

RESEARCH ARTICLE

Effects of reclamation and natural changes on coastal wetlands bordering China's Yellow Sea from 1984 to 2015

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Abstract

Coastal wetlands are rapidly disappearing worldwide, which is posing a substantial threat to the integrity of coastal ecosystems. In addition to the direct area reduction caused by reclamation, coastal wetlands experience natural changes due to sediment transport in coastal regions. Arguably, the reclamation rates must be less than the net accretion rate to guarantee the restoration of coastal wetlands. By applying an automatic and replicable shoreline algorithm to all available Landsat imagery from 1984 to 2015 using the Google Earth Engine Cloud Platform, we developed distribution maps of coastal wetlands and reclamation in China's Yellow Sea (CYS) at 4- or 5-year intervals. In addition, we divided coastal wetlands into saltmarshes and mudflats and analysed their trends separately. Over the past 30 years, the area of coastal wetlands decreased by 53% (from 6,463 to 3,036 km²), including a 67% decrease in saltmarshes (from 1,471 to 489 km²) and a 49% decrease in mudflats (from 4,992 to 2,547 km²). Meanwhile, the reclaimed area was 7,696 km² (including 1,276 km² of saltmarshes and 3,002 km² of mudflats), which exceeded the area of newly formed coastal wetlands (852 km²). The natural state of mudflats gradually changed from accretion to erosion, but without considering the natural state of coastal wetlands, reclamation will continue at a high rate in CYS according to China's national marine functional zoning (MFZ) for 2010–2020. In view of their important ecological services, there is an urgent need to revise the national MFZ to achieve 'no net loss' of coastal wetlands.

KEYWORDS

Google Earth Engine, land cover change, mudflat, national marine functional zoning, saltmarsh

1 | INTRODUCTION

Nourished by the material exchanged between the continent (land and rivers) and the ocean, coastal wetlands provide a wide range of critical services to human society (Barbier et al., 2011; Kirwan & Megonigal, 2013). However, they are also one of the most vulnerable ecosystems. During the past century, estimated losses of 50% or more than 80% of the original coastal wetlands occurred in many countries around the world (Airoldi & Beck, 2007; Kennish, 2001; Lotze et al., 2006). Threats from both the land and sea have led to wetland losses, including reclamation (Kennish, 2002; Ma et al., 2014), sediment starvation (Syvitski, Vörösmarty, Kettner, & Green, 2005), and sea-level rise (Kirwan & Megonigal, 2013; Nicholls, 2004). Among these factors, reclamation by seawall construction may cause direct and irreversible reduction of coastal wetlands, whereas other factors may cause continuous slow change (natural pattern) due to sediment transport. Coastal reclamation may cause offshore eutrophication, soil heavy metal and organic pollutant concentration, and finally cause wetland degradation and biodiversity loss (Balmford et al., 2005). Thus, monitoring the relative dynamics of reclamation and natural changes of coastal wetlands can provide basic data support for preventing coastal wetland degradation. In addition, to guarantee the recovery and sustainable use of coastal wetland resources, the reclamation rate of coastal wetlands should be controlled such that it does not exceed their accretion rate (Hodoki & Murakami, 2006). However, due to restrictions in monitoring techniques, very few studies have analysed the relative influence of reclamation and natural changes on the horizontal dynamics of coastal wetlands, especially in a large area.

In temperate and high latitudes, coastal wetlands can be divided into vegetated (saltmarshes) and barren flat (mudflats). They complement each other in supporting ecosystem services, but each has its unique characteristics. For example, saltmarshes play a greater role in storm protection, nutrient removal, and carbon sequestration (Deegan et al., 2012), whereas mudflats function more as feeding grounds for millions of migratory shorebirds (MacKinnon, Verkuil, & Murray, 2012; Melville, Chen, & Ma, 2016). Additionally, saltmarshes and mudflats are facing different levels of threats from both the land and sea. Near the land, saltmarshes have been reclaimed and modified on a large scale over the past century (Gedan, Silliman, & Bertness, 2009). Although invasion, mostly from the single genus *Spartina* (Levin, Neira, & Grosholz, 2006), can increase the area of saltmarshes, it can also have serious ecological consequences for local ecosystems (Li et al., 2009). In addition, coastal eutrophication can cause saltmarsh erosion by increasing aboveground leaf biomass and shallow dense root systems (Deegan et al., 2012; Wolters, Gillis, Bouma, Van Katwijk, & Ziegler, 2016). Exposed to the open water, mudflats are more sensitive to sediment starvation (Yang, Ding, & Chen, 2001), and sea-level rise may be ultimately responsible for their long-term erosion (Zhang, Douglas, & Leatherman, 2004). Owing to the dissimilarities in their ecosystem services and threats, saltmarshes and mudflats should be monitored and managed separately, which could assist in guiding conservation-oriented science and formulating sustainable development policies.

The Yellow Sea (including Bohai Bay) has attracted a great deal of research not only because of the extensive coastal wetlands (Murray, Ma, & Fuller, 2015), rich biodiversity (MacKinnon et al., 2012), and high economic value fishery output (Jin, Xu, & Tang, 2003) but also for the large-scale reclamation (Wang, Liu, Li, & Su, 2014) and the consequent series of acute environmental consequences (Studds et al., 2017). The development of coastal wetlands bordering the Yellow Sea depends on abundant riverine sediment supply, which is mainly from two rivers, the Yellow and Yangtze Rivers. Due to the construction of dams and reservoirs, soil and water conservation programmes, water consumption, and sand mining in the watershed, the sediment flux of the Yellow and Yangtze Rivers in the 2000s dropped to 14% and 10%, respectively, of the levels in the 1950s (Wang et al., 2007; Yang, Milliman, Li, & Xu, 2011). Sediment starvation should have a large impact on coastal wetlands, but few studies have monitored the natural changes of coastal wetlands at a regional scale. On the other hand, with a human population of 335 million, and a contribution of 35% of the national gross domestic product (NBS, 2014), there are strong socio-economic forces driving the reclamation of coastal wetlands bordering China's Yellow Sea (CYS; Ma et al., 2014). Due to the combination of sea-level rise (Feng & Tsimplis, 2014), land subsidence (Xue, Zhang, Ye, Wu, & Li, 2005), *Spartina* invasion (Zuo, Zhao, Liu, Wang, & Liang, 2012), and other factors, coastal wetlands bordering CYS suffered a 40% reduction in the 2000s (Murray, Clemens, Phinn, Possingham, & Fuller, 2014). If both coastal and fresh wetlands are taken into account, reclamation alone may account for 82% of the total wetland loss in China over the past half century (An et al., 2007). To date, only a handful of studies have mapped intertidal habitats (e.g., Gong et al., 2010; Murray et al., 2014; Murray, Phinn, Clemens, Roelfsema, & Fuller, 2012; Sagar, Roberts, Bala, & Lymburner, 2017); we progressed to the next step and provided the first map of coastal wetlands bordering CYS with more detailed habitat division. Based on these maps, we could further evaluate the suitability of reclamation according to the natural state of coastal wetlands bordering CYS.

To curb the widespread loss of coastal wetlands and the related biodiversity, marine spatial planning is increasingly considered an effective tool that can coordinate conflicts among various human uses and the marine environment (Kenchington & Day, 2011). In China, marine functional zoning (MFZ), created by China's State Oceanic Administration, was recently deemed a marine spatial planning practice (Douvere, 2008). However, the current MFZ mainly focuses on coordinating conflicts between users while largely ignoring conflicts with the environment (Fang, Zhang, Zhang, & Hong, 2011). In addition, as an important basis for the approval of reclamation, MFZ suffers from inadequate data monitoring to evaluate its performance. Furthermore, ecosystem-based principles are sometimes waived to meet the demands of local economic development (Wang et al., 2014). Thus, dynamic monitoring of coastal wetlands and reclamation is the cornerstone of determining coastal management policies and evaluating the rationality of existing policies. By applying time-series Landsat imagery and operating on the Google Earth Engine Cloud Platform, we (a) traced the historic spatio-temporal dynamics of coastal wetlands

and reclamation in CYS from 1985 to 2015 at 4- or 5-year intervals, (b) calculated the change rates of reclamation and the natural patterns of coastal wetlands, and (c) estimated the future impact of reclamation on coastal wetlands according to the national MFZ for 2010–2020.

2 | MATERIALS AND METHODS

2.1 | Study area

The Yellow Sea, a marginal sea of the Pacific Ocean, rests on a flat, broad, and tectonically stable seafloor with an average water depth of 55 m (Wang et al., 2010). CYS extends from the Yalu River estuary (40°59'N, 124°19'E) in the north to the Yangtze River estuary (30°46'N, 117°31'E) in the south (Figure 1a). The tides are typically semidiurnal, ranging from 1.5 to 8 m but generally approximately 2–4 m. According to the landform, there are two main types of coasts along the CYS, cliffed and alluvial coast. The cliffed coast is distributed along the western and southern parts of the Liaodong Peninsula and the eastern and southern parts of the Shandong Peninsula; the rest is alluvial coast. Due to the special hydrodynamic environment and sediment transport process, a radial tidal sand ridge system formed off the Jiangsu coast (Li, Zhang, Fan, & Deng, 2001), and this system constantly transports sediment towards the coastal wetlands (Xing, Wang, & Wang, 2012). The dominant native marsh plants are *Suaeda salsa*, *Phragmites australis*, *Aeluropus littoralis*, *Zoysia maerostachys*, *Imperata cylindrical*, and the introduced *Spartina alterniflora* (Yang & Chen, 1995).

2.2 | Landsat images and preprocessing

We utilized all TM and ETM+ images from 1984 to 2015 in the LEDAPS/LE7_L1T_SR and LEDAPS/LT5_L1T_SR datasets (a total of 11,264 images) to analyse the land cover changes in CYS. Images were computed with atmospheric corrections using the LEDAPS method (<http://ledaps.nascom.nasa.gov/>; see flow chart in Figure S1). A

Quality Assessment (QA) band was used to generate the cloud and snow masks to exclude bad observations. By processing images on the Google Earth Engine Cloud Platform (Levin et al., 2006), we generated a time-series of Landsat Land Surface Water Index (LSWI; Xiao et al., 2004) and Normalized Difference Vegetation Index (NDVI; Tucker, 1979) datasets as follows:

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}, \quad (1)$$

$$LSWI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}}, \quad (2)$$

where ρ_{red} , ρ_{NIR} , and ρ_{SWIR} are the surface reflectance values of Band 3 (red, 0.63–0.69 μm), Band 4 (near infrared, 0.76–0.90 μm), and Band 5 (shortwave infrared, 1.55–1.75 μm) in the Landsat TM/ETM+ sensors.

2.3 | Maps of reclamation

We screened one cloudless image for each period: 1985 (1984–1987), 1990 (1988–1992), 1995 (1993–1997), 2000 (1998–2002), 2005 (2003–2007), 2010 (2008–2011), and 2015 (2012–2015) and processed them into false colour composite images (musR/G/B = NIR/Red/Green). Artificial shorelines are formed by many types of ground features, such as sea dikes, buildings, aquaculture ponds, salt pans, roads, and cliffs. Given their complex structures, we delineated the artificial shorelines through visual interpretation and defined reclamation as the change in area between the artificial shorelines of successive periods. In addition, we ignored the changes in artificial shorelines within a period.

2.4 | Maps of coastal wetlands (saltmarshes and mudflats)

Monitoring the horizontal dynamics of coastal wetlands involves the following three main steps: developing an algorithm to determine the shoreline position, determining the wetland area at specific periods, and detecting the changes in area (Boak & Turner, 2005). To eliminate disturbance from water turbidity, we adjusted an automatic and repeatable shoreline algorithm ' $LSWI > NDVI + 0.5$ ' to ' $LSWI > NDVI + 0.4$ ' (Chen et al., 2016; Figure S2a–d). Then, we applied this adjusted algorithm to all Landsat images to extract water bodies and stacked all water body products within a 5-year period to generate water body frequency products. Due to the tidal cycle, the water body frequency of coastal wetlands should range between 0 and 1. However, random factors, such as water turbidity and bad observations, can lower the frequency values and blur the 'real' shorelines (Pekel, Cottam, Gorelick, & Belward, 2016), which is especially obvious near the cliffed coast. Thus, we reduced the highest water body frequency values of coastal wetlands to 0.75 along the alluvial shore and 0.35 along the cliffed coast (Figure S2e–g) and applied data delineation tools to extract the seaward boundaries of the coastal wetlands (Figure 1). Because Landsat sensors cannot detect high-tide

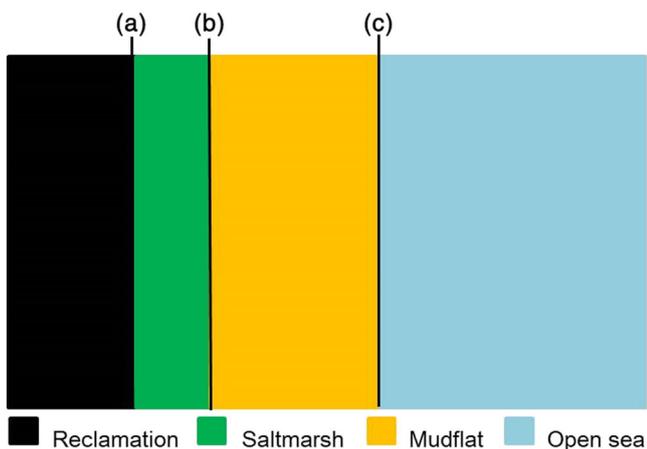


FIGURE 1 Schematic map of different types of land cover and shoreline. (a) Artificial shoreline; (b) the shoreline between saltmarsh and mudflat, and (c) the shoreline between mudflat and open sea [Colour figure can be viewed at wileyonlinelibrary.com]

shorelines under dense vegetation, we considered artificial shorelines as the shoreward boundary (Figure 1), and coastal wetland maps were developed.

Gross (2005) defined 'NDVI < 0.1' as barren land and 'NDVI \geq 0.1' as vegetated land. Referring to this method, we used the NDVI product extracted from all available Landsat images within a period to calculate the mean value and then applied the threshold to coastal wetland maps and divided them into saltmarshes and mudflats (Figure 1).

2.5 | Accuracy assessment

We independently validated our maps (saltmarsh, mudflat, and reclamation) in each period according to methods used in previous studies (Chen et al., 2016; Olofsson et al., 2014; Olofsson, Foody, Stehman, & Woodcock, 2013). We chose an image with cloudless conditions, at low tide, and in the growing season (May to October) to validate the data (Table S1). In addition, we used GPS-referenced photographs collected from field surveys, the Global Geo-Referenced Field Photo Library (<http://www.eomf.ou.edu/photos>) and high spectral resolution images in Google Earth TM for validation. Reference data were derived by an independent analyst who labelled each sample point with one of the three output classes or another class. As a result, the estimated overall accuracy was >89%; the estimated user accuracies of the saltmarsh, mudflat, and reclamation maps were >72%, >89%, and >84%, respectively; and the estimated producer accuracies were >57%, >92%, and >94%, respectively (Table S2).

2.6 | Change detection of coastal wetlands and reclamation

Uniting coastal wetland and reclamation maps of all periods into one shapefile, the land cover types of CYS include saltmarsh, mudflat, reclamation, and open sea. Through analysing the attribute table, we calculated the area of changes between different land cover types.

Reclaimed saltmarsh was calculated by the area of newly reclaimed saltmarsh minus the area converted from reclamation to saltmarsh, which is similar to calculate the reclaimed areas of mudflat and the open sea. Natural changes of saltmarsh was calculated by newly formed saltmarsh from mudflat and open sea minus the area converted from mudflat and open sea to saltmarsh, which is similar to calculate natural changes of mudflat. The average change rates of different variables were calculated by dividing the total change in area by the year interval in which the changes occurred.

2.7 | The national MFZ for 2010–2020

Based on the same projection coordinate system 'Asia North Albers Equal Area Conic' as the maps produced above, we digitalized the national MFZ. There are eight types of marine functional areas in China, including the agriculture and fishery zone, port and shipping zone, construction zone for industrialization and urbanization, mineral

and energy zone, tourism and recreation zone, marine protected area, special functional zone (for research, military, disposal, and dumping purposes), and reserved zone (SOA, 2012). Among these areas, only the industrialization and urbanization areas are completely reclaimed, and other types of functional areas may include reclamation and natural wetland habitats. Therefore, we considered the industrialization and urbanization areas to be the estimated minimum area of reclamation. Although the planning period was from 2010 to 2020, by stacking the coastal wetland maps and the national MFZ, we calculated the estimated area of reclamation from 2015 to 2020.

All the above processing steps were performed using the Google Earth Engine Cloud Platform, ArcGIS 10.1, and ENVI 5.2. The code for processing the Landsat images is presented in Table S3.

3 | RESULTS

3.1 | Dynamics of coastal wetlands and reclamation in CYS from 1984 to 2015

Over the past three decades, the area of coastal wetlands decreased by 53% (from 6,463 to 3,036 km²) in CYS. Saltmarshes suffered the most dramatic decline, with a net loss of 67% (from 1,471 to 489 km²), while mudflats decreased by 49% (from 4,992 to 2,547 km²; Figure 2b). The average change rates of saltmarshes and mudflats were -31.7 and -78.8 km² yr⁻¹, respectively. The remaining coastal wetlands are mainly distributed along the Jiangsu coast in the southern portion of CYS (47%), followed by large river estuaries such as those of the Yellow, Yangtze, Liao, and Yalu Rivers (Figure 2a). Focusing on the regions with larger wetland area, most coastal wetlands have been replaced by reclaimed land in the 30 years since 1985 (Figure 2c–h).

During the study period, reclamation occurred on many soft shores bordering CYS, with a total area of 7,294 km². With some seawalls continuously moving towards the sea, the land cover types subjected to reclamation gradually transitioned from coastal wetlands to the open sea during the study period. In 1985, 91% of the reclaimed land was coastal wetlands (41% on saltmarshes and 50% on mudflats), whereas in 2015, most reclaimed land (53%) was shallow sea rather than coastal wetlands (Figure 3).

3.2 | Relative influence of reclamation and natural patterns on the horizontal dynamics of coastal wetlands

From 1984 to 2015, for both saltmarshes and mudflats, the rates of reclamation always surpassed the net accretion rates, which caused net loss. For saltmarshes and mudflats, the reclaimed area was 1,276 and 3,002 km², respectively, and the net accretion area was 294 and 557 km², respectively. The reclamation rate of saltmarshes slowed down, and their erosion turned to accretion in the 1990s (Figure 4a). The reclamation rate of mudflats fluctuated, whereas the accretion rate continued to drop and finally converted to erosion (Figure 4b). The conversion between different land cover types is shown in Table S4.

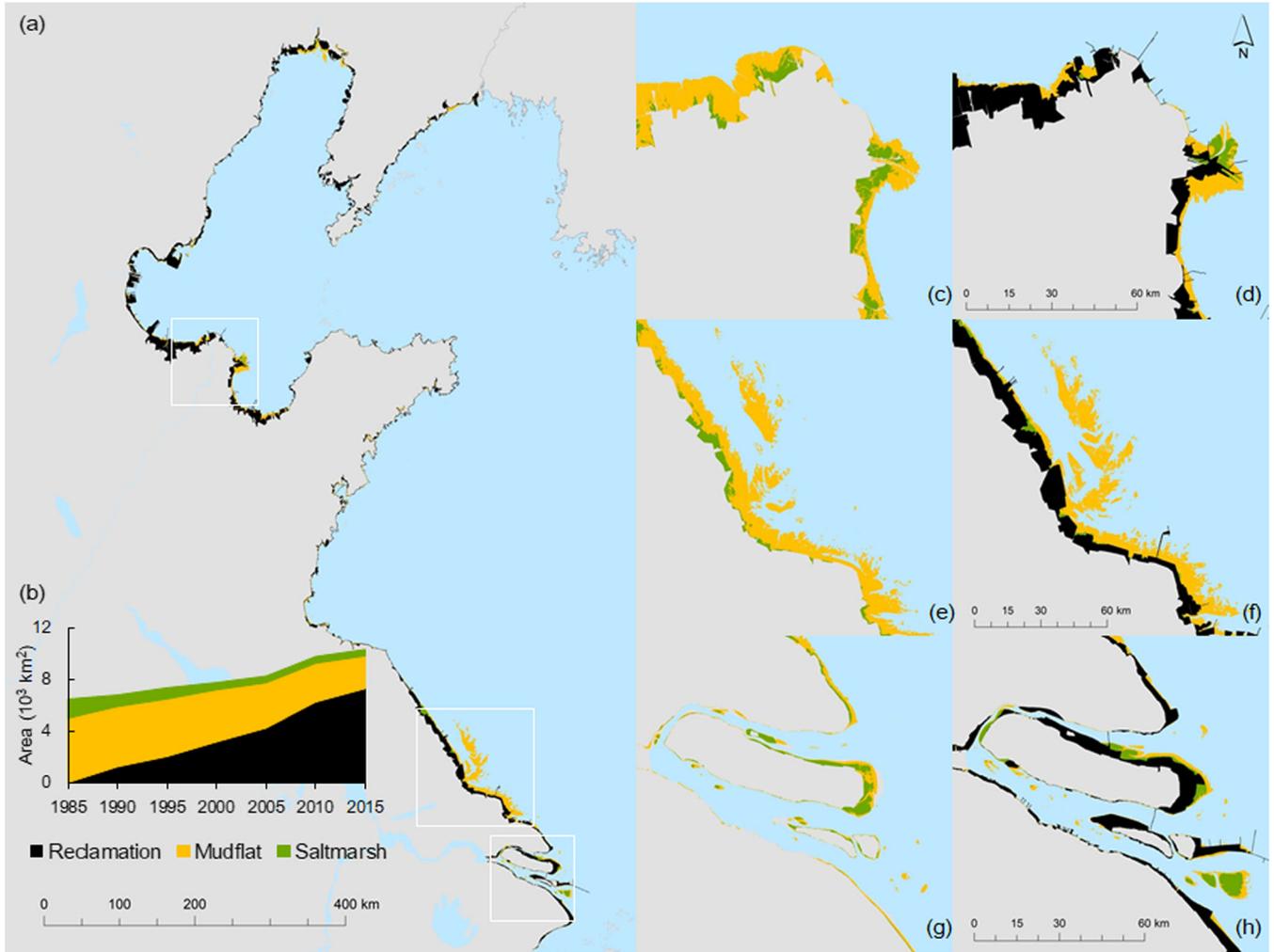


FIGURE 2 Land cover of the Yellow River estuary in the 1985 and 2015 period. (e–f) Land cover of Jiangsu coast in the 1985 and 2015 period. (g–h) Land cover of the Yangtze River estuary in the 1985 and 2015 period [Colour figure can be viewed at wileyonlinelibrary.com]

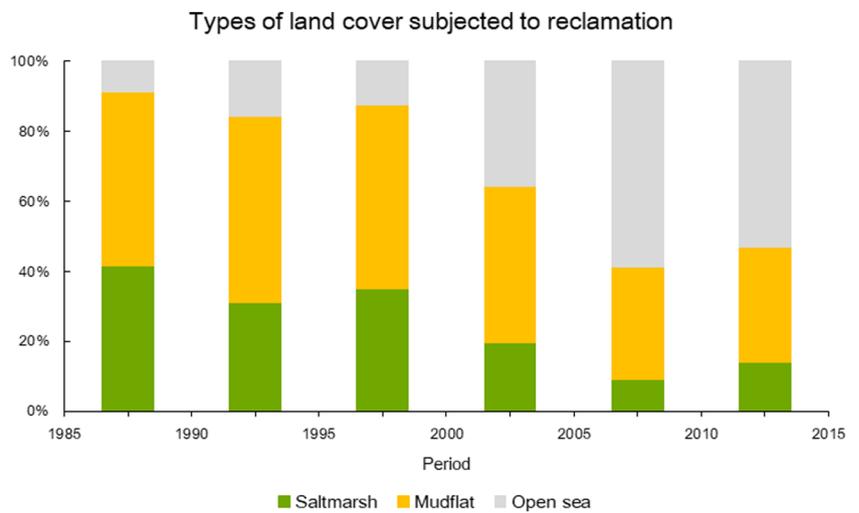


FIGURE 3 The percentage of different types of land cover subjected to reclamation [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Assessing the future impact of reclamation on coastal wetlands bordering CYS

Comparing the land cover composition map with the digitalized national MFZ for 2010–2020, the minimum estimated area of reclamation was 4,619 km², of which 47% had been reclaimed by 2015. Therefore, it is expected that a minimum area of 2,461 km² of land will be newly reclaimed from 2015 to 2020. Although most reclamation were predicted to be built on the open sea (77%) rather than on coastal wetlands, it will still remove 7% of the remaining saltmarshes and 21% of the remaining mudflats by 2015. Compared with historical changes, the future reclamation rate of mudflats would continue at a high rate, regardless of the current state of erosion (Table 1). For example, most of the wetlands connected to the Jiangsu coast will be reclaimed by 2020 according to the national MFZ, which will preserve nearly half of the coastal wetlands remaining in 2015 (Figure 5 a). Moreover, offshore sand ridges have been included in future reclamation planning (approximately 600 km²; Figure 5b).

4 | DISCUSSION

4.1 | Coastal wetlands halved and reclamation soared in CYS from 1984 to 2015

Over the past three decades, the area of coastal wetlands halved in CYS (from 6,463 to 3,036 km²); saltmarshes suffered a greater proportional loss (67%) than mudflats (49%), but mudflats suffered much greater total area losses (2,445 km²) than saltmarshes (982 km²). The coastal wetlands remaining in 2015 were mainly distributed along the Jiangsu coast and large river estuaries. Meanwhile, the area of reclamation reached 7,294 km², which is equivalent to more than 10-times the land area of Singapore, and the reclaimed land cover types gradually transitioned from coastal wetlands to the open sea. Due to the differences in data sources, shoreline determinations, shoreline extraction methods, and spatio-temporal resolution and coverage, it is very difficult to compare the actual area change among studies rather than the general trend. Consistent with previous findings, in this study, coastal wetlands bordering CYS were shown

TABLE 1 Comparing the past and future annual change rates (km² yr⁻¹) of reclamation and the natural patterns of coastal wetlands in CYS

Wetland type		1985–2015	2010–2015	2015–2020
Saltmarsh	Reclamation	42.53	5.99	6.67
	Natural change	9.81	22.28	
Mudflat	Reclamation	100.07	92.76	105.65
	Natural change	18.58	-4.85	

Note. For natural changes in coastal wetlands, the negative values indicate erosion.

Abbreviation: CYS, China's Yellow Sea.

to have suffered great losses and degradation, whereas reclamation is accelerating over a wide area (An et al., 2007; Gong et al., 2010; Murray et al., 2014).

4.2 | The influence of reclamation and natural changes on saltmarshes

Reclamation surpassed the net accretion and caused a reduction in the area of saltmarshes bordering CYS in most periods. Despite the massive reclamation in 1985, the natural state of saltmarshes gradually changed from erosion to accretion in 1990.

Among many vital ecosystem services provided by saltmarshes, buffering the coastlines from natural hazards is one of the most important services (Shepard, Crain, & Beck, 2011). In the context of global sea-level rise and intensified natural hazards, many low-elevation coastal zones are vulnerable to coastal flooding, and CYS is highly threatened due to dense coastal populations (Nicholls & Cazenave, 2010). It is estimated that sea-level rise may cause a 22% loss of the world's coastal wetlands by the 2080s, but combined with reclamation, the losses may increase to 70% (Nicholls, Hoozemans, & Marchand, 1999). Evidence suggests that saltmarshes could increase their vertical sediment deposition or migrate onto adjacent uplands to actively resist the deleterious effects of sea-level rise (Foster, Hudson, Bray, & Nicholls, 2013). However, the conventional coastal defence method (seawalls) would block their landward progression, and the narrowing width of tidal wetlands would cause serious

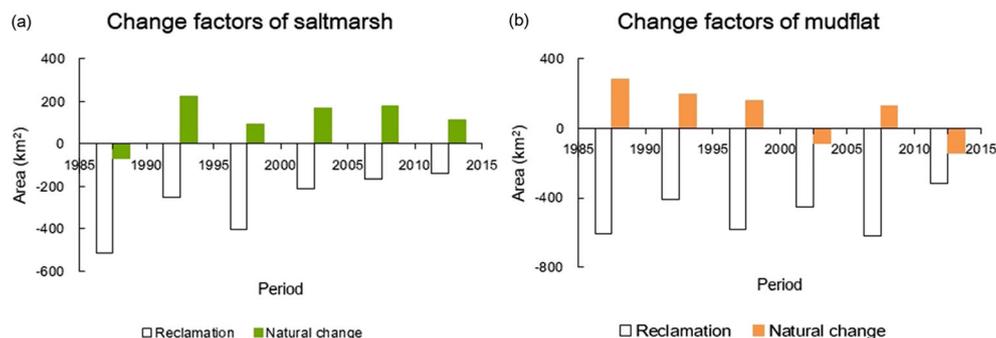


FIGURE 4 Relative influence of reclamation and natural changes on saltmarsh and mudflat in China's Yellow Sea from 1985 to 2015. The positive values indicate accretion and the positive values indicate erosion [Colour figure can be viewed at wileyonlinelibrary.com]

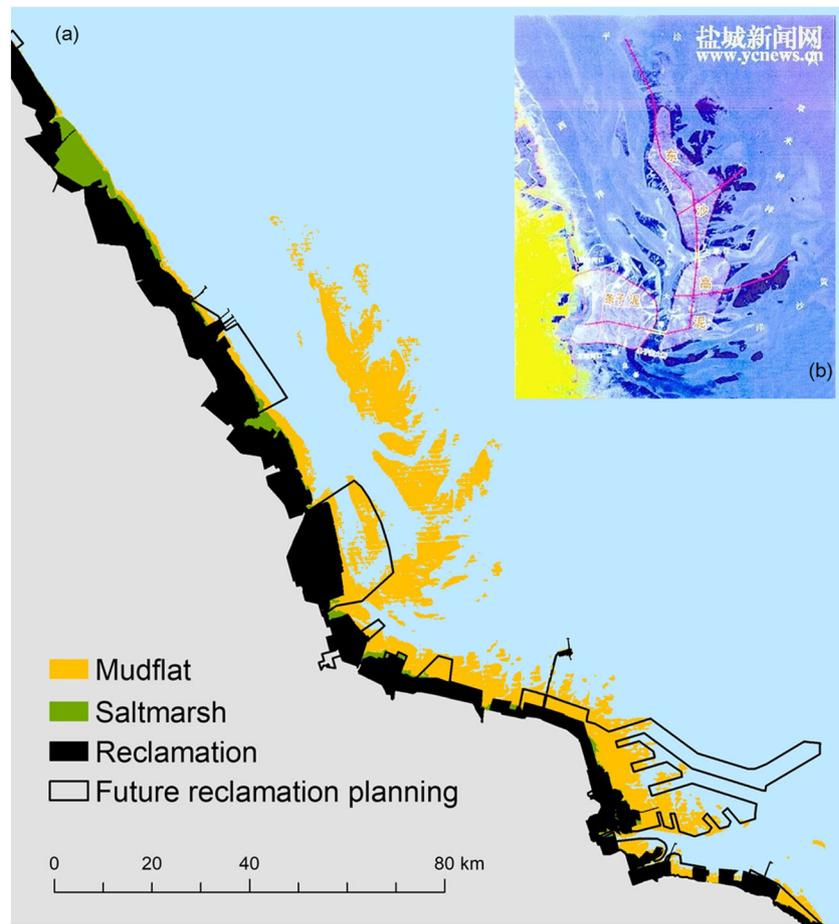


FIGURE 5 Future planning of reclamation and remaining tidal wetland in the 2015 period along part of Jiangsu coast. (a) Estimated reclamation in the national marine functional zoning for 2010–2020. (b) Future planning of 'Millions of acres of reclamation' in Jiangsu [Colour figure can be viewed at wileyonlinelibrary.com]

wave-induced boundary erosion to saltmarshes (Mariotti & Fagherazzi, 2013). Moreover, as the reclaimed land is converted into industrial parks and towns, increasing severe terrigenous eutrophication may also cause substantial erosion of saltmarshes (Deegan et al., 2012; Kovacs, 2000). If the impacts caused by reclamation escalate and exceed the tolerance of saltmarshes (Xie, Xu, Duan, & Xu, 2012), coastal residents and property will be directly exposed to the threat of storm surges and floods.

After extensive reclamation in 1985, the natural state of saltmarshes changed from erosion to accretion. The main reason for saltmarsh accretion is the world's largest invasion of *S. alterniflora* (Qiu, 2013), which was introduced to China for the purpose of erosion control and promoting reclamation. Populations of *S. alterniflora* rapidly expanded in the 1990s (Zhang, Shen, et al., 2004), which coincided with the transition of the natural state of saltmarshes from erosion to accretion. By 2007, *S. alterniflora* had expanded to an area of 345 km², of which the Jiangsu coast accounted for 70% (Zuo et al., 2012). Although *S. alterniflora* can increase the area of saltmarshes, they change the structure and function of local vegetation and ecosystems (Li et al., 2009). For example, the proliferation of *S. alterniflora* can occupy a large area of mudflats, which would impact migratory shorebirds, which strongly depend on these mudflats, particularly in the Yellow Sea, as feeding grounds (Iwamura et al., 2013; Piersma et al., 2016).

4.3 | The influence of reclamation and natural changes in mudflats

Similar to saltmarshes, the reclaimed rate surpassed the natural changes in mudflats bordering CYS. Unlike saltmarshes, mudflats have converted from accretion to erosion over the past decade.

The progress in technology and equipment, in particular the use of geotextile tubes for seawall construction (Xie, Zuo, & Dou, 2010), allowed reclamation to expand seawards. Even so, reclaiming mudflats can disturb the balance of the natural hydrodynamics and sediment dynamics, which damages the stability and sustainability of the coastal environment (Kuang, Huang, Lee, & Gu, 2013). Large-scale reclamation can simplify coastlines, therefore increasing the alongshore sediment transport (Kuang et al., 2013) and reducing the suspended sediment concentration by 15–20%, which directly affects coastal landform evolution (Mitchell & Uncles, 2013). In addition, following sequential reclamation, mudflats become narrower and steeper, and the redistribution of tidal energy could have far-reaching effects on tidal dynamics across the sea (Song, Wang, Zhu, & Bao, 2013). Moreover, the increased hydrodynamics would cause the progressive shoreward elimination of the finest sediments (Flemming & Nyandwi, 1994), which may change the biogeochemical cycles, the composition of mud-living organisms and, consequently, the ecosystem characteristics (McCave, 1984).

Sediment delivery was determined to be a primary regulator of coastal wetlands (Jaffe, Smith, & Foxgrover, 2007). Without vegetation coverage, mudflats are more vulnerable than saltmarshes to erosion caused by sediment starvation (Yang et al., 2001). Two of the world's four rivers with the largest sediment loads empty into CYS; the Yellow and Yangtze Rivers discharged 1.1 and $0.5 \times 10^9 \text{ t yr}^{-1}$ of sediment, respectively, before the 1950s (Milliman & Meade, 1983); the current loads have been reduced to 14% and 10% of the previous sediment flux (Wang et al., 2007; Yang et al., 2011). As a result, sediment starvation would eventually cause coastal erosion or deltaic growth stagnation (Yang et al., 2003), especially for the open coasts with smaller sediment supplies. Therefore, the remaining coastal wetlands bordering CYS are currently only concentrated on the Jiangsu coast and large river estuaries, where there is relatively more sediment deposition. Given that state of mudflats has already converted to erosion in recent years, reclamation planning should be carefully designed to maintain the integrity of coastal wetland ecosystems.

4.4 | Reclamation will continue to occupy coastal wetlands according to the national MFZ for 2010–2020

In creating the guideline for exploiting marine and coastal resources and protecting the environment (Lu, Liu, Xiang, Song, & McIlgorm, 2015), MFZ should consider the natural characteristics of the environment (Fang et al., 2011). Thus, to maintain the high-value ecosystem services provided by coastal wetlands, reclamation should be controlled according to their natural pattern. Combining two datasets, we found that regardless of the dramatic decline in coastal wetlands bordering CYS, reclamation is planned to continue at a rapid rate, further eliminating the remaining wetlands. According to the national MFZ for 2011–2020, a total area of $2,496 \text{ km}^2$ of land will be reclaimed from 2011 to 2020 in CYS (Wang et al., 2014), which is only one half of our estimates based on the digitized data. Moreover, compared with other land use types, such as aquaculture and port, the industrialization and urbanization areas only account for a small proportion (10%) of the reclaimed land (Islam, Miah, & Inoue, 2016), which means that the scale and extent of coastal wetland reclamation in the next few years may far exceed our estimates.

Meng et al. (2017) suggested that neither economics nor population density but policies are the direct driving forces of China's reclamation of wetlands. For instance, to maintain the total amount of cultivated land, reclaiming coastal wetlands is the fastest and least expensive way to increase the construction land quota, which may bring substantial economic benefits to the local government (Alphan, 2012). However, given the context of global sea-level rise, many countries have adopted management policies such as the "Integrated Coastal Zone Management" strategy and the 'no-net-loss' policy, which had been shown to effectively control the downward trend in the area of coastal wetlands (Gedan et al., 2009). In the Wadden Sea, another of the largest intertidal areas in the world, the Dutch and German parts have been designated as a UNESCO World

Heritage Site (CWSS, 2008). Reclamation in that region had slowly ceased in the 1980s because nature was valued above economic gains (Wolff, 1992). The surrounding three countries (including the Netherlands) have formed the Trilateral Wadden Sea Cooperation and worked together to preserve the Wadden Sea (Wilhelmshaven, 2009). Until recently, CYS was tentatively nominated as a World Heritage Site (<http://whc.unesco.org/en/tentativelists/6189/>).

Under the impetus of researchers and conservationists, China has moved to protect coastal wetlands, and some response policies have been determined (Stokstad, 2018). For example, the central government created a 'red line' to protect 53 million hectares of wetlands, most of which are in danger of reclamation. China's State Oceanic Administration created 16 marine parks, setting aside $124,000 \text{ km}^2$ of coastal and marine areas under various levels of protection. However, due to the lack of national wetland protection laws, the extent of the implementation of the policies remains to be seen. Furthermore, conservation jurisdictions can be unclear in the intertidal zone. Managed by multiple agencies, China's coastal wetlands are still considered as 'unused lands,' and then stimulating the exploitation of wetland resources (Ma et al., 2014). Based on the dynamics of coastal wetlands and reclamation, we urge the government to strictly control reclamation and invest more in wetland restoration.

4.5 | Improvement and uncertainty of the method of monitoring dynamics of coastal wetlands

Building on the initial studies of Murray et al. (2014, 2012) that developed tidal wetland maps of CYS, we applied the waterline technique to Landsat time-series imagery to analyse the dynamics of coastal wetlands bordering CYS. Additionally, the image processing method applied in this study was improved in the following aspects. First, we used a rapid, automatic, and repeatable shoreline algorithm to detect the low-tide shorelines, which were considered the seaward boundaries of the coastal wetlands (Chen et al., 2016). This algorithm not only reduces the effect of suspended sediment near shorelines by introducing NDVI but also avoids the subjective manual thresholding process by the logical combination of indices, which can speed up the processing time. Second, we called all available Landsat images during one period to extract coastal wetlands, rather than selecting images with less than 30% cloud coverage and within the 10% range of high tide and low tide for analysis. Through this process, all effective pixels of the Landsat images can be used to analyse the ever-changing coastal wetlands. Third, we chose artificial shorelines as the landward boundary of the coastal wetlands instead of the high-tide shorelines. When applying the waterline technique to determine the landward boundary of coastal wetlands, there may be two problems. First, because Landsat sensors cannot penetrate dense vegetation to detect waterlines, this method may exclude dense saltmarshes outside the intertidal zone. Since 2000, populations of *S. alterniflora* have expanded on the coast of CYS (Zuo et al., 2012). Therefore, failing to include dense saltmarshes may lead to the

inaccurate estimation of wetland dynamics. Second, aquaculture ponds, salt pools, and other water bodies may be erroneously misclassified as coastal wetlands. Although the extraction of artificial shorelines is based on subjective visual interpretation, and introducing some of the uncertainties mentioned below, this will solve the above problems and lead to more accurate results for dynamics analysis of coastal wetlands. Moreover, by using an NDVI threshold division method to divide coastal wetland into saltmarsh and mudflat (Gross, 2005), we provided the first map of coastal wetlands bordering CYS with a more detailed habitat division (reclaimed land, saltmarshes and mudflats).

Although we mined serial Landsat imagery to conduct the wetland dynamic analysis, there was still uncertainty in this study. First, the tide range revealed by images among periods may introduce errors to the calculation of the actual change in the area of coastal wetlands. Due to the mismatch of the satellite period (16 days) with the daily rhythm of the tide, as well as the interference of clouds and wind, the possibility of satellites capturing the lowest tide shoreline is very low. Therefore, rather than using the largest extent of coastal wetlands, we applied a fixed shoreline algorithm and water body frequency to reduce this interference. We quantified this error (7%) using a tide table for the Yangtze River estuary (Chen et al., 2016). However, due to the cost and inaccuracy of tide tables, we did not try to quantify this error in this article and only regard it as one of the error sources. Second, when we chose artificial shorelines as the landward boundary of the coastal wetlands, some supratidal zone may be included in the intertidal zone, which may lead to overestimation of saltmarsh area. Because most supratidal flats had been reclaimed in China's coastal zone by 2000 (Chen, 2000), applying artificial shorelines as the landward boundary of coastal wetlands is reasonable when analysing the dynamics of saltmarshes. Third, the influence of Scan Line Corrector (SLC)-off does exist when analysing the wetland dynamics. Because coastal wetlands are highly dynamic compared with other fixed ground features, any patch repair method supplemented by iteration or historical data may not be suitable for this area. Therefore, we recognize it as a source of error and did not try to eliminate it. Last, the estimated producer accuracies were low (>57%) for saltmarshes, mainly due to the mismatch between the validation data and products. Lacking historical validation data, we called one Landsat image in each period to verify the products that were processed by all images in a certain period. Therefore, some confusion and misjudgement may occur; for example, due to the tidal effects, the low-elevation tidal flats may be flooded, and the original vegetation or flat pixels may be classified as water. Therefore, the actual Pixel Area (PA) for saltmarshes and mudflats should be higher than the result of the current assessment. Despite these uncertainties, the estimated overall accuracy of our products (>89%) is acceptable. In addition, although Landsat imagery has many advantages for analysing wetland dynamics, such as zero cost, medium resolution, global coverage, and the existence of long-term time-series, it is still unable to detect the maximum exposure area of coastal wetlands. Thus, additional data sources should be used to address this problem in future research.

5 | CONCLUSIONS

Here, we provide the first maps of coastal wetlands with more detailed habitat divisions in CYS. According to the analysis of these time-series maps, coastal wetlands bordering CYS have halved in area in the past three decades (from 6,463 to 3,036 km²) and will continue to decrease in the next few years. Among the coastal wetlands, saltmarshes suffered a greater proportional loss (67%) than mudflats (49%), and mudflats suffered much greater total area losses (from 4,992 to 2,547 km²) than saltmarshes (from 1,471 to 489 km²). Meanwhile, the area of reclaimed land reached 7,294 km² in CYS and surpassed the natural changes to dominate the reasons for wetland losses. With seawalls continuously moving towards the sea, the rate of reclaiming saltmarshes gradually slowed down, whereas the rate of reclaiming mudflats remained high. Furthermore, the natural state of mudflats has been transitioned from accretion to erosion. Although saltmarshes have started to accrete, to a large extent, it was a false increase caused by *Spartina* invasion. In the context of global sea-level rise, there is an urgent need to revise the national MFZ, highlighting the conservation value of coastal wetlands, and to achieve sustainable social, economic, and ecological development in the coastal regions.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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