting our ability to predict future ecosystem changes (Murray et al. 2022). However, the explosive growth of Earth observation data and the rapid advancement in cloud computing technology, particularly Google Earth Engine, have revolutionized global-scale geospatial data analysis (Yao et al. 2019). Technological advances and artificial intelligence have enabled efficient data analysis through open-source programming platforms (e.g. Python and its scientific packages). These tools now provide automated and reproducible approaches for long-term monitoring and assessment of coastal wetlands at large spatial scales (Guo et al. 2017; Jafarzadeh et al. 2022). While coastal wetland ecosystems-including mangroves, seagrass beds, shellfish beds, coral reefs, unvegetated intertidal flats, tidal marshes and adjacent freshwater marshes-all participate in biogeochemical and trophic exchange facilitated by migratory coastal organisms, they are typically studied and protected as discrete units (Carlson et al. 2021; Domingos and Lana 2017; Sheaves 2009; Worthington et al. 2024). Existing spatiotemporal analyses often target these systems individually, while comprehensive assessments of the overall coastal zone dynamics remain limited (Friess et al. 2019; Thomas et al. 2017; Wang et al. 2020a).

China has over 1.8×10^4 km of coastline and abundant coastal wetland resources, with the world's second largest area of tidal flats (Murray et al. 2019). However, rapid coastal economic and urbanization development has led to dramatic land-use changes and severe losses of coastal wetlands in recent decades (Fluet-Chouinard et al. 2023; Murray et al. 2022). Since 1980, reclamation projects have transformed approximately 8,960 km^2 of mainland China's coastal areas into artificial land, such as construction land, ports, salt pans and aquaculture ponds (Yan et al. 2023). This rapid land-use transformation has led to substantial losses of coastal ecosystems, including a 50% reduction in temperate intertidal wetlands, a 73% decline in mangrove coverage, and an 80% decrease in coral reef extent (Lei et al. 2017). In response, China has implemented a series of protective measures, including the establishment of ecological redlines in 2011, the promotion of ecological civilization construction in 2012, a national ban on coastal reclamation in 2018, and the enactment of the Wetland Protection Law of the People's Republic of China in 2022 (Wang et al. 2021; Yang et al. 2022). This policy transformation signals a significant shift towards prioritizing coastal wetland conservation and integrated coastal management, while also highlighting the urgent need for research on coastal wetlands changes and underlying drivers (Yang et al. 2022).

To quantify China's coastal marsh changes and reveal key drivers is important for strengthening integrated coastal management and sustainable development. To address this task, our study assessed coastal marsh changes and their drivers along China's coastline during a critical period of ecological policy transformation. Our study area extended from −10 m water depth to 10 km inland from the coastline, comprehensively examining changes in the total area of coastal marshes. We defined coastal marshes as areas located between land and water that are periodically or permanently flooded and typically covered with vegetation, including salt marshes, mangroves, brackish marshes, and freshwater marshes. First, we quantified the changes in the total area

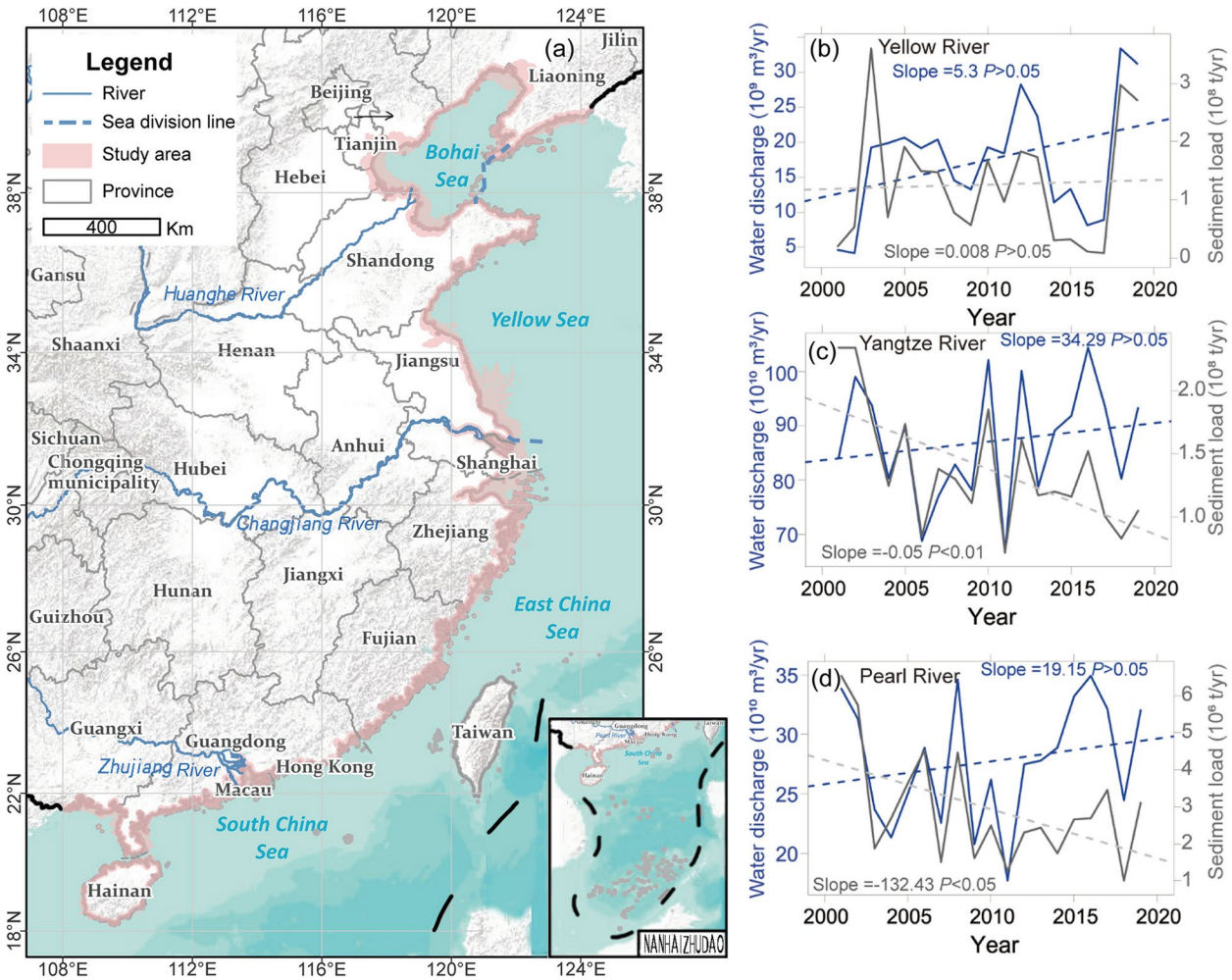


Fig. 1 Location map of the study area (**a**). River sediment load and water discharge of the Yellow River (**b**), Yangtze River (**c**), and Pearl River (**d**)

of coastal marshes within the defined region. Second, we explored the underlying drivers of these changes by analyzing land-use transformation processes and integrating various anthropogenic factors (aquaculture and cropland area) and environmental drivers (invasive species, river sediment load, and water discharge), along with their spatial and temporal distribution patterns. Based on open-source datasets and reproducible analysis, our methodology offers valuable experience for coastal ecosystem monitoring in developing regions with similar data limitations.

2 Materials and methods

2.1 Study area

The study area boundaries were established based on both ecological and physical criteria. The landward boundary was defined using global inland water dynamics distribution data (Pickens et al. 2020), where we created a 10 km buffer zone inland from the coastline in areas with mean water percentage $\leq 10\%$. For the seaward boundary, we used the -10 m water depth contour, determined using GEBCO_2020 Grid digital elevation data (15 arc-second resolution). This boundary selection considers both China's maximum average tidal range of approximately 5 m and the Ramsar Convention's wetland definition (water depths not exceeding 6 m at low tide) (Yang et al. 2013). The total study area covers 2.1×10^5 km^2, encompassing the complete coastal ecosystem transition zone (Fig. 1a).

In this research, we define coastal wetland as the collective assemblage of three distinct ecosystems that occur within the designated study boundaries: nearshore seawater, inland water, and coastal marsh. We analyzed the composition of coastal wetlands at the provincial level. Provincial administrative boundary data for coastal regions were downloaded from the Standard Map Service Website of the National Bureau of Surveying, Mapping

and Geographic Information of China, with the approval number GS (2024) 0650.

2.2 Identification of coastal marsh gain and loss areas

The coastal marsh data used in this study is derived from the 30 m global land cover data (GlobeLand30)[1] for the years 2000, 2010, and 2020, which was donated by the Ministry of Natural Resources of China to the United Nations. GlobeLand30 was chosen for its high spatial resolution, temporal consistency, and detailed classification accuracy, making it well suited for long-term coastal marsh change analysis at the national scale. The overall classification accuracy of dataset exceeds 80%. In GlobeLand30, wetlands are defined as lands with shallow water or waterlogged soil located in the transition zone between terrestrial and aquatic environments, typically dominated by hydrophytes or hygrophytes. This broad category includes inland marshes, lake marshes, forested/shrub wetlands, peat bogs, mangroves, salt marshes and so on. For our study, we specifically referred to this collective category as "coastal marsh". Similarly, water bodies in the dataset were defined as "inland water".

In this study, we utilized coastal marsh spatial data from two consecutive time periods to identify and quantify gain and loss areas through spatial overlay analysis using ArcGIS 10.7. Specifically, areas present in the earlier period but absent in the later period were classified as "loss area", while those absent in the earlier period but present in the later period were designated as "gain area". Areas that persisted across both time periods were defined as "stable area". Figure 2 illustrates the identification of gain, loss, and stable areas through comparison of coastal marsh distribution between two consecutive time periods, using a magnified example from the Bohai Sea region of eastern China (Fig. 2a-c). To effectively visualize and quantify the spatial patterns of coastal marsh changes, we constructed a hexagonal grid system (25 km^2 per hexagon) and employed the Tabulate Intersection tool in ArcGIS Pro 3.0.2 to calculate the gain and loss area within each grid cell. The results were then displayed using a graduated color scheme to show change intensity.

2.3 Land-use transformation processes and driving factors of coastal marsh

Following Ma et al., (2019), we classified the drivers of coastal marsh changes into five categories based on land use transformation processes and the initial and final land use types: accretion (conversion from nearshore seawater to coastal marsh), ecological recovery (conversion from other land use types to coastal marsh), no change (maintained as coastal marsh), erosion (conversion from coastal marsh to nearshore seawater), and reclamation (conversion from coastal marsh to other land use types) (Table 1). Based on the "National Marine Functional Zoning Plan (2011–2020)", the study area was divided into four major sea regions: Bohai Sea, Yellow Sea, East China Sea, and South China Sea. Following the specified boundary points of these sea regions, coastal marsh and other land use data in different sea regions were extracted for underlying drivers analysis.

2.4 Anthropogenic and environmental driving factors

For human disturbances factors, we chose marine aquaculture and cropland area data. For natural environmental factors, we collected hydrological data of three major rivers and the distribution area of invasive species *Spartina alterniflora* (*S. alterniflora*). Additionally, intertidal wetland data from Murray et al., (2022) was used for latitude distribution comparison analysis. All data sources and detailed information are listed in Table 2.

To analyze latitudinal distribution patterns, we calculated area changes of multiple variables (coastal marsh, intertidal wetland, cropland, marine aquaculture, and *S. alterniflora* distribution) using 0.2° grids, combining data from grids at the same latitude. The Tabulate Intersection tool was used for area calculations, and R 4.3.2 was used for latitudinal area statistics and analyses.

3 Results

3.1 Changes of China's coastal wetland

Based on the 2020 GlobeLand30 data, China's coastal wetland consists of nearshore seawater (77.2%), inland water (18.3%), and coastal marsh (4.6%). During 2000–2020, these three ecosystems showed different change patterns. Nearshore seawater areas continuously decreased at an annual rate of 253 km^2, with Liaoning, Shandong, Jiangsu, and Zhejiang provinces each experiencing reductions exceeding 300 km^2. Inland water (including rivers, lakes, reservoirs, and ponds) increased annually by 58.3 km^2 from 2000 to 2010, but showed a declining trend from 2010 to 2020. Regional variations were significant, with Tianjin, Jiangsu, and Shanghai showing continuous decreases, while Liaoning, Guangdong, Fujian and Zhejiang experienced significant increases (Fig. 3).

Coastal marsh showed an overall increasing trend, with a total increase of 865.8 km^2 from 2000 to 2020, though this growth was primarily concentrated in the 2000–2010 period, with only 36.6 km^2 increase during 2010–2020. By 2020, the total area of coastal marsh had reached 4,629.9 km^2. Despite the overall expansion of coastal marshes from 2000–2020, substantial areas were still converted to other land use types. Our

[1] https://www.webmap.cn/commres.do?method=globeIndex

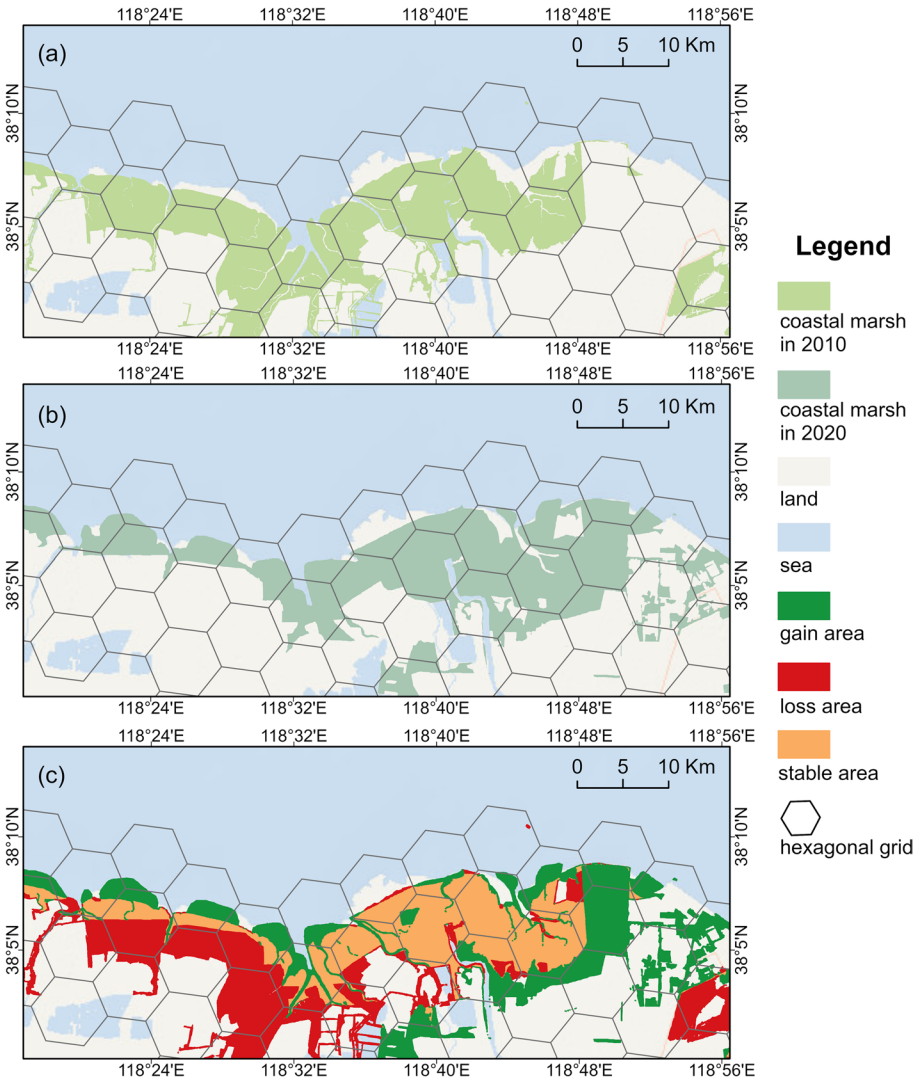


Fig. 2 An illustrative example of coastal marsh distribution in the Bohai Sea region of eastern China in 2010 (**a**), 2020 (**b**), and the gain, loss, and stable areas between 2010 and 2020 (**c**)

Table 1 Categorization of underlying drivers based on land use transformation processes and their corresponding start and end point land use types

Start-point type	End-point type	Driving processes	Consequence
Nearshore seawater	Coastal marsh	Accretion	Gain
Cropland, Forest, Grass, Shrub, Inland water, Artificial surface, Bare land	Coastal marsh	Ecological recovery	Gain
Coastal marsh	Coastal marsh	No change	Stable
Coastal marsh	Nearshore seawater	Erosion	Loss
Coastal marsh	Cropland, Forest, Grass, Shrub, Inland water, Artificial surface, Bare land	Reclamation	Loss

Note: This table classification is based on the GlobeLand30 dataset. The "wetland" category was redefined as "coastal marsh" in this study

Table 2 Detailed information of anthropogenic and environmental driving factors selected for this study

Driving factors	Data information
Marine aquaculture	Data from Quadrennial Series Dataset of Coastal Aquaculture Distribution of China Based on Landsat Images (1990–2022) by Yin et al., (2023). 30 m resolution. 1998, 2010, and 2022 were selected for this study
Cropland	Data from a 30 m annual cropland dataset of China from 1986 to 2021 by Tu et al., (2023). 2000, 2010, and 2020 were selected for this study
S. alterniflora	Data from 30 m Resolution Spatial Distribution Dataset of *Spartina alterniflora* in China (1990–2020) by Wang et al., (2020c). 2000, 2010, and 2020 were selected for this study
River sediment load and water discharge	River sediment load and water discharge data (2000–2019) were collected for three major rivers: the Yellow River (Lijin Station), Yangtze River (Datong Station), and Pearl River (Gaoyao, Shijiao, and Boluo Stations). Data were obtained from the Sediment Bulletin of China's Rivers
Intertidal wetland (salt marsh, tidal flat, mangrove)	Data from Global Tidal Wetland Change v1.0 (1999–2019), which provides spatial information on the distribution, losses, and gains of tidal wetlands (including salt marsh, tidal flat, and mangrove). 30 m resolution

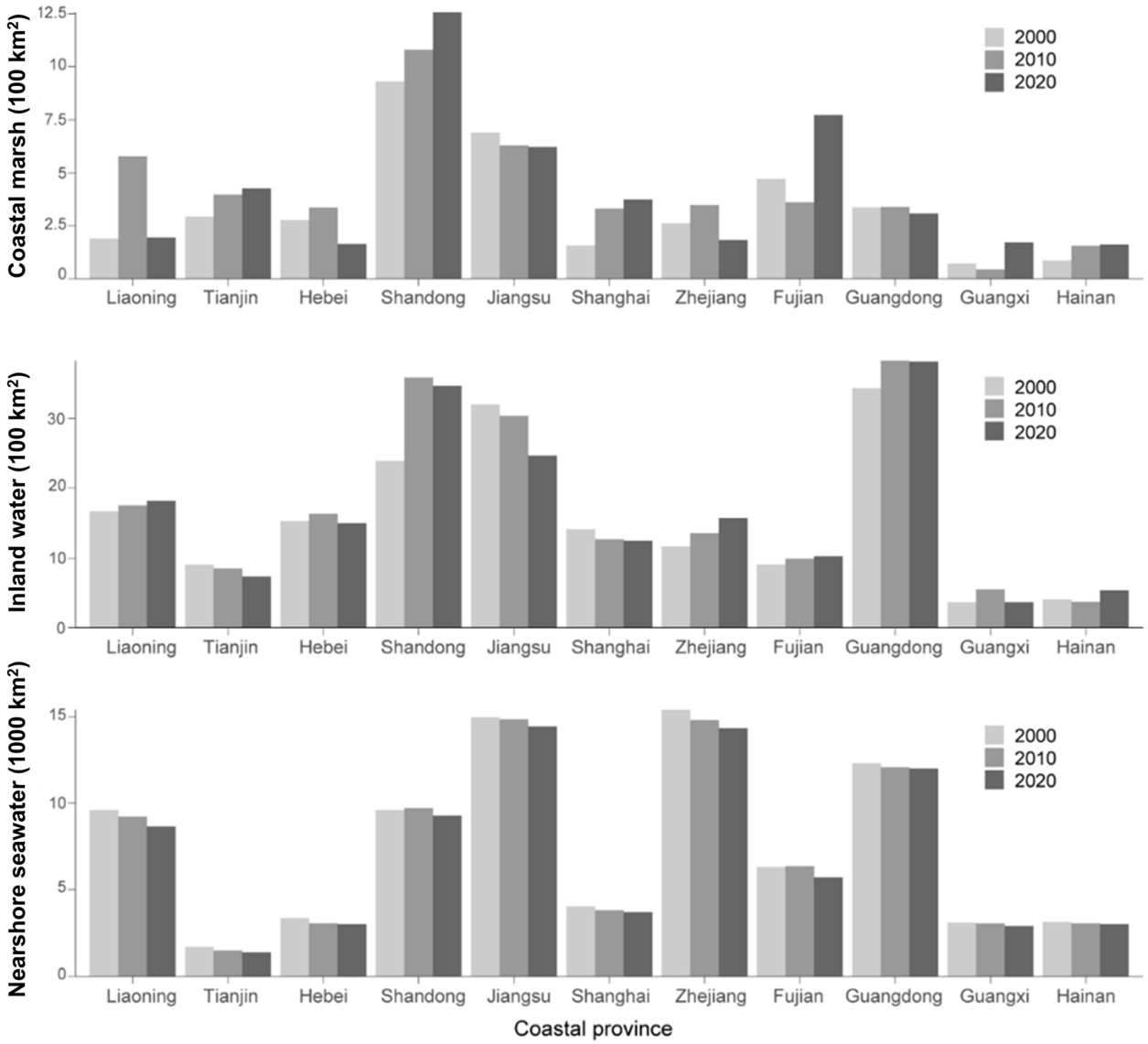


Fig. 3 Area changes of nearshore seawater, inland water and coastal marsh in China's coastal provinces from 2000 to 2020 (based on GlobeLand30 dataset)

study results revealed 1,955.0 km^2 of coastal marsh converted to other land use types in 2000–2010, and 2,484.5 km^2 converted in 2010–2020, with less than half of the coastal marsh remaining unchanged between consecutive periods (48.1% during 2000–2010 and 45.9% during 2010–2020) (Table 3). Spatially, Shandong and Jiangsu provinces have the largest coastal marsh area. Among the 11 coastal provinces and municipalities, 6 showed net growth, while Hebei and Zhejiang provinces experienced the most severe coastal marsh loss. Hebei's coastal marsh area in 2020 was only 60% of its 2000 level. Liaoning province demonstrated significant periodic characteristics: after substantial growth in 2010, it declined sharply, with its 2020 area returning to approximately the same level as in 2000 (Fig. 3).

3.2 China's coastal marsh losses and gains

During 2000–2010, coastal marsh gains were primarily concentrated in three key regions: the Bohai Rim (37°N-41°N), the Yangtze River Delta (30°N-33°N), and the coasts of Leizhou Peninsula and Hainan (around 20°N) (Fig. 4a-c and e). Among hexagonal grids showing substantial gains (> 1,250 ha), 59.6% were in the Bohai Rim (37°N-41°N), while 27.728.% occurred in the Yangtze River Delta (30°N-33°N). During the same period, coastal marsh losses had a similar geographic distribution, with evident losses in the Bohai Rim and Yangtze River Delta, while Hainan experienced relatively minor losses (Fig. 4f-h and j). Of grids showing huge losses (> 1,000 ha^2), 60.0% were in the Bohai Rim (37°N-41°N) and 20.0% in the Yangtze River Delta (30°N-33°N). The Pearl River Delta showed relatively minor changes in both gains and losses (Fig. 4d and i).

During 2010–2020, the spatial patterns of coastal marsh gains and losses remained similar compared with those in 2000–2010 (Fig. 5a-d and f-i), but the central part of Fujian (24°N-27°N) emerged as a new region with significant gains and losses (Fig. 5e and j). Higher values of coastal marsh losses per hexagonal grid were still observed in the Bohai Rim (37°N-41°N) and Yangtze River Delta (30°N-33°N) (Fig. 5g-h). Among grids showing major losses (> 1,000 ha^2), 89.8% were concentrated in these two regions. Similarly, of grids showing substantial gains (> 1,250 ha^2), 75.0% were in these same regions. The proportion of major coastal marsh loss grids (> 1,000 ha) increased by 9.8% in these two regions, suggesting that parts of the coast of Bohai Rim (37°N-41°N) and the Yangtze River Delta (30°N-33°N) showed deterioration compared to the previous period. Compared to 2000–2010, the Pearl River Delta showed smaller changes in both gains and losses during 2010–2020 (Fig. 5d and i).

3.3 Driving factors behind different land use transformation processes

Spatially, the Bohai Sea, East China Sea, and South China Sea regions overlap with areas of the most active coastal marsh changes and important river deltas: the Bohai Rim (37°N-41°N), the Yangtze River Delta (30°N-33°N), the Pearl River Delta and the coasts of Leizhou Peninsula and Hainan (20°N-22°N). Among these, the Bohai Sea region showed the most striking changes during 2000–2020, with its coastal marsh gains and losses each accounting for over 40% of their national totals. The gains were primarily driven by ecological recovery, which contributed 79.5% and 53.2% of total gains in 2000–2010 and 2010–2020 respectively, while reclamation-induced marsh losses in this region accounted for 46.1% of China's total reclamation-caused marsh loss (Fig. 6). During 2010–2020, reclamation areas in the Bohai Sea region increased by 790.3 km^2. The East China Sea region showed a similar pattern but with less reclamation area growth of 261.2 km^2, and its coastal marsh gains were mainly contributed by accretion, which accounted for over 65% of total gains in both 2000–2010 and 2010–2020 periods. The South China Sea region was the only sea region where reclamation areas decreased by 175.5 km^2 compared with the 2000–2010 period, with accretion and ecological recovery consistently accounting for approximately 55% and 45% of the region's gains respectively across both periods. Although the proportion of reclamation-induced coastal marsh loss varied across sea regions, it consistently accounted for over 60% of total losses during different periods.

The Bohai and East China Sea regions have the largest accreted coastal marsh areas, with riverine sediment input playing a crucial role in this process. Studies have shown that approximately 1,185.4 $\times 10^6$ tons of fine-grained sediment accumulate annually in the mud areas of the East China sea region, with riverine sediment inputs accounting for over 75% (9.2 $\times 10^8$ tons/yr) (Qiao

Table 3 Area of coastal marsh converted to other land use types in 2000–2010 and 2010–2020 periods

Land use (km^2)	Coastal marsh	Cropland	Forst	Grass	Shrub	Inland water	Nearshore seawater	Artificial surface	Bare land
2000–2010	3764.1①	356.3	63.0	48.8	3.1	847.9	553.3	79.2	3.4
2010–2020	4593.3②	447.0	30.2	269.8	0.1	1103.5	221.3	410.6	2.0

Note: Symbols ① and ② represent the coastal marsh areas in 2000 and 2010, respectively

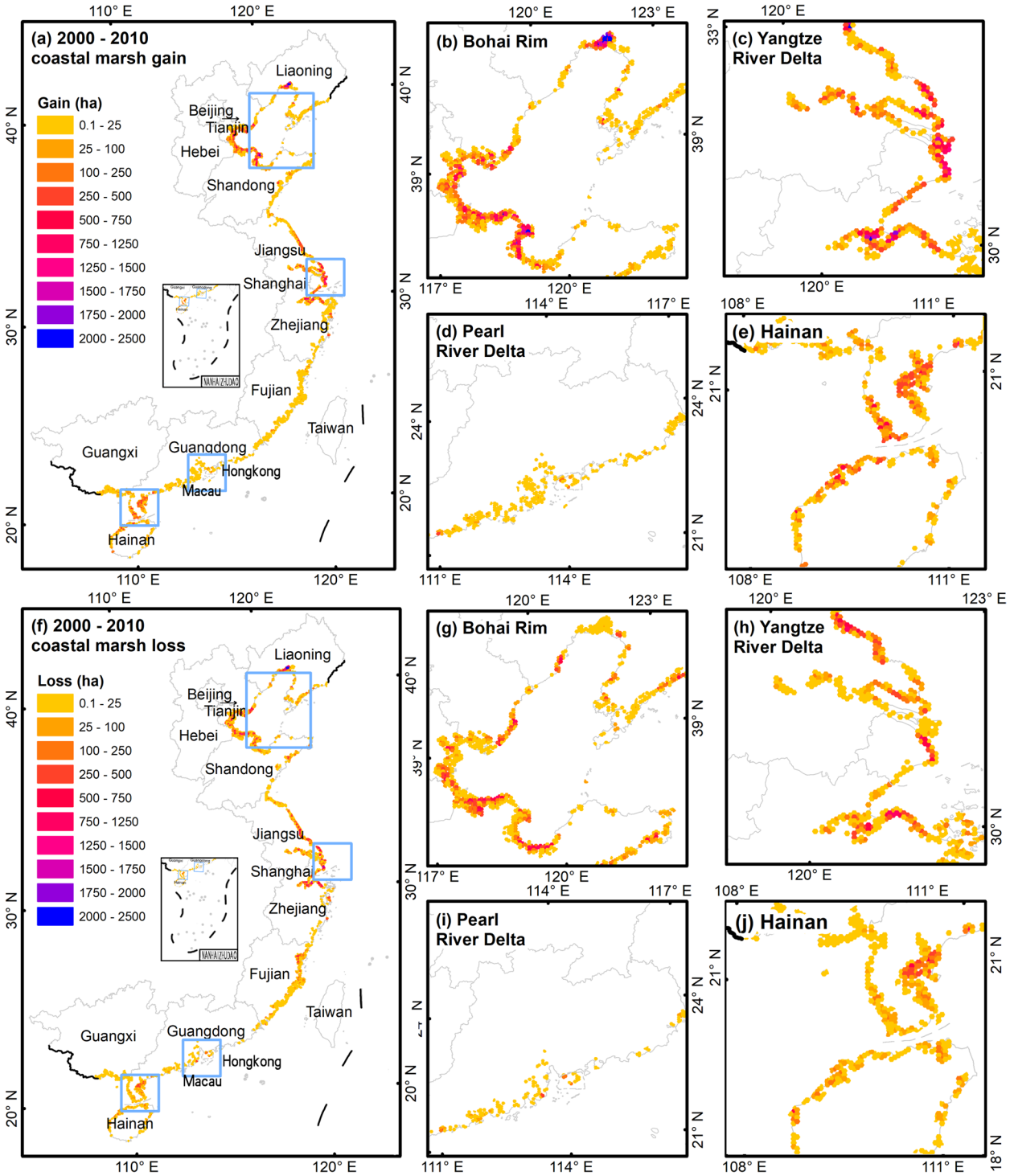


Fig. 4 Spatial distribution of coastal marsh gains (**a**) and losses (**f**) in China, 2000–2010. Panels b-e and g-j show local details. Visualized using 25 km^2 hexagonal grids, and the values in the legend represent the absolute area of coastal marsh gained or lost within each grid cell during 2000–2010

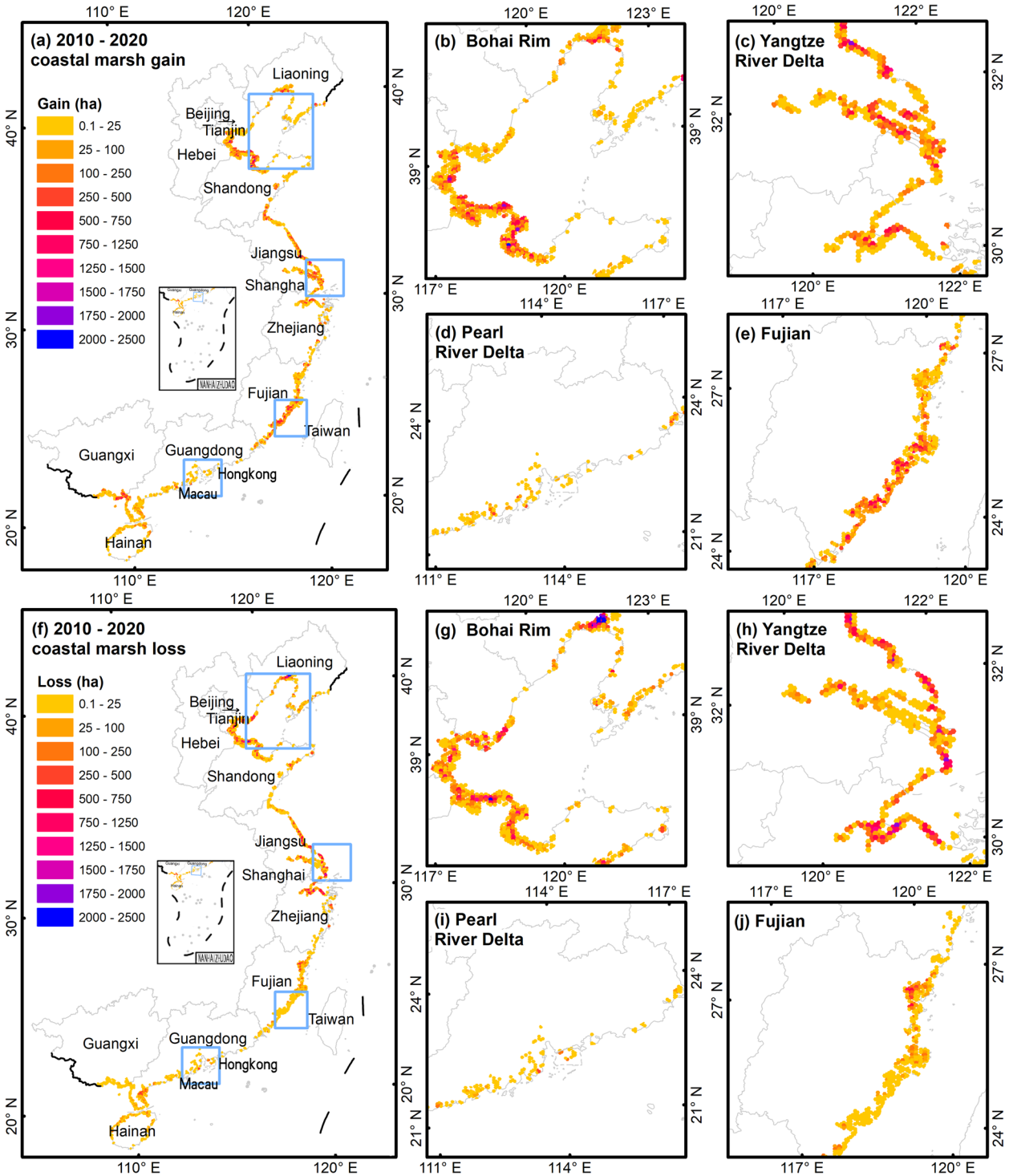


Fig. 5 Spatial distribution of coastal marsh gains (**a**) and losses (**f**) in China, 2010–2020. Panels b-e and g-j show local details. Visualized using 25 km^2 hexagonal grids, and the values in the legend represent the absolute area of coastal marsh gained or lost within each grid cell during 2010–2020

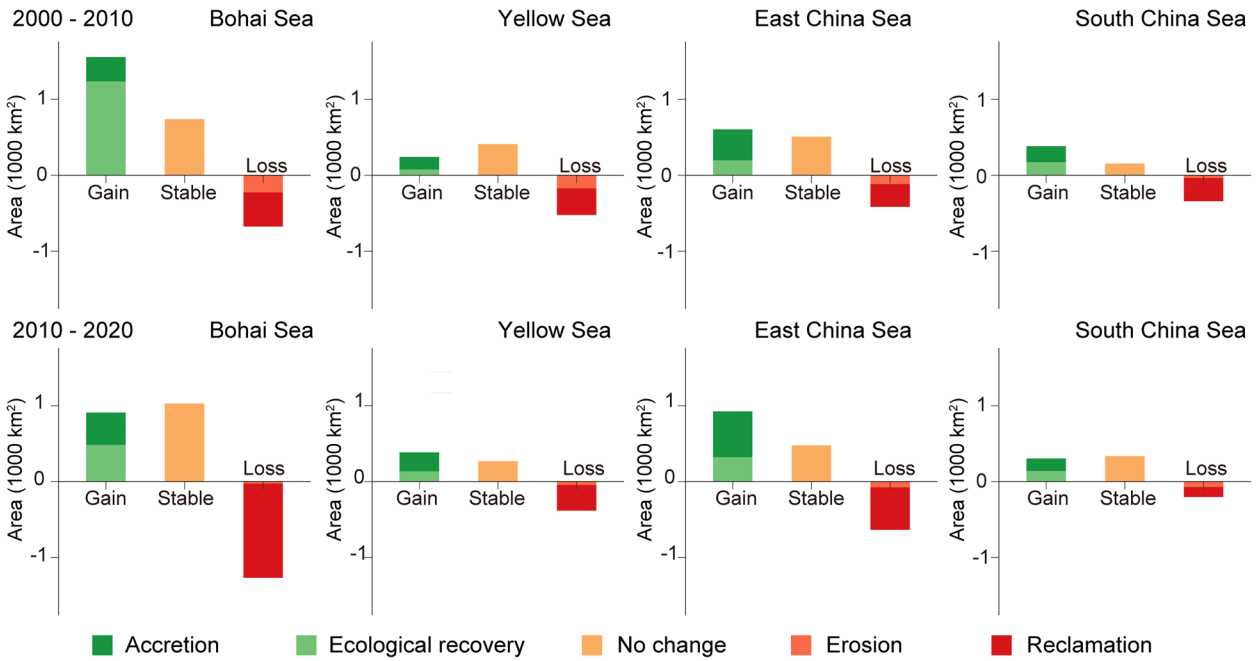


Fig. 6 Driving factors of coastal marsh changes in China's major sea regions derived from land use transformation processes

et al. 2017). These regions are influenced by two major rivers, the Yellow River and Yangtze River, which exhibit distinct sediment transport patterns. The Yellow River shows no significant linear decline in annual sediment load ($P > 0.05$), while both the Yangtze River and Pearl River have experienced sharp decreases in annual sediment load over the past two decades ($P < 0.05$) (Fig. 1b-d). This difference likely explains the increase of accretion area of coastal marshes in the Bohai region, as the relatively stable sediment supply provides the material foundation for natural wetland growth. The South China Sea region experienced a 21.9% decrease in accreted coastal marsh area during 2010–2020 compared to the previous period, coinciding with the reduced sediment discharge from the Pearl River.

Although the Yangtze River's annual sediment load has the same declining trend as the Pearl River, the accretion area of coastal marsh in the East China Sea region continues to grow during 2000–2020. This phenomenon appears to be associated with the expansion of the invasive species *S. alterniflora*. Analysis shows that the Yangtze River Delta region (30°N-33°N) is the peak area for both coastal marsh area gains and losses, and it was also the significant expansion zone of *S. alterniflora* during 2000–2010 (25°N-34°N) (Fig. 7a, f, e and j). From 2010 to 2020, the expansion trend of *S. alterniflora* continued and showed growth across a wider latitudinal range (Fig. 7j). *S. alterniflora* reduces erosion and promotes accretion by retarding tidal flow velocity and facilitating sediment deposition, while also contributing to elevation building through organic matter accumulation and root biomass production (Meng et al. 2020). Taking the Jiuduansha Shoals as an example, its wetland area increased by 70 km^2 from 2000 to 2018, with the expansion of *S. alterniflora* accounting for over 70% of the wetland area growth, effectively offsetting the impact of the decrease in Yangtze River sediment load (Zhang et al. 2023a).

3.4 Latitudinal distribution patterns of coastal ecosystems and their driving factors

Coastal marsh and intertidal wetlands (including mangrove, tidal marsh, and tidal flat), show similar patterns of gains and losses in several latitude zones, particularly in the Bohai Rim (37°N-41°N) and Yangtze River Delta (30°N-33°N) regions (Fig. 7a-b and f-g). These patterns partially overlap with the spatial distribution of marine aquaculture and cropland changes in specific latitude zones, suggesting potential land-use interactions in these areas (Fig. 7c-d and h-i). Overall, the wetland area changes north of 30°N were greater than those in the southern regions.

The Bohai Rim region (37°N-41°N) experienced the most significant coastal marsh losses while simultaneously showing a substantial increase in marine aquaculture area. Besides, analyses of land transformation process revealed that 60.3% and 66.9% of the coastal marsh losses during these two respective periods were attributable to direct conversion into cropland and

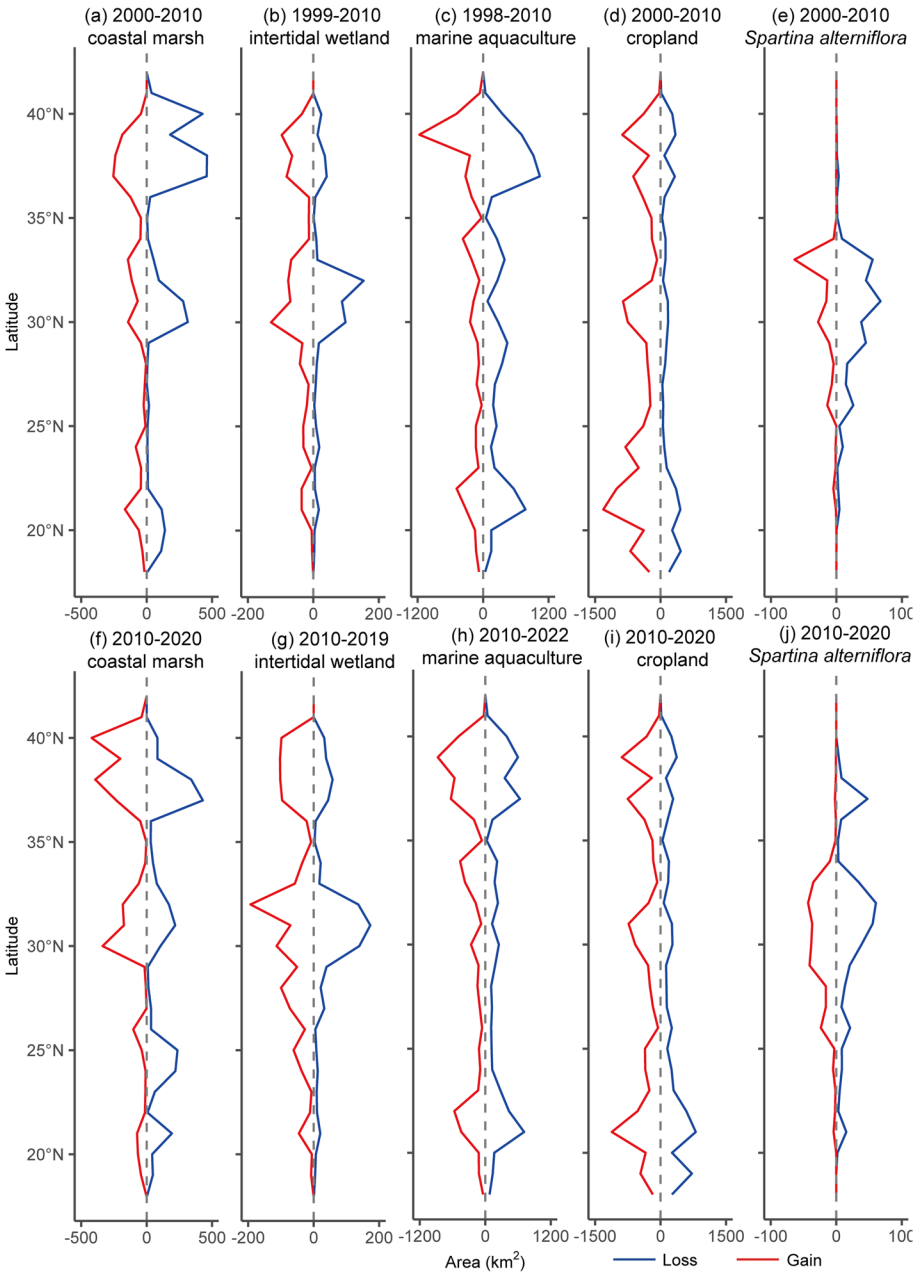


Fig. 7 Area changes in coastal marsh (**a**, **f**), intertidal wetland (**b**, **g**), marine aquaculture(**c**, **h**), cropland (**d**, **i**) and *S. alterniflora* (**e**, **j**) across different latitudes in the 2000–2010 and 2010–2020 periods. All data sources and detailed information refer to Table 2

inland water. Based on the spatial overlap and temporal correspondence between coastal marsh changes and aquaculture changes in the Bohai Rim region, we infer that coastal marsh losses were primarily driven by land reclamation for marine aquaculture development. This is supported by previous studies showing that the aquaculture in the Bohai Rim expanded significantly over the past decades (Ding et al. 2019; Wang and Liu 2024; Wei et al. 2022). Between 1984 and 2022, the aquaculture area increased from 146 km^2 to 1,812 km^2 in Shandong province and from 173 km^2 to 1,447 km^2 in Liaoning province (Wang and Liu 2024). This aligns with the region's historical strategy of marine economic development. Additionally, the analysis of cropland changes shows a widespread trend of losses exceeding gains across most latitude zones during both 2000–2010 and 2010–2020 periods (Fig. 7d and i).

4 Discussion

4.1 Coastal wetland area changes

Although our study shows an increasing trend in the total area of coastal marsh, other studies indicate that the intertidal wetland area remains significantly lower than in the late twentieth century, despite increased conservation and restoration efforts promoting salt marsh recovery and expansion (Chen et al. 2022; Cui et al. 2022; Song et al. 2020; Wang et al. 2021). This discrepancy might stem from differences in wetland types included in the studies. Our study encompassed a broad range of wetland types within the specified study area (from −10 m water depth to 10 km inland), including inland marshes, lake marshes, forested/shrub wetlands, peat bogs, mangroves, and salt marshes. However, other research focused primarily on salt marshes, tidal flats, and mangroves.

Different wetland ecosystems can provide complementary ecosystem services, as exemplified by how both tidal marshes and freshwater wetlands contribute to water purification. Nevertheless, each wetland type maintains its unique and irreplaceable roles. Salt marsh, for instance, can increase vertical sediment deposition or migrate onto adjacent uplands to actively resist the deleterious effects of sea-level rise (Chen et al. 2019). Some shorebird species show preference for tidal flats with shallow water or bare mud and unobstructed views, as these conditions are critical for predator detection and foraging activities (Jackson et al. 2021). Previous studies have confirmed a global trend where natural wetlands, including both marine/coastal and inland areas, show persistent decline, while human-made wetlands exhibit continuous expansion (Davidson and Finlayson 2018). Therefore, focusing solely on the increase in total coastal marsh area may mask the actual reduction in area and degradation of ecological functions of certain important wetland types.

Although wetland restoration efforts have substantially increased wetland area in some regions, questions remain about whether these restored wetlands can provide ecosystem services equivalent to those of lost natural wetlands, both in terms of quality and functionality (Meli et al. 2014; Moreno-Mateos et al. 2012). Even natural wetlands may experience varying degrees of degradation due to multiple stressors, making it particularly challenging to evaluate and achieve functional equivalence in restored systems (Lin et al. 2021). The distribution and dynamics of coastal wetlands vary significantly among provinces. Some regions, such as Shandong and Shanghai, showed an increase in coastal marsh area over the past two decades (Fig. 3). However, this increase may largely result from the expansion of artificial wetlands or the expansion of invasive *S. alterniflora*, rather than natural wetlands. Therefore, net changes in wetland areas alone cannot effectively reflect the success of regional conservation efforts over time (Xu et al. 2019).

4.2 Analysis of factors influencing coastal marsh dynamics

Coastal marsh in China has undergone significant changes in recent decades. Understanding the spatial patterns and driving forces of these changes is crucial for coastal wetland conservation and management.

The spatial distribution of coastal marsh changes varies along China's coastline, with greater changes observed north of 30°N compared to southern regions. North of Hangzhou Bay, where the Bohai Sea coastal wetlands and coastal Jiangsu region are located, the coastline is dominated by sandy beaches and mudflats (Niu et al. 2009). These areas have undergone evident changes due to their broad muddy tidal flats being suitable for development. In contrast, the coastal area south of Hangzhou Bay is mainly characterized by rocky coast and a few estuary deltas, thus more noticeable coastal marsh changes occurring in these estuarine regions (Niu et al. 2009; Wu et al. 2014).

Multiple driving forces have significantly impacted China's coastal marshes, with human activities, particularly reclamation activities and related land-use transformation processes, playing a crucial role. Land reclamation has emerged as the primary driver, with its most intensive impact concentrated in three major coastal city clusters: the Bohai Rim, Yangtze River Delta, and Pearl River Delta regions. These regions collectively accounted for 95% of China's total coastal reclamation area between 1985 and 2016 (Liu and Li 2020). The intensity of reclamation in these regions can be attributed to several interconnected factors. These city clusters, which contain 36.4% of the national population and contribute 50.8% of the national GDP in 2015, experience substantial pressure for land resources due to high population density, rapid urbanization, and economic development (Lin and Yu 2018; Tian et al. 2016). This pressure has been amplified by policy orientation towards economic development, coupled with substantial economic returns from reclamation projects and the strategy of maintaining the national cultivated land quota (Meng et al. 2017).

During the 2000 s, major development initiatives such as the Binhai New Area, the Pearl River Estuary Bay Area, and the Yellow River Delta High Efficiency Eco-economic Zone led to extensive reclamation activities, marking the largest reclamation period since the 1980 s (Wu et al. 2014; Yan et al. 2023). Beyond reclamation, other significant anthropogenic pressures include agricultural activities, aquaculture, oil–gas exploitation and so on. The Bohai Rim hosts China's second-largest crude oil production area, encompassing the offshore Bohai Sea

fields and the Shengli, Dagang, and Liaohe oil fields. The coastal plains (North China Plain, Yellow-Huaihai Sea Plain, and Liao River Plain) serve as crucial agricultural regions, while the Bohai Sea supports extensive aquaculture operations, functioning as China's largest marine farming base (Wang et al. 2022). Additionally, the sedimentation promotion projects implemented by the local government and the natural lateral expansion of tidal wetlands have jointly promoted the growth of accretion area in this region (Chen et al. 2019; Lin et al. 2021; Wei et al. 2019).

Natural factors also contribute significantly to coastal marsh changes. Statistical analysis has shown that about 70% of China's sandy coast, and most mudflats and coral coasts in open water have been eroded, and the erosion in the north has been more severe than that in the south (Liu et al. 2020). Climate change and sea-level rise may alter the currently observed patterns and increase the vulnerability of coastal marsh. The middle coast of Jiangsu is expected to face a high sea level rise vulnerability due to severe subsidence and low elevation along with a large tidal range (Yin et al. 2012). In the Yangtze River Delta, without consideration of sedimentation, Tian et al., (2010) predicted that 7% and 14% of salt marshes in Chongming Dongtan could be lost as a result of 0.88 m of sea level rise by 2050 and by 2100. Yin et al., (2012) assessed vulnerability of the China's coast by integrating eight factors (sea-level rise, coastal geomorphology, elevation, slope, shoreline erosion, land use, mean tide range, and mean wave height), identifying Laizhou Bay, Bohai Bay, the North Jiangsu coastal plain, the Yangtze River Delta, and the Pearl River Delta as the most vulnerable regions. Furthermore, widespread eutrophication in China's coastal waters has led to increased algal mat proliferation in salt marshes, reducing their resilience to sea level rise (Jiang et al. 2019; Wasson et al. 2017).

In some major river deltas, decreased runoff and sediment loading are generally important natural factors affecting the variation and stabilization of coastal wetlands. For example, the Yellow River is well known as a sediment-laden river and several hundred million tons of sediment per year are transported to the estuary and deposited in the slow flowing landform, resulting in vast floodplain and special coastal marsh landscape. The correlation analysis between annual average sediment loading and annual average erosion/accretion rates of coastal wetlands suggests that the variations and stabilization of coastal wetlands, to a greater extent, were significantly influenced by the inter-annual changes of sediment loading (Sun et al. 2015).

Invasive species have also played a significant role in shaping coastal marsh dynamics. *S. alterniflora* was introduced in the 1980 s for the purposes of seashore stabilization, land reclamation, and soil amelioration (Chung 2006). By 2018, its distribution area had exceeded 500 km^2, invading most mid-latitude coastal regions of China and seven national nature reserves (Zhang et al. 2023b). Through its well-developed underground root system, this species promotes sediment deposition and alters local hydrological conditions, significantly affecting the vegetation community structure and dynamics of coastal marshes. While contributing to wetland area expansion, it has also modified the original ecosystem processes (Zhang et al. 2023a). The accretion in salt marshes with *S. alterniflora* coverage in Jiangsu coastal areas was more than mudflats, and more than 1,000 ha land was created each year (Meng et al. 2020).

In summary, coastal marsh changes result from the complex interactions between human activities (e.g. reclamation, urbanization, aquaculture, agriculture) and natural processes (e.g. sedimentation, erosion, sea-level rise). However, active restoration efforts and conservation policies have shown promise in promoting the sustainability of coastal wetland ecosystems.

4.3 Implications for policy and management strategies

Historically, China's coastal wetlands have long been viewed as development and production reserve land for alleviating land-use conflicts (An et al. 2007). Following the 2003 national wetland resources survey, the importance of wetland conservation and restoration was highlighted, accelerating the development of national protection policies (Sun et al. 2015). In 2011, the Chinese government enacted the "Ecological Protection Red Line" policy (Liang and Zhuang 2024). In 2012, "Ecological Civilization Construction" was adopted as a national strategy, which provided a framework integrating environmental protection with development priorities. In 2016, China's State Council issued a notice declaring a commitment to preserve at least 46.7 million hectares of natural wetlands as an ecological red line that must not be crossed. This was followed in 2018 by a comprehensive ban on all land reclamation projects from the sea. In 2022, China's first wetland protection law was issued (Ma et al. 2023). It is apparent that a philosophy of change from "land reclamation from the sea" to "comprehensive conservation" is underway (Duan et al. 2022; Yang et al. 2022).

Based on the historical ecological challenges, we propose region-specific management strategies. During the development of the marine economy, large areas of coastal wetlands were reclaimed for aquaculture ponds. Meanwhile, hydraulic engineering, oil–gas exploitation, and fishery pollution have significantly impacted wetland ecosystems (Liu et al. 2020). In major estuarine areas, decreasing sediment discharge in the Yangtze and Pearl

River estuaries, coupled with climate change and sea-level rise, poses multiple challenges to the current policy of complete *S. alterniflora* removal, potentially weakening wetlands' resilience to coastal hazards and extreme weather events (Zhang et al. 2020).

For northern coastal regions, we recommend: (1) appropriate conversion of aquaculture ponds to wetlands to restore tidal rhythms; (2) strengthened pollution control and environmental risk assessment of fisheries and oil–gas exploitation; (3) gradual rather than complete removal of *S. alterniflora* to ensure smooth ecological transition; (4) active restoration of native vegetation to compensate for potential ecological function loss, especially in the erosion coastlines; and (5) adaptive management strategies with continuous monitoring of wetland ecosystem changes.

For southern coastal areas, particularly the Pearl River Delta region, different approaches are needed due to limited land resources, developed economy, and intense human-land conflicts that make large-scale nature reserves impractical (Ma et al. 2019). Given the severe impacts of storm surges in these areas (Feng et al. 2023), we suggest: (1) ecological restoration of historically degraded wetlands; (2) creation of small-scale urban wetlands to establish ecological corridors; (3) implementation of market-based mechanisms (e.g., carbon trading) to incentivize wetland protection; and (4) strict protection of existing natural coastlines while incorporating wetland conservation into urban development planning to maximize ecological benefits.

Furthermore, to enhance restoration effectiveness, we propose establishing comprehensive evaluation metrics beyond simple area measurements. This should include indicators of ecosystem functions, biodiversity, and ecosystem services. Additionally, research on the dynamic transformation among different wetland subtypes in coastal zones should be strengthened to better understand their interactions and succession patterns. Such an integrated land-sea research approach would provide crucial insights for adaptive management and policy-making, ultimately contributing to more resilient coastal wetland ecosystems.

4.4 Limitations

This study integrated multiple data sources to analyze coastal wetland spatiotemporal changes and their driving factors along China's coastline during 2000–2020. Although our study enabled comprehensive analysis, methodological limitations and uncertainties remained. The GlobeLand30 dataset didn't separate sub categories of coastal marsh (such as inland marshes, lake marshes, salt marshes and mangroves), while the Murray et al., (2022) dataset only covered three intertidal wetlands types (mangroves, salt marshes, and tidal flats). Despite many attempts to improve earth observation approaches and mapping methods for wetland, current methodologies still struggle to effectively differentiate between various wetland types, particularly in distinguishing natural wetlands from artificial ones, and inland wetlands from those in coastal and nearshore marine environments (Davidson et al. 2018). Besides, the temporal coverage varied across datasets (aquaculture: 1998–2022; GlobeLand30: 2000–2020; intertidal change: 1999–2019), which may affect driving factor analysis accuracy. While all datasets demonstrated high classification accuracy (> 80%), differences in satellite imagery sources and classification methods introduced some uncertainty, with wetland mapping accuracy impacted by flooding and vegetation phenology conditions (Wang et al. 2020b). Furthermore, the complex interactions between multiple driving factors (aquaculture, *S. alterniflora* invasion, sediment supply changes) warrant further investigation (Kirwan and Megonigal 2013). Future studies would benefit from datasets with higher spatial resolution and continuous temporal coverage to better understand these dynamics.

5 Conclusion

Using land use transformation processes analysis combined with anthropogenic and environmental factors, we conducted a systematic assessment of China's coastal marsh changes and its underlying drivers from 2000 to 2020 based on open-source datasets. Our research provides a feasible methodology for developing countries with limited geospatial monitoring capabilities.

Our findings revealed that the total area of coastal marsh increased by 865.8 km^2, with most changes occurring during 2000–2010. Although the total coastal marsh area showed a net increase during the study period, there were distinct spatial patterns in coastal marsh changes across regions, with more evident changes occurring north of 30°N, especially in the Bohai Rim (37–41°N) and the Yangtze Delta (30–33°N). Among 25 km^2 hexagonal grids showing major losses (> 1,000 ha), 80.0% and 89.8% were concentrated in these two regions (37°N-41°N and 30°N-33°N) during 2000–2010 and 2010–2020, respectively. Similarly, for grids with substantial gains (> 1,250 ha), 87.2% and 75.0% occurred in these same regions during respective periods. The rising concentration of major marsh losses in these two regions indicates persistent degradation in specific areas—a pattern that overall area statistics fail to capture.

The drivers of coastal marsh changes varied across different latitude zones. Land reclamation was the predominant driver of wetland loss nationwide, with the most

substantial impacts observed in the Bohai Sea region. In the Bohai sea region, reclamation-induced marsh losses accounted for 46.1% of China's total, while gains were mainly driven by ecological recovery. Coastal marsh loss in the Bohai Rim showed strong spatial correlation with marine aquaculture expansion across latitude zones. In the East China Sea region, where the Yangtze River Delta is located, accretion drove marsh gains (> 65%) in both 2000–2010 and 2010–2020 periods. Against the backdrop of reduced sediment input from the Yangtze River, the latitude zones with more pronounced coastal marsh changes overlapped with the distribution area of *Spartina alterniflora*. The South China Sea region was the only sea area where reclamation areas decreased by 175.5 km^2 compared with the 2000–2010 period, with accretion and ecological recovery consistently accounting for approximately 55% and 45% of the region's gains respectively across both periods.

These findings underscore the critical need for region-specific coastal zone management strategies that balance economic development with ecological conservation. The spatially explicit understanding of driving forces provided by this study can inform targeted policy interventions and restoration efforts, ultimately contributing to more sustainable coastal marsh management across China's diverse coastal regions.

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Authors' contributions
Jiangjing Wang: Writing-original draft, Methodology, Data analysis, Visualization. Shiwei Lin: Writing-original draft, Conceptualization, Data analysis, Visualization. Wenzhen Zhao: Writing – review. Shupu Wu: Writing – review. Lv Gong: Writing – review. Yuanhao Song: Writing – review. Yang Hu: Writing – review. Xiuzhen Li: Supervision, Writing – Review & editing.

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Data availability
The datasets supporting the conclusions of this article are publicly available.

Declarations

Competing interests
The authors declare no competing interests.

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