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Impacts of Coastal Reclamation on Natural Wetlands in Large River Deltas in China

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Abstract: Little information is available on the impacts of coastal reclamation on wetland loss in large-river deltas at a regional scale. Using remote sensing data of coastal wetland and reclamation in four deltas in China from 1978 to 2014, we tracked their continuous area changes in four periods: 1978–1990, 1990–2000, 2000–2008, and 2008–2014. The areal relation between wetland loss and reclamation was quantified and used to identify coastal reclamation mode intensity coupled with another three indicators: reclamation rate, accretion rate and land-use intensity of coastal reclamation. The results showed that coastal reclamation driven by economic development reduced, or even reverse the original growth of delta which was determined by the offset between wetland acceleration rate and wetland loss rate. Generally, the area of reclamation showed a positive linear correlation with the area of wetland loss. The findings imply that human activities should control reclamation rate and intensity to alleviate total wetland loss and maintain wetland 'net gain'. Inappropriate coastal reclamation modes can magnify total wetland loss; therefore, coastal reclamation with a slow increment rate and low impervious surface percent is of great importance for sustainable development in future coastal management.

Keywords: coastal reclamation; wetland loss; coastal reclamation mode; multi-case comparison; large river delta; coastal management

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1 Introduction

With the rapid economic development and population growth, coastal reclamation has become an important way to compensate for a shortage of land resources at the expense of ecosystem degradation in coastal regions (Lotze et al., 2006; Halpern et al., 2008; Bianchi and Allison, 2009; Bai et al., 2015a; Gaglio et al., 2017; Nguyen et al., 2017; Wang et al., 2017). Over the past four decades, coastal wetlands have undergone dramatic degradation and loss worldwide due to large-scale exploitation for agriculture, industry and aquiculture (Barbier et al., 2008; Halpern et al., 2008; Gittman et al., 2015; Xiao et al., 2015; Zhao et al., 2016). Wetlands in deltaic areas especially provide critical habitats for important fishery resources and the stopover breeding and wintering habitats for waterbirds in the East Asian-Australasian Flyway (Bai et al., 2015b; Murray and Fuller, 2015; Sun et al., 2015). However, the highest intensity of coastal reclamation has been conducted on eastern China's coastline since 1970s (He et al., 2014; Ma et al., 2014; Jiang et al., 2015; Meng et al., 2017; Xia et al., 2017; Chen et al., 2018; Ren et al., 2018). It is urgent that we should manage coastal reclamation in cooperation with wetland conservation, to maintain long-term sustainable development in China's coastal regions

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regions (Wang et al., 2014; Cui et al., 2016; Xia et al., 2017; Yang et al., 2017). Understanding the response of natural wetlands to coastal reclamation is critical to evaluate its impact at a regional scale.

A large number of literatures showed that coastal reclamation was the significant driving force for coastal wetland loss (Murray et al., 2014; Cui et al., 2016; Ma et al., 2019a). Various ecological processes, including hydrology, sediment deposition, plant evolution and landscape connectivity had been altered by human activities (Lotze et al, 2006; Barnard et al., 2013; Wang et al., 2014; Chen et al., 2016; Zhu et al., 2017; Mou et al., 2018). These changes usually caused the degradation or loss of wetlands and presented as wetland area loss at a regional scale. However, the evaluation of wetland area loss caused by reclamation activities was usually not effective. A majority of studies have focused on the calculation of directly occupied area due to coastal reclamation (Van Rees and Reed, 2014; Yan et al., 2015; Chen et al., 2016; Xia et al, 2017). Few studies have described the dynamic changes and the quantitative relationship between coastal wetland and reclamation at a spatiotemporal scale. In addition, wetland loss caused by potential impacts of reclamation is usually complicated and overlooked. For example, intense and disorderly reclamation could hinder the adaptation of coastal wetlands moving inland to sea level rise, leading to the coastal squeeze that narrows wetland growth (Kirwan and Megonigal, 2013). Thus, the wetland area loss driven by coastal reclamation would be larger than the actual area occupied by the reclamation. However, which indicator drives the variations in the responses of wetlands to reclamation and their areal relationships are still poorly known at a regional scale.

Large-river deltas, especially estuarine zones, have been identified as natural 'recorders' of global environmental change and display a sensitive response to external disturbances (Bianchi and Allison, 2009). Most researches have been conducted as a single case study to analyze the impacts of coastal reclamation on ecosystems and environments. Ecological consequences of coastal reclamation in each of the large river deltas in China have been studied from different perspectives (Li et al., 2012; Chen et al., 2018; Ren et al., 2018; Wan et al., 2018; Ma et al., 2019b). Additionally, the total area of a delta keeps growing in natural environments because river-derived sediments continue to accumulate in a coastal water bodies (Lotze et al., 2006; Bianchi and Allison, 2009). It is significant for coastal management to investigate whether human activities push deltaic wetlands far from their original dynamic balance by comparing multiple cases.

Indexes or frameworks associated with coastal reclamation have been developed to evaluate environment pressures from coastal reclamation (Yan et al., 2015; Xu et al., 2017). However, few studies have explored the development mode of coastal reclamation, which is more applicable to direct future management at a regional scale. For the coastal reclamation mode (CRM), the developing rate, land-use intensity and the area of wetland loss caused by coastal reclamation are crucial to assess the total area of reclaimed wetlands: 1) The rate of reclamation generally opposes the rate of acceleration and self-recovery of deltaic wetlands. The comparison between reclamation rate and accretion rate of wetlands can reflect the net change of coastal wetlands. A high development rate usually causes natural ecosystem to be quickly destroyed as natural ecosystems have less time to renew or restore. 2) Land use type, to some extent, represents the intensity of coastal reclamation (Li et al. 2013). The 'soft' and 'hard' engineering of coastal reclamation along shorelines can be categorized (Lai et al. 2015). Soft types, such as mariculture and cropland, or reclamation of natural wetlands to artificial wetlands, retain some functions of wetlands, such as providing the alternative habitats for waterbirds (Ma et al., 2004; Bellio et al., 2009; Marquez-Ferrando et al., 2014; Green et al., 2015). With high-intensity coastal reclamation, hard engineering indicate impervious constructions, such as ports, dams and other infrastructures, which reconstruct the local wetlands into a man-made environment and also dramatically change features of surrounded ecosystems (Kirwan and Megonigal, 2013; Gittman et al., 2016). 3) The area of wetland loss caused by coastal reclamation would be determined by the relationships between reclaimed area and wetland area loss, which indicates the impact intensity of coastal reclamation mode in terms of area. Therefore it is useful to group these indicators and compare them in different regions to explore the CRM for wetland ecosystems.

The objectives of this paper are to explore the impacts of coastal reclamation on natural wetlands by the comparison of multiple deltas and to assess the reclamation mode to give practical suggestions for coastal conservation and management. Four major river deltas in China were used as case studies, where natural wetlands were widely distributed while anthropogenic activities were dramatically expanded (Bianchi and Allison, 2009; Zhang et al., 2010; Li et al., 2012; Chen et al., 2016; Zhu et al., 2017). We tracked the continuous change in the area of natural wetlands and coastal reclamation in four periods from 1978 to 2014 by available remote sensing images. The CRM was assessed in each of the four deltas.

2 Materials and Methods

2.1 Study area

We selected four large river deltas in China as study areas, including the Liaohe River Delta in Liaoning (LRD, 40°45′N–41°10′N and 121°30′E– 122°00′E), the Yellow River Delta in Shangdong (YRD, 36°55′N–38°12′N and 118°07′E–119°18′E), the Yangtze River Delta in Jiangsu/Zhejiang and Shanghai (YtRD, 30°30′N–31°30′N and 120°E–121°E) and the Pearl River Delta in Guangzhou Province (PRD, 21°34′N–23°56′N and 111°58′E–114°38′E) (Fig. 1). They are alluvial plains formed by sediment deposition from the Liaohe River, the Yellow River (Huanghe River), the Yangtze River (Changjiang River) and the Pearl River. Increasing vulnerability of coastal wetlands was observed in the four large river deltas due to intense coastal reclamation activities. In the last few decades, a large number of coastal reclamation engineering projects have been constructed (Ma et al., 2015; Chen et al., 2016; Xu et al., 2017).

In the LRD, approximately 57 000 ha of reed marshes are one of the largest such areas in the world. The wetlands in the LRD have been protected since 1986 by-Shuangtaihekou National Nature Reserve (Yan et al., 2018). However, as a result of the exploration its area has dramatically shrunk for fish and rice, energy, building materials, and water supplication (Li et al., 2012; Wan et al., 2018). In addition, as the traditional agro-economic zone for growing rice and aquaculture fields, large-scale wetlands were converted to croplands (Li et al., 2012).

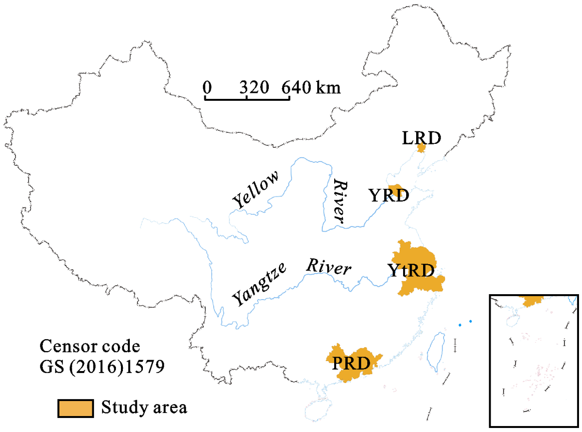

Fig. 1 Location of the four large river deltas in China. LRD is the Liaohe River Delta; YRD is the Yellow River Delta; YtRD is the Yangtze River Delta; PRD is the Pearl River Delta

The YRD is the largest and youngest river delta in China. With an abundance of vegetation and aquatic biodiversity, natural wetlands in the YRD have provided waterbird habitats for breeding, foraging and wintering. This is an important stopover in the inland of Northeast Asia and one of the crucial sites on the East Asian-Australasian Flyway (Murray and Fuller, 2015). However, the natural wetlands in the YRD have been greatly decreased by urban expansion, aquaculture and oil exploration (Ren et al., 2018), even though major estuarine wetlands has been protected by the Yellow River Delta National Nature Reserve since 1992.

The YtRD is one of the world's largest alluvial deltas, which is located in the most developed economic zone in China, supporting 8.1% of the national population with 1.2% of the total land area of China according to the 2014 China census. The rapid development of industrialization and urbanization greatly threaten the regional ecology and environment by transferring coastal wetlands to mariculture, cropland and industrial construction (Chu et al., 2013; Li et al., 2014; Chen et al., 2016; Chen et al., 2018).

The Pearl River is discharged into the South Sea with eight river branches, resulting in a complicated spatial distribution of natural wetlands with abundant biodiversity. With seven major developed cities, the deltaic region is comparatively dense in population with an average of 1209 persons/km^2. To meet the development of agriculture and industry, most natural wetlands have been transformed into man-made space; therefore the PRD was called the 'Word Industry' (Zhang et al., 2010).

2.2 Data acquisition and processing

To investigate the continuous change in the area of coastal wetlands and reclamation since the implement of 'Reform and Opening-Up' Policies in China in 1978, four periods were classified based on the economic development rate: early stage (1978–1990), medium stage (1990–2000), economy accelerated stage 2000–2008), and consolidation stage (2008–2014). We collected 65 available Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper+ (ETM+) images with a cloud cover of approximately 10% or less for 1978, 1990, 2000, 2008 and 2014 from the United States Geological Survey Data Center (http://glovis.usgs.gov/). We delineated coastal reclamation by artificial visual interpretation of the false color-composited images with the resolution of 30 m × 30 m. Three reclamation types (mariculture, cropland, and impervious construction) were identified by their specific texture in images. This was verified by field work.

Then, we generated the maps of coastal reclamation by stacking images of successive periods. Data of coastal wetlands in 1978, 1990, 2000 and 2008 were provided by the Institute of Remote Sensing Applications, Chinese Academy of Sciences. We extracted and reclassified wetland types into coastal intertidal zones (the tidal flats zone inundated by tide) and river estuaries (the mouth of river zone) in four large river deltas. Using the same data acquisition and processing, we produced maps of natural wetlands in our study regions in 2014 by artificial visual interpretation on the relevant remote sensing images (Niu et al., 2008). Then, we conducted an overlay analysis of the maps of coastal wetlands and coastal reclamation using ArcGIS10.2 software package.

2.3 Area calculation and statistical analysis

The equations for calculating the cumulative areas of wetland loss (A_{loss}) and the newly-formed coastal wetlands (A_{gain}) are given as follows:

$$A_{\text{loss}} = A_{j=0} + \sum_{j=1}^{n} A_{\text{gain}} - A_j \tag{1}$$

$$A_c = A_{j=0} + \sum_{j=1}^{n} A_{\text{gain}} \tag{2}$$

where A is the area of natural wetlands (km^2), 0 is the starting year of a period, n is the number of periods and j is the period. A_{loss} is the area of disappearing wetlands, A_{gain} is the area of newly-formed wetlands by accretion, and A_C is the assuming area of wetlands with gain instead of loss. A_j is the area in the map of existing wetlands in period j. A_{gain} is the new part in the map of existing wetlands in some periods than in last period, which was generated by the overlay analysis using ArcGIS10.2 software package. Then the area of wetlands, coastal reclamation and the A_c were calculated for 1978, 1990, 2000, 2008, and 2014. Furthermore, the relationships between the areas of coastal reclamation and wetland loss (A_{loss}) were analyzed by the linear regression analysis using Origin 8.0 software package. Their proportionality coefficients were identified as the impact coefficients to evaluate the impacts of coastal reclamation on wetland loss.

2.4 Exploring the coastal reclamation mode

Using multiple indicators including reclamation rate, wetland accretion rate, land use intensity (i.e., the percent of impervious construction) and the impact coefficient (i.e., the impact of reclamation on coastal wetland area), we developed the coastal reclamation mode intensity (*CRMI*) to identify the impacts of CRM on coastal wetlands, which is calculated by Eq. (3):

$$CRMI = \frac{R_r}{R_a} \times I_s \times \frac{A_{\text{loss}}}{A_r} \tag{3}$$

where R_r is reclamation rate calculated by the average reclamation area per year; R_a is accretion rate calculated by the average accretion area of wetlands per year; I_s is the impervious surface percent indicating the ratio of construction area to the area of all land use and land cover types including wetland area and reclamation area; A_{loss} and A_r is the area of wetland loss and reclamation, respectively. In this study, the low impact CRM was identified as the relative low disturbance of coastal reclamation in the historic period, which was illustrated by previous researches. Firstly the reclamation rate was less than or equal to the wetland accretion rate (Chen et al., 2016). Secondly land use intensity do not exceed the state in low impact historic period. Finally in terms of the wetland loss caused by reclamation, the potential areal loss wouldn't be considered excepting for the occupied wetland area. Therefore, we assumed that when R_r was less than or equal to R_a (Chen et al., 2016), A_{loss}/A_r, which is the impact coefficient for evaluating the impacts of coastal reclamation on wetland loss, got the minimum value, and I_s was less than or equal to the historic average value before 1990 when was demonstrated as the historic period with relative low intense reclamation (He et al., 2014; Wang et al., 2014), the *CRMI* value presented the low-impact CRM.

3 Results

3.1 Area changes of coastal reclamation and natural wetlands

As shown in Fig. 2, wetlands maintained a net increase in the PRD but a net loss in the LRD, YRD and YtRD in 1978–2014. The loss rates of natural wetlands in the LRD, YRD, YtRD and PRD were 11.00 km^2/yr, 45.67 km^2/yr, 73.47 km^2/yr, and 26.11 km^2/yr, respectively and the corresponding reclamation rates were 5.40 km^2/yr, 25.63 km^2/yr, 37.63 km^2/yr, and 14.43 km^2/yr. Natural wetlands showed an increase in the early stages but consistently decreased from 2000 to 2014. Meanwhile, the reclamation area in the four deltas consistently increased. The area of natural wetlands could maintain a net increase when it was slowly reclaimed in the early stage (1978–1990) in all the four deltas. However, when coastal reclamation was widely expanded, the wetland area decreased quickly, especially in the economy-accelerating stage (2000–2008). The assuming area of wetlands without loss but including newly-formed wetlands calculated by the Equation (2) was presented in Fig. 2. Obviously, the area of natural wetlands in the four deltas will show a net increase if there is no loss, and the original acceleration rates calculated by the average accretion area per year in the LRD, YRD, YtRD and PRD were 10.92 km^2/yr, 32.06 km^2/yr, 49.89 km^2/yr and 29.81 km^2/yr, respectively, showing the abilities of wetland growth for different accreting deltas. The higher increasing rates of coastal reclamation were observed in the YtRD and YRD since 2000. Comparatively, either the acceleration rate of wetlands or the increasing rate of coastal reclamation was relatively slight in the LRD and PRD.

3.2 Quantitative impacts of coastal reclamation on wetland loss

Fig. 3 illustrated that the area of wetland loss was strongly positively correlated with coastal reclamation, but the regression equations showed different proportionality coefficients (slopes) in the four deltas. The slopes of wetland loss to coastal reclamation were identified as the impact coefficients, and greater impact coefficients implied a larger area of wetland loss driven by coastal reclamation. The impact coefficients were all more than 1.0, which means the total area of wetland loss was larger than the reclamation area. Different

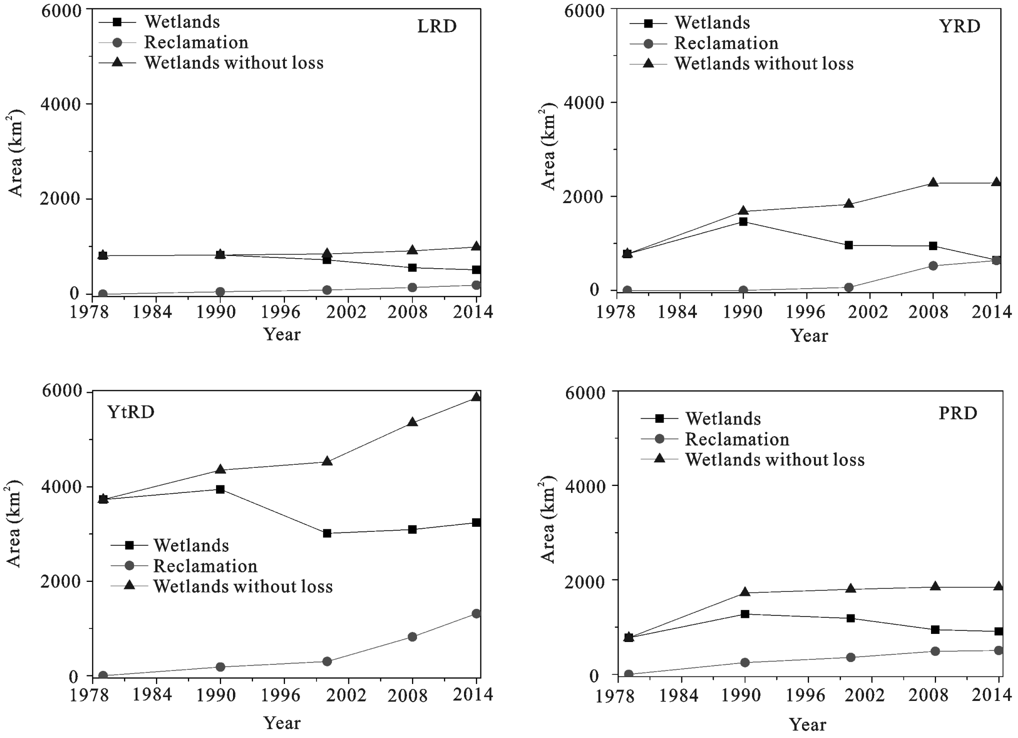

Fig. 2 Changes in the areas of coastal reclamation and natural wetlands in the four large river deltas during 1978–2014. LRD is the Liaohe River Delta; YRD is the Yellow River Delta; YtRD is the Yangtze River Delta; PRD is the Pearl River Delta

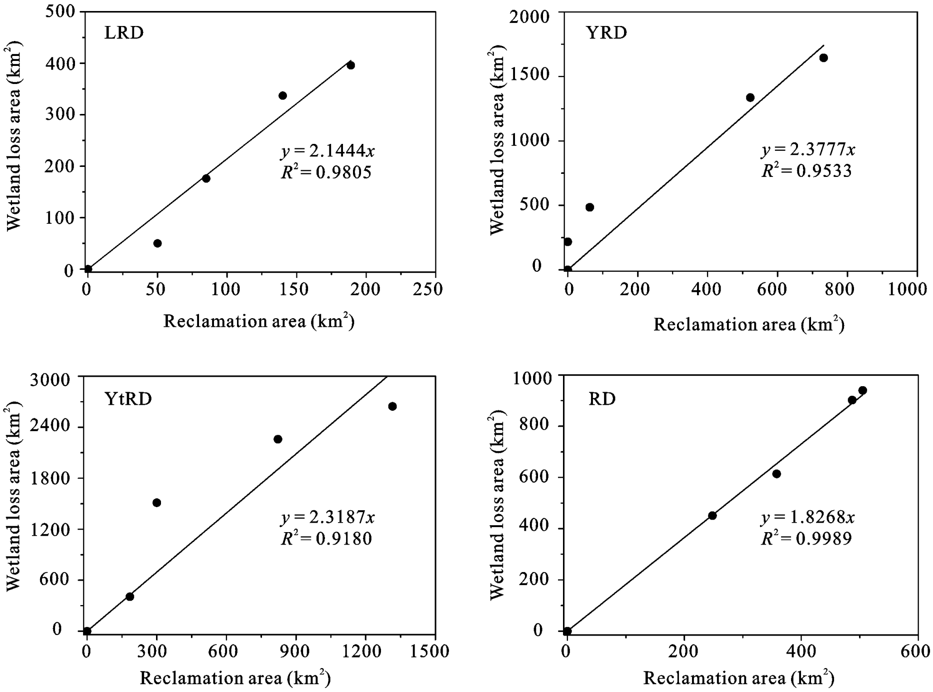

Fig. 3 Relationships between the areas of wetland loss and coastal reclamation in the four large river deltas of China. LRD is the Liaohe River Delta; YRD is the Yellow River Delta; YtRD is the Yangtze River Delta; PRD is the Pearl River Delta

coefficient values denoting the impact extent of coastal reclamation on natural wetland were not identical in the four deltas. The greater impact coefficients of the YRD and YtRD indicated that coastal reclamation would cause more wetland loss in the YRD and YtRD compared with the LRD and PRD. The largest impact coefficients occurred in the YRD, while the smallest coefficients were observed in the PRD, indicating that coastal reclamation would result in a larger impact on wetlands in the YRD than those in other deltas.

3.3 Coastal reclamation mode

The geographical location of coastal reclamation was identified by its spatial expansion (Fig. 4). Most coastal reclamation occurred in the intertidal zone along the shoreline in the YRD and YtRD. Notably, coastal reclamation eventually occupied almost the whole intertidal zone in the YRD, but the reclaimed area was mostly located in middle- or high-tide zones (avoiding the low-tide zone) in the YtRD. Most reclaimed area occurred in the river estuaries of the LRD and PRD.

The percentages of the three reclamation types in each delta during 1978–2014 were calculated. As shown in Fig. 5, mariculture was the major reclamation type in the four deltas, especially in the YRD. Cropland was relatively abundant in the LRD and YtRD. There was a high intensity of impervious construction in the PRD. The LRD had a similar percent structure of these three reclamation types to the YtRD. The construction percentage implied the reclamation intensity, because construction with the impervious surfaces represented a complete transition of wetlands into man-made spaces while artificial wetlands, cropland and mariculture still provide some ecosystem services.

We identified the CRM by a comparative analysis of the CRMI in four deltas (Table 1). Result showed all the CRMIs in the four deltas exceeded the scope of low impact CRMI, which were larger in the YtRD and PRD than in the PRD and YRD. Different groups of CRM indicators generated different CRMI values. Though the percentage of reclamation rate to accretion rate and the impact coefficients were relative smaller in the PRD, but the high impervious percentage dominantly contributed to the CRMIs, which was the biggest value in the four deltas. In contrast, the YRD had the highest ratio of reclamation rate to accretion rate and the impact coefficient, but with the least CRMI due to the lowest impervious percentage. Both of the YRD and YtRD had a

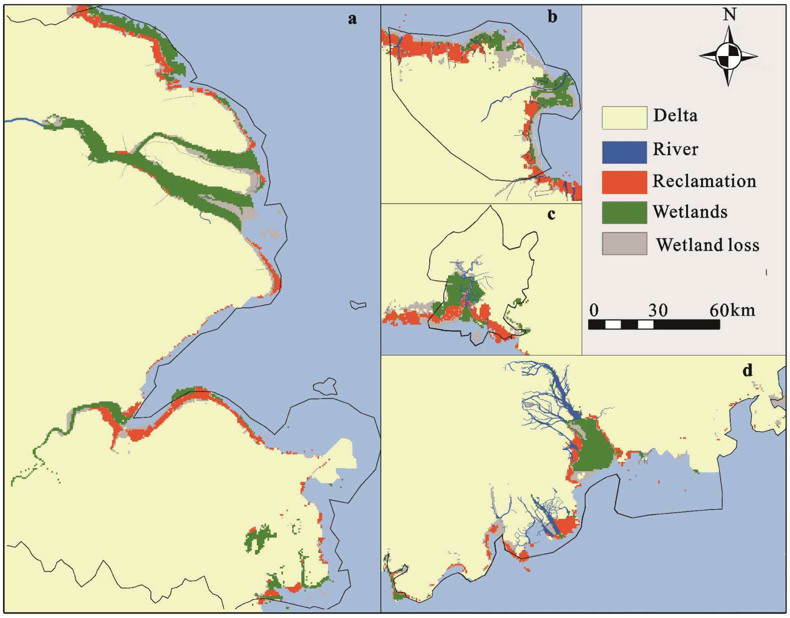

Fig. 4 Spatial distributions of natural wetlands and reclaimed wetlands in the four deltas. Coastal reclaimed area was obtained by the area of wetlands occupied by mariculture, cropland and construction during 1978–2014. Coastal wetland area was the existing area in 2014. Wetland loss was generated by the Equation (1). a, the Yangtze River Delta; b, the Yellow River Delta; c, the Liaohe River Delta; d, the Pearl River Delta

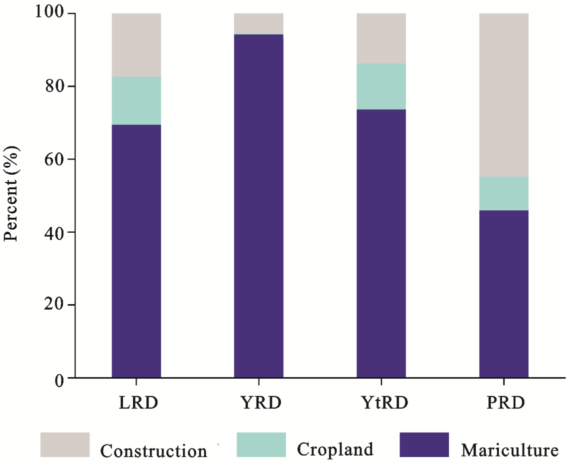

Fig. 5 The percentages of coastal reclamation types in the Liaohe River Delta (LRD), the Yellow River Delta (YRD), the Yangtze River Delta (YtRD) and the Pearl River Delta (PRD) during 1978–2014

high rate of coastal reclamation and wetland accretion, and similar impact coefficient, but coastal reclamation in the YRD showed a lower percentage of impervious surface which made the CRMI in YRD much smaller than in the YtRD. The LRD and YRD had a similar CRMI, which was dominated by impervious construction percent and reclamation rate, respectively.

4 Discussion

The findings revealed that wetland loss driven by anthropogenic interferences can modify the original growth of river deltas. Modifications such as shrinkage, stopping or reversal could be determined by the balance of wetland formation and loss rates. The natural accretion of coastal wetlands in previous research was usually neglected in the impact assessment of human activities, which mostly focused on the wetland loss (Ma et al., 2014; Tian et al., 2016), whereas the newly-formed wetlands in the four deltas were apparent at a regional scale, especially when long temporal scales were taken into consideration (Murray et al., 2014; Chen et al., 2016). This study showed that when we assumed that there was no reclamation disturbance, deltas would maintain a net growth, but when the area loss was larger than new formation, a delta would have a net loss in wetland area. Thus, sustaining the valuable ecosystem services provided by natural wetlands will require the accretion rate of coastal wetlands in excess of wetland loss rate (Chen et al., 2016). Then, the appropriate area of coastal reclamation can be calculated using the impact coefficient to determine total wetland loss. It is now imperative to create management policies which should

Table 1 Indicators of coastal reclamation modes and the coastal reclamation mode intensities (CRMIs) in the four large river deltas of China

Delta	Reclamation rate (km^2/yr)	Accretion rate (km^2/yr)	Reclamation rate/Accretion rate (%)	Impervious construction (%)	Impact coefficient	CRMI	Low-impact CRMI
LRD	5.40	10.92	49.95	30.53	2.14	0.32	≤ 0.07
YRD	25.63	32.06	79.94	6.92	2.38	0.13	
YtRD	37.63	49.89	75.43	26.35	2.32	0.38	
PRD	14.43	29.81	48.41	54.06	1.83	0.48	

Notes: LRD is the Liaohe River Delta; YRD is the Yellow River Delta; YtRD is the Yangtze River Delta; PRD is the Pearl River Delta. The impact coefficients were generated by the ratios of wetland loss area to reclamation area. The maximum of low impact CRMI was calculated when the reclamation rate equaled to wetland accretion rate, the reclaimed area equaled to wetland area loss, and the percentage of impervious construction could be generated by the average value of the impervious construction percentage in the four river deltas during 1978–1990

pay more attention to the original dynamics to maintain not only ‘no net loss’ but also ‘net gain’ in deltaic regions by controlling reclamation activities (Kassakian et al., 2017).

The area of coastal wetland loss could be caused by coastal erosion, the sinking of deltas, and human activities (Syvitski et al., 2009; Murray et al., 2014). If we only calculate the contributions of area occupied by coastal reclamation to wetland loss, the contribution would be 47.73%, 44.53%, 49.79%, and 53.72% in the LRD, YRD, YtRD and PRD, respectively. The area of wetland loss caused by coastal reclamation was larger than the reclaimed area and these two types of areas showed a positive linear correlation, which implies that the potential impact from coastal reclamation also contributed to the total wetland loss. Previous researches demonstrated that the effects on wetlands from other disturbances could be magnified when recombining with human reclamation (Kirwan and Megonigal, 2013; Pontee, 2013). For example, Taramelli et al. (2015) illustrated that wetland subsidence in a delta had increased significantly due to the impact of intense human activity. The intense and disorderly reclamation could hinder the adaptation of coastal wetlands to sea level rise, causing a coastal squeeze (Kirwan and Megonigal, 2013). Further research should focus on the development of a multi-disturbance integrated method to assess wetland loss by multi-case comparison.

The response of wetland loss to reclamation, coupled with the ratio of reclamation rate to wetland accretion rate and land use intensity in deltaic regions to a large extent can compare and distinguish the advantages of CRMs. By the comparison of multiple indicators in a multi-case study, we could observe that the intensity for different CRM varies markedly over the relative amount of wetland loss caused by coastal reclamation, increment rate, and land-use intensity. Long-term reclamation with high development rate would intensify the impacts of human activities on natural wetlands (Tian et al., 2016). The percentages of impervious construction essentially indicated the intensity of coastal reclamation, since the engineering structures such as seawalls would block the wetland hydrological and biological connectivity (Lotze et al., 2006; Cui et al., 2016). A high percentage of impervious surface means a larger percentage of wetland function loss in one region. In this study, the CRMIs for all the four deltas exceeded the value of low impact, indicating coastal management should re-plan the current CRMs to reduce the impacts of coastal reclamation (Wang et al., 2014). The reclamation rate was less than the wetland accretion rate and the wetland loss exceeded the occupied wetland area in all deltas. The impervious construction percent became the crucial indicator for their CRMIs. The percentage of impervious construction was driven by the economic development coupled with local natural resources (Tian et al., 2016). There were large-area tidal flats in Chinese northern deltas such as the YRD, with the dependency on agricultural and aquaculture products for local economic growth, which provided the natural conditions and economic needs for the development of agriculture and mariculture (Murray et al., 2014). However, the rapid development of urbanization and industrialization caused the high percent of impervious construction, which improved the CRMIs such in the YtRD and the PRD (Tian et al., 2016). Meanwhile, the low reclamation rate determined the relative low CRMI in the LRD though it had the high percent of impervious construction, indicating the efficient protection of the natural reserve in the LRD. In addition, despite of the occupied area, coastal reclamation in the inappropriate geographic locations could also threaten the surrounding living coastlines (Cui et al., 2016). At a regional scale, human activities will disturb sequential succession, and its impact is more severe when it occurs in an inferior ecosystem (Lazarus et al., 2016; Zhu et al., 2016). A disorderly reclamation distribution can also strengthen the impacts of sea level rise on coastal wetlands, reduce sediment supply, accelerate coastal erosion and lead to the subsidence of deltas (Kim, 2012; Kirwan and Megonigal, 2013; Taramelli et al., 2015). Coastal reclamation in the intertidal zone caused more severe ecological loss than that in an estuarine area. The intertidal region is a systematic ecosystem with the high, middle and low tides formed by the dynamic interactions between land and ocean (Morris et al., 2002). Stable and multiple successions from ocean to land allow the development of a wetland ecosystem. Once the intertidal zone is reclaimed, total succession periods would be interrupted, and it would take a long time to restore their original evolutionary system (Zhang et al., 2015). However, environmental conditions are more dynamic and unitary in a river estuary with the sedimentation carried by the river every year (Bianchi and Allison, 2009). When there is a disturbance in an estuary, other homogeneous areas would take over the function, or it would be compensated by the newly-formed wetlands. Thus, through this comparative analysis of CRMs among four deltas, we proposed that where and how fast the coastal reclamation occurs would be more significant for practical management than what it would be used for at a regional scale. Ecological vulnerable areas should be prevented from reclamation, and coastal reclamation with a slow increment rate and low percentage of impervious surface are also recommended to maintain the living coastline in a deltaic region.

Comparative studies are ultimately necessary to understand the connections between anthropogenic activities and ecological loss, and to enable better environmental and social outcomes from planning initiatives (Kittinger et al., 2014; Ma et al., 2019a). Integrating the multi-indicators of human activities in multiple cases to find the response of coastal ecosystem to external disturbances may assist practitioners in developing more comprehensive analyses for decision making, balancing ecological conservation and economic development.

5 Conclusions

Four large river deltas in China were selected to track the continuous changes in the areas of coastal wetlands and reclamation to supply a reference evaluation of coastal reclamation impacts on natural wetlands and suggest a cooperative coastal reclamation strategy for coastal wetland management. We identified the quantitative areal relationships between wetland loss and coastal reclamation and the CRM identified by the CRMI values. The direction of growth for an accelerating delta can be influenced by long-term human activities, and the positive linear relationships between the area of wetland loss and coastal reclamation indicated that the contribution of coastal reclamation to wetland loss was not only from the occupied area but also from the expanded potential impacts. Therefore, to sustain the ecosystem services of coastal wetlands, it’s necessary that the wetland loss rate should not exceed the accretion rate of the delta. The increase rate of coastal reclamation can be calculated based on the impact coefficients between total wetland loss and coastal reclamation to maintain a ‘net gain’ in deltaic regions, besides ‘no net loss’. Furthermore, to decrease the reverse impacts of coastal reclamation on coastal wetlands, the reclamation rate, wetland accretion rate, land-use intensity and geographic location of coastal reclamation should be balanced, and priority indicators should be identified during the comprehensive planning. It is proposed that the coastline management be realigned to emphasize natural dynamic principles and insist on a low-impact CRM, integrating with natural wetland conservation.

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