Joint Effect of Spartina alterniflora Invasion and Reclamation on the Spatial and Temporal Dynamics of Tidal Flats in Yangtze River Estuary

Yi-Fei Liu 1, Jun Ma 1, Xin-Xin Wang 1, Qiao-Yan Zhong 1, Jia-Min Zong 1, Wan-Ben Wu 1, Qing Wang 2 and Bin Zhao 1,*

Abstract: Tidal flats, which are non-vegetated land–sea transition areas, have an important ecological function in the global ecosystem. However, they have been shrinking in recent years due to natural and anthropogenic activities. Although many studies focus on tidal flats in the Yangtze River estuary (YRE) in China, how reclamation and plant invasion affect the expansion and erosion of tidal flats are still unclear. In this study, we analyzed all of the available Landsat TM/ETM+ /OLI imagery from the period 1996 to 2018 using the Google Earth Engine (GEE) cloud computing platform to obtain annual maps of coastal tidal flats of YRE at 30 m spatial resolution. We chose three sample tidal flats where severe Spartina alterniflora (S. alterniflora) invasion, reclamation, and control areas existed to explore the joint impact of plant invasion and reclamation on tidal flats. We also point out the main driving factor of tidal flat expansion of each island in YRE by multiple linear regression. Our results suggest that the tidal flats of YRE had obvious expansion from 1996 to 2018, and the speed of expansion is getting slower because of the decreasing deposits in the Yangtze River. Invasive S. alterniflora is effective at promoting silting, and tidal flats with S. alterniflora invasion expanded 2.54 times faster than the control group. Chongming and Hengsha Islands were mainly affected by sediment concentration, while Changxing and Jiuduansha Islands were affected by reclamation and S. alterniflora invasion, respectively. The results could be used to support coastal zone management and biodiversity conservation of the YRE.

Keywords: tidal flats; plant invasion; reclamation; Google Earth Engine; Yangtze River estuary

1. Introduction

Coastal tidal flats are land–sea transition zones neighboring coastal vegetation areas, and are usually referred to as non-vegetated coastal areas. Coastal tidal flats often serve as important habitats for zoo-benthos (crabs, nematodes, mollusks, etc.), fish, waterfowl, and migrating birds [1–5]. Moreover, they help prevent coastal erosion and protect terrestrial ecosystems from storms and other natural disasters, due to their location as a buffer zone [6]. Although tidal flats have crucial ecological functions, around 16% of global tidal flats were lost between 1984 and 2016, and 50–80% were lost in the Yellow River Delta between the 1950s and the 2000s, arousing global concern [7,8].
The erosion of tidal flats can stem from many factors, such as reduced sediment supply from rivers, sinking estuary deltas, rising sea levels, artificial projects, and biological invasion [9–13], the most important of which are reclamation and plant invasion [14]. Natural land formation of coastal plains would take hundreds of years of deposits from river sediment, and reclamation is an ecological engineering measure to accelerate the procedure [15]. The reclamation of tidal flats transfers the land cover type to farmland, fish ponds, forest land, and settlements for anthropogenic activities [14]. Therefore, large-scale reclamation causes a decrease in large areas of tidal flats.

Invasive plants are introduced from a separate ecosystem and compete strongly with native species, posing a huge threat to the local ecosystem by superseding dominant native vegetation types, diminishing the abundance and survival of native species, and altering the nutrient cycle, hydrology, and energy budget [16]. Spartina alterniflora (S. alterniflora), an invasive plant from North America (North Carolina, Georgia, and Florida), was introduced to tidal flats and offshore sands of the Yangtze River estuary starting in 1997 to accelerate the natural land formation [3,17], and it successfully sped up sediment accretion [15,18]. However, it replaced many native species and became the dominant species in the local ecosystem, with its robust reproductive capacity, fast growth, and high salt tolerance, leading to great difficulties in managing the plant [3]. Tidal flats invaded by S. alterniflora faced tall and dense vegetation and reduced food resources, which significantly affected the migratory waterbird communities [19]. There are many studies focused on the distribution of S. alterniflora invasion in China [3,10,20–23], but the exact data are lacking on how fast it accelerates tidal flat accumulation, and the joint effect of reclamation and S. alterniflora invasion on tidal flats.

Reclamation and plant invasion are not isolated phenomena. In December 2013, to restore the bird habitat of the Scirpus mariqueter (S. mariqueter) community and tidal flats, an ecological control project was conducted in Chongming Dongtan National Nature Reserve to replace S. alterniflora with native S. mariqueter and Phragmites australis (P. australis). A 25-km-long dike was built to cut off the expansion route of S. alterniflora, with a guiding strategy of “enclosure, cutting, inundation, solarization, cultivation, adjusting” and re-vegetation practice of S. mariqueter supported at tidal flats [24,25]. Thus, studying the effect of S. alterniflora on tidal flats and analyzing the dynamics of the tidal flats during the control project period are crucial for understanding the joint effect of reclamation and plant invasion.

With their high resolution, free access, and global coverage, satellite images provide stable, high-repetition rates of images, which is a time- and effort-saving approach to multitemporal monitoring of the dynamic of tidal flats and vegetation cover. In traditional coastal wetland studies, identifying coastline from a single satellite image was an important issue [26]. As the satellite image capture time is inconsistent with the tidal periodic dynamics, the tidal height is uncertain in the image, which is a great error for long-term sequences in traditional single-image coastline analysis [27]. Secondly, many global land cover data products provide a wetland layer in recent years; however, their classification systems are different [28–35], along with the research into wetland distribution in China [36,37]. Thirdly, previous studies about tidal flats mainly focused on short-term monitoring (single year) [23,27,35–41], and few studies explored mapping tidal flats on Google Earth Engine (GEE) [8,42,43] (Table 1). Both long-term analysis of the evolutionary process of one certain region and the potential driving forces behind the change were rarely explored based on GEE. Long-term observation is necessary; it can help us better understand the development process of tidal flats and is more conducive to local sustainable development and ecological protection. The GEE cloud computing platform provides access to satellite images in all Google servers, and customizes algorithms to each pixel unit, maximizing the utilization of all available pixel data (even images affected by large coverage of cloud layer can be utilized efficiently), and reduces the influence of tide, vegetation phenology and image quality on the results [44,45]. Furthermore, GEE maintains the consistency of global products. Users using the same algorithm to process the same data source on the platform will obtain the same result, which avoids the product error caused by differences in personal processing methods.
Table 1. A summary on remote sensing research and maps on coastal wetlands in China in the past 10 years.

| Selected Years | Study Area | Region | Global |
|----------------|------------|--------|--------|
| 1990,2000      | China      | Gong et al. (2010) [36] |        |
| 1978,1990,2000,2008 | China      | Niu et al. (2012) [37] |        |
| 1985,1990,1995,2000,2005,2010,2014 | Yangtze River estuary | Chen et al. (2016) [39] | Gong et al. (2013) [34] |
| 2010          | Global     | Chen et al. (2017) [27] |        |
| 2015          | China      | Liu et al. (2018) [23] |        |
| 2015          | China eastern coastal zone | Zhang et al. (2019) [40] |        |
| 1995,2015     | China      | Han et al. (2019) [41] |        |
| 2017          | Global     | Chen et al. (2019) [43] | Gong et al. (2019) [35] |
| 1984–2015     | Yellow River estuary | Wang et al. (2018) [42] | Murray et al. (2019) [8] |
| 1984–2016     | China      |        |        |
| 1996–2018     | Yangtze River estuary | This study |        |

The Yangtze River Estuary (YRE), with severe *S. alterniflora* invasion, reclamation, and control areas existing together, was selected as our study area to compare the impact of plant invasion and reclamation on tidal flat development through analyzing time-series Landsat TM/ETM+/OLI images from 1996 to 2018 and using the GEE cloud computing platform. The main objectives of this study include the following:

1. To generate tidal flat mapping in YRE during the period 1996–2018;
2. To analyze the spatial and temporal dynamics of tidal flats in YRE;
3. To explore the influence of reclamation and plant invasion on the development of tidal flats in YRE.

2. Materials and Methods

2.1. Study Area

The study area is located at the mouth of the Yangtze River in eastern China, between 31°05′–31°40′N and 121°40′–122°10′E, including Chongming Island (CMI), Changxing Island (CXI), Hengsha Island (HSI), and Jiuduansha Island (JDSI). The development of CXI and HSI is closely associated with reclamation, and their shorelines are smooth and straight. Eastern CMI and JDSI have natural developing tidal flats and rough shorelines. Therefore, our study focused on eastern CMI and middle and lower JDSI with natural shorelines (Figure 1). There is a simple plant zonation pattern in YRE. The three dominant species are *P. australis*, *S. alterniflora*, and *S. mariqueter*, which have zonal distribution. *S. mariqueter* occupies the low tide zone and *P. australis* occupies the high tide zone [46]. *S. alterniflora* competes with *P. australis* and *S. mariqueter* in the middle tide zone. *P. australis* and *S. alterniflora* usually grow to 1.5–2.0 m tall, while the height of mature *S. mariqueter* is only 0.3–0.7 m [47]. *S. alterniflora* was introduced to JDSI in 1997 and Dongtan in 2001 [3,17], so our study period started at 1996, one year before the introduction of *S. alterniflora*.

Three sample bands 2 km wide were selected to compare the effect of plant invasion and reclamation on tidal flats: Dongtan (DT) on eastern CMI, with both plant invasion with disturbance and reclamation; Jiuduansha (JDS), with only plant invasion and no disturbance; and the control group (CG) on southeastern CMI, with neither plant invasion nor reclamation (Figure 2). The control group and two sample areas are at the same estuary, which reduces the background interference and allows a comparison of comprehensive disturbances at the same time. At the point of 31°32′13″N, 121°52′53″E, two lines were radiated with a depression of 15° and 48° to traverse the Dongtan Nature Reserve and farm on CMI. The DT line was parallel with the outline of dike 2013, and the CG line was through the center of the farm. The other point was the center of the upper JDSI wetland, at 31°11′38″N, 121°58′48″E, then the same operation was conducted with a depression of 12°, in the same direction as...
the JDSI tidal flat expansion. For each central line of the three samples, 1 km rectangular buffer samples were generated on both sides, leading to a 2 km wide rectangle with a length varying according to the spatial and temporal development of each sample.

Figure 1. Location of mouth of Yangtze River and dikes with construction years on eastern Chongming Island (CMI).

Figure 2. Locations of sample areas: (a) light blue boxes are locations of (b,c); (b) red box is Dongtan (DT) and orange box is control group (CG); (c) white box is Jiuduansha (JDS).

2.2. Landsat Data and Pre-Processing

Compared with the conventional approach using only a single image per year, all available Landsat 5/7/8 images from 1996 to 2018 were included in this research on the GEE platform,
where all image pre-processing tasks could be carried out efficiently using programming and image-processing techniques [45]. We counted the number of good-quality observations of Landsat images (Figure 3a), the total number of observations of individual pixels by Landsat 5/7/8 (Figure 3b), and the distribution of annual good-quality observations of all pixels from 1996 to 2018 (Figure 3c). We used a total of 1763 images to generate water frequency maps after removing poor-quality observations, including clouds, shadows, and scan-line corrector (SLC) off gaps by quality assurance (QA) band.

**Figure 3.** Availability of time series Landsat images from 1996 to 2018: (a) number of good-quality observations of all Landsat images (path: 118, row: 38); (b) number of Landsat 5/7/8 images from 1996 to 2018 used in this study; (c) distribution of annual good-quality observations of all pixels from 1996 to 2018.
Nominalized difference vegetation index (NDVI) [48], enhanced vegetation index (EVI) [49,50], modified normalized difference water index (mNDWI) [51], and land surface water index (LSWI) [52,53] were calculated from the surface reflectance data. NDVI and EVI indicate the greenness of vegetation, while mNDWI is related to open surface water bodies. These four indices were combined to reduce the disturbances of vegetation on water mask and water on vegetation mask [54–56].

\[
\text{NDVI} = \frac{\rho_{\text{nir}} - \rho_{\text{red}}}{\rho_{\text{nir}} + \rho_{\text{red}}} \quad (1)
\]

\[
\text{EVI} = 2.5 \times \frac{\rho_{\text{nir}} - \rho_{\text{red}}}{\rho_{\text{nir}} + 6 \times \rho_{\text{red}} - 7.5 \times \rho_{\text{blue}} + 1} \quad (2)
\]

\[
\text{LSWI} = \frac{\rho_{\text{nir}} - \rho_{\text{swir}}}{\rho_{\text{nir}} + \rho_{\text{swir}}} \quad (3)
\]

\[
\text{mNDWI} = \frac{\rho_{\text{green}} - \rho_{\text{swir}}}{\rho_{\text{green}} + \rho_{\text{swir}}} \quad (4)
\]

In the equations above, \(\rho_{\text{red}}, \rho_{\text{blue}}, \rho_{\text{green}}, \rho_{\text{nir}}\) and \(\rho_{\text{swir}}\) are the surface reflection data of Landsat TM/ETM+ /OLI, and the bands are red (630–690 nm), blue (450–520 nm), green (520–600 nm), near-infrared (NIR: 760–900 nm), and shortwave infrared (SWIR: 1550–1750 nm), respectively.

2.3. Algorithm to Identify Open Surface Water Body, Vegetation, and Tidal Flats

2.3.1. Open Surface Water Body and Vegetation Annual Frequency Mapping

We used the mNDWI and VIs algorithm to detect water bodies with mixed pixels of vegetation and water body [54]. If the water signal is stronger than the vegetation signal (mNDWI > EVI or mNDWI > NDVI) with green vegetation excluded (EVI < 0.1), we considered this pixel as a water pixel. Thus, the final criterion of the surface water detection algorithm is ((mNDWI > EVI or mNDWI > NDVI) and (EVI < 0.1)) [54,57].

We identified water frequency as the proportion of water observations in all good-quality observations, ranging from 0 to 1. The frequency of water was calculated by Equation (5) below, where \(\text{SUM}_{\text{water}}\) is the number of water observations each year recognized using the above-mentioned mNDWI and VIs algorithm, \(\text{SUM}_{\text{total}}\) is the total observations each year, and \(\text{SUM}_{\text{bad}}\) is the number of bad observations each year.

\[
\text{WaterFreq} = \frac{\text{SUM}_{\text{water}}}{\text{SUM}_{\text{total}} - \text{SUM}_{\text{bad}}} \quad (5)
\]

Pixels with water frequency larger than 0.05 of the period were classified as open surface water [54]. The adaptive-thresholding algorithm was proved to map open surface water bodies in many regions successfully [42,54,57], which turned out to be more robust than constant thresholds for further analysis.

NDVI, EVI, and LSWI have been used to identify vegetation and exclude water [58]. Similarly, we used the criterion (EVI \(\geq\) 0.1 and NDVI \(\geq\) 0.2 and LSWI > 0) and Equation (6) to calculate the vegetation frequency [42].

\[
\text{VegeFreq} = \frac{\text{SUM}_{\text{vegetation}}}{\text{SUM}_{\text{total}} - \text{SUM}_{\text{bad}}} \quad (6)
\]

2.3.2. Identification of Annual Tidal Flats

Based on our previous study, we considered pixels with vegetation frequency < 0.05 and 0.05 < water frequency < 0.95 as non-vegetation tidal flats [42]. After separating tidal flats by the above-mentioned algorithm, annual maps were filtered to remove all tidal flats inside the dikes, which had an orderly structure with smooth edges. The remaining tidal flats outside the dikes were regarded as our research targets.
2.4. Identification of Dike and S. alterniflora

Dikes were identified by manual interpretation according to high-resolution satellite images in Google Earth for each year. We used standard false color images of Landsat TM/ETM+/OLI and phenology signals of dominant species to identify S. alterniflora distribution areas from 1997 to 2018 according to the methods in [47]. The intertidal zone was extracted and classified into seven classes: S. alterniflora, S. maritimus, P. australis, mudflat, water and diked area. High-spatial-resolution images, historical data in the Resource Monitoring Report from Shanghai Chongming Dongtan National Nature Reserve, and distribution data from previous research were collected to assist with feature recognition and validation. Mudflat mask was covered and large areas of certain plants in the historical data were used to train samples [3,59,60]. S. maritimus can be easily distinguished from P. australis and S. alterniflora by significant texture, lower zonal distribution, and shorter growing season. P. australis sprouts in early April and grows rapidly in early May. S. alterniflora sprouts in early May and grows rapidly in late June and early July [47]. Thus, green P. australis showing bright red, in contrast to withered S. alterniflora showing dark brown, in standard false color images of early May, can be identified by maximum likelihood classification (Figure 4) [21]. Interpretation results were converted to vector maps and calculated the areas of S. alterniflora.

![Figure 4. Distribution of Spartina alterniflora in (a) CMI and (b) JDSI; standard false color image of (c) CMI and (d) JDSI of Landsat TM image (Date: 2006.04.20; Path/Row: 118/38); water is not shown in (a,b).](image)

2.5. Calculating Accumulated and Expanded Tidal Flats Area

The same measures of calculating accumulated and expanded tidal flats area from 1996 to 2018 were adopted in the three sample areas of DT, CG, and JDS (Figure 5). We used accumulated area to demonstrate the distance that tidal flats have extended toward the sea since 1996. The accumulated tidal flats area of year N was the average value of mosaic-extracted sample tidal flats from 1996 to year N. To separate the expanded tidal flats for each year and avoid the issue of calculating the overlapping
area twice, we merged the tidal flats of this year and last year and then extracted those of last year. $S$ in Equations (7) and (8) represents the area of samples.

\[
\text{Accumulated Area}_{N} = \sum_{1996}^{N} S \tag{7}
\]

\[
\text{Expanded Area}_{N} = \sum_{N-1}^{N} S \tag{8}
\]

Figure 5. Computational method of overlapping sample area. For single sample area of Year$_{N}$ and Year$_{N+1}$: red ($S_{a} + S_{b}$): tidal flats area of Year$_{N}$; blue ($S_{b} + S_{c}$): tidal flats area of Year$_{N+1}$; dark blue ($S_{b}$): overlapping area of Year$_{N}$ and Year$_{N+1}$; $S_{a} + S_{b} + S_{c}$: accumulated area of Year$_{N}$ and Year$_{N+1}$; $S_{c}$: expanded area of Year$_{N+1}$.

2.6. Statistical Analysis of Relationship between Tidal Flats Dynamics and Driving Factors

We took river sediment deposits, $S. alterniflora$ and reclamation area into consideration as three driving factors for tidal flat development. For the time frame of 2000–2018, we conducted multiple linear regressions to quantify and rank the contributions of three features (annual sediment concentration, $S. alterniflora$ area of each year, and reclamation area of each year) among the four islands (CMI, CXI, HSI, and JDSI) and three samples (DT, CG, and JDS) to tidal flat areas. For sample DT, we conducted two models for 2000–2013 and 2000–2018 separately, as the $S. alterniflora$ control project changed the pattern in DT. The $S. alterniflora$ area, reclamation area, and tidal flats area calculated at the same place were correspondingly at the same scale. All subsets regression models were applied to take all independent features into account and inspect all possible multiple linear regression models. The best model was selected according to the adjusted $R^2$ of the possible models. D-W tests were conducted to guarantee that there was no multi-collinearity among features. The coefficient in the formulas indicates the contribution of each feature.
3. Results

3.1. Accuracy Assessment for Image Classification

We verified the supervised classification results with QuickBird (Date: 2011.09.24) and SuperView-1 (Date: 2018.08.05) high-resolution imagery, assisted by historical field data. A confusion matrix was calculated to compute classification accuracy (Table 2), which presented a high consistency between ground reference maps and classification maps. The overall accuracy of the classification result was 94.60%, and the kappa coefficient was 0.9293.

| Class               | S. alterniflora | S. mariqueter | P. australis | Tidal Flats | Water | Diked Area | Total Map Pixels | User's Accuracy |
|---------------------|-----------------|---------------|--------------|-------------|-------|------------|------------------|----------------|
| Ground Reference Pixels | 129             | 6             | 3            | 0           | 0     | 0          | 138              | 93.48%         |
| Map pixels          | 4               | 111           | 4            | 13          | 0     | 0          | 132              | 84.09%         |
| Tidal flats         | 1               | 4             | 1            | 223         | 2     | 0          | 231              | 96.54%         |
| Water               | 0               | 0             | 0            | 2           | 368   | 0          | 370              | 99.46%         |
| Diked area          | 1               | 2             | 0            | 0           | 0     | 50         | 53               | 94.34%         |
| Total ground truth pixels | 139             | 130           | 73           | 239         | 370   | 50         | 1000             |                |

3.2. Spatiotemporal Dynamics of Tidal Flats Area in YRE

The tidal flats of YRE showed an obvious trend of expansion from 1996 to 2018, following the flow direction of the Yangtze River towards the East China Sea (Figure 6). The northern CMI expanded toward the north, which was nearly in union with southern Jiangsu Province, while the eastern CMI expanded in the northeastern direction toward the sea. The northern expansion of CXI demonstrated a clear outline of the Qingcaosha reservoir, and HSI experienced a reclamation of about 150 km² along the YRE deep water channel. The upper JDSI gradually grew upon the water, with expansion in the northwest direction. The middle and lower JDSI merged in 2000 and expanded toward the southeast.
The total tidal flat areas of CMI and JDSI had large inter-annual variations from 1996 to 2018 (Figure 7, Table 3), indicating natural growing tidal flats of the two islands, and they both had increasing island area from 1996 to 2018. Contrary to the fluctuant tidal flats in CMI and JDSI, CXI had a steady tidal flat area. The sudden increase in island area in 2009 was due to the enclosed construction of the Qingcaosha reservoir, which started in 2007 and was completed in 2010, after which the island area kept steady. The tidal flats area in CXI was also steady before 2006; the consequent increase was due to reclamation along the eastern shoreline. For the same reason, the island area of HSI was steady before 2006, and kept increasing until the reclamation completed in 2017. After the reclamation, HSI was larger than CXI.

![Figure 7. Reclamation, tidal flats, and island areas in (a) CMI, (b) CXI, (c) HSI, and (d) JDSI from 1996 to 2018. Reclamation and tidal flats use the primary y-axis on the left, and islands use the secondary y-axis on the right.](image)

| Area (km²) | CMI | CXI | HSI | JDSI |
|-----------|-----|-----|-----|------|
| Tidal flats area | Average <sup>1</sup> | 33.68 ± 4.63 | 8.37 ± 1.01 | 8.25 ± 2.61 | 17.42 ± 3.03 |
| | Maximum <sup>2</sup> | 51.06 (2002) | 12.20 (1997) | 24.44 (2013) | 37.44 (2013) |
| | Minimum <sup>2</sup> | 8.81 (2017) | 4.30 (2003) | 1.39 (2003) | 5.27 (2007) |
| Island area | Average <sup>1</sup> | 1410.53 ± 23.65 | 134.48 ± 8.55 | 81.49 ± 14.67 | 57.30 ± 11.80 |
| | Maximum <sup>2</sup> | 1507.24 (2017) | 159.87 (2017) | 175.34 (2018) | 106.24 (2018) |
| | Minimum <sup>2</sup> | 1321.71 (1996) | 113.71 (2005) | 56.12 (1999) | 9.70 (1996) |

<sup>1</sup> Uncertainties within the 95% confidence interval. <sup>2</sup> Year of maximum and minimum area in brackets.

Regarding the accumulated tidal flats areas of the three sample areas, DT had the largest accumulated tidal flats area in 2018, which was about 15.66 km². JDS had a relatively larger accumulated tidal flats area, covering about 13.74 km², while CG had the smallest, at 10.71 km². The accumulated area of DT increased from 3.90 km² in 1996 to 13.78 km² in 2006, and gradually increased afterward, then a sudden rapid increase of 0.91 km² was found in 2013. The accumulated tidal flats area of CG increased 5.77 km² before 2002, followed by a steady slight increase of 0.65 km² for 7 years, then was maintained at 10.7 km² since 2009. The accumulated tidal flats area of JDS increased over all the years, from 1.07 km² in 1996 to 13.74 km² in 2018, as the rate of increase became faster (Figure 8). The accumulated tidal flats area in DT was 0.36 km² smaller than CG in 1996. However, the rate of increase of DT was much larger than that of CG.
in the following years. The accumulated tidal flats area of DT exceeded that of CG in 2000, and JDS exceed CG in 2016, but was always smaller than DT. The decline in 1998, followed by subsequent increases in DT (red up arrow) and CG (blue arrow), indicated the dike constructed in 1998 in CMI, which was across our sample area DT and CG. The sudden increase in 2013 in DT (red down arrow) indicated the S. alterniflora control project across DT that year.

Figure 8. Accumulated tidal flats areas of three sample areas from 1996 to 2018.

S. alterniflora was introduced to Dongtan in 2001 and its control project started in 2013 [25]. Thus, we divided the timelines into three periods: 1996 to 2001 with reclamation and introduction of plant invasion, 2002 to 2012 without control, and 2013 to 2018 with plant invasion control. The mean value of the expanded area of DT in the three periods was 1.827, 0.948, and 1.152 km², respectively, which decreased significantly and then increased slightly. However, the trend of JDS was the exact opposite, with mean values of 0.624, 1.253, and 1.238 km², separately. The average expanded areas of CG had a clear trend of decreasing over the entire time, at 1.464, 0.707, and 0.303 km², independently (Figure 9). The average expansion of JDS in the last two periods occurred 2.54 times faster than CG, and the average expansion of DT occurred 2.08 times faster than CG.

Figure 9. Expanded tidal flats area of sample boxes in three periods: 1996–2001, 2002–2012, and 2013–2018.
3.3. Major Driving Factors of Tidal Flats Expansion Patterns

Chongming Dongtan experienced rapid growth due to a large quantity of deposits by the Yangtze River over the last century. However, the deposits decreased since the beginning of the 21st century. According to data from the Yangtze River Datong Hydrological Station, the annual sediment load decreased from $3.39 \times 10^8$ t in 2000 to $0.831 \times 10^8$ t in 2018, and the annual average sediment concentration reduced from 0.366 kg/m$^3$ in 2000 to 0.104 kg/m$^3$ in 2018 (Figure 10), leading to slower estuary tidal flats expansion or even erosion in the northern area of CMI [9,61]. Moreover, there is a strong negative correlation between the accumulated tidal flats area of the three sample areas and annual sediment load (DT: $R^2 = 0.920***$; CG: $R^2 = 0.748***$), and between the accumulated tidal flats area and annual sediment concentration (DT: $R^2 = 0.926***$; CG: $R^2 = 0.920***$; JDS: $R^2 = 0.825***$). Therefore, we can draw the conclusion that the decreased river deposits are the reason why the expansion speed of tidal flats got slowed.

![Figure 10](image-url)  
**Figure 10.** Annual average sediment concentration and sediment load of Yangtze River from 2000 to 2018. Data were collected from Yangtze River sediment bulletin of Datong gauging station.

*S. alterniflora* is mainly distributed in the northern and northeast CMI. Its area increased from 530.12 ha in 2001 to 2067.46 ha in 2010, and then decreased to 1714.52 ha in 2013. After ecological engineering covered most of the *S. alterniflora* population, there were still 718.87 ha of patches remaining outside the dike. The area of *S. alterniflora* in JDSI increased by 214% in the past 15 years. *S. alterniflora* in JDSI experienced less disturbance and demonstrated clear zonal distribution of natural succession, of which *P. australis* is in the highest intertidal zone, *S. alterniflora* is in the middle and lower zones, and *S. mariqueter* is in the lowest intertidal zone (Figure 4).

To quantify the contribution of river sediment, *S. alterniflora* invasion, and reclamation in each island, a multiple linear regression was conducted (Table 4). Among the four islands, we found that river sediment concentration was the factor contributing the most in CMI and HSI. CXI was largely affected by reclamation, while JDSI was totally promoted by *S. alterniflora*. The most influential factor in sample CG was sediment concentration. Sample JDS had the same result as JDSI. For sample DT, *S. alterniflora* was the factor contributing the most before 2013, but, for the whole period, river sediment was still the major factor as CMI.
Table 4. Statistical summary of the multiple linear regression formula in four islands and two samples.

| Islands and Samples | Formula $^1$ | Adjusted $R^2$ |
|---------------------|-------------|----------------|
| CMI                 | $T = -45.08SC^{***} - 17.40SA^{**} + 9.53R + 1427.94^{***}$ | 0.773 $^{***}$ |
| CXI                 | $T = -0.905C + 8.24R^{***} + 119.85^{***}$ | 0.803 $^{***}$ |
| HSI                 | $T = -18.94SC^* + 12.36R + 86.58^{***}$ | 0.349 $^*$ |
| JDSI                | $T = 2.975C + 26.96SA^{***} + 65.74^{***}$ | 0.954 $^{***}$ |
| Sample DT           | $T = -0.67SC^* + 0.94SA^{**} + 12.74^{***}$ | 0.915 $^{***}$ |
| Sample CG           | $T = -1.78SC^{***} - 0.195A + 13.65^{***}$ | 0.857 $^{***}$ |
| Sample JDS          | $T = -0.41SC^{***} + 10.42^{***}$ | 0.837 $^{***}$ |

$^1$ T, tidal flats; SC, sediment concentration; SA, S. alterniflora, and R, reclamation. $^{***} 0 < p < 0.001$; $^{**} 0.001 \leq p < 0.01$; $^* 0.01 \leq p < 0.05$.

4. Discussion

4.1. Reliability and Uncertainty of Tidal Flats Mapping

In this study, we demonstrated the reliability of generating annual tidal flats mapping at 30 m spatial resolution in YRE. The user’s accuracy, producer’s accuracy and overall accuracy of classification results were all higher than 90% (Table 2). We used an average of 75 Landsat images each year in the study area (Figure 3b). More than 96.6% of the pixels had four or more good-quality observations, and each pixel had an average of 431 good-quality observations from 1996 to 2018 (Figure 3c). The study was conducted successfully with plenty of good-quality data and accurate classification.

Many global-scale land cover maps including a wetland layer were already produced [29–32,34], and several researchers have mapped coastal wetlands in China [42,62,63]. In 2019, Murray [8] mapped global tidal flats during 1984–2016 using a random forest algorithm within 3-year windows on the GEE platform. Our results for the trend of tidal flats area in YRE from 1996 to 2016 are consistent with previous results (Figure 11a–d). However, Murray’s values were obviously larger due to the inclusion of fish ponds and water channels (outline of reclamation projects) as tidal flats (Figure 11e). The water frequency of the orange area in JDSI (Figure 11g) was 0.99–1, classified as tidal flats in Murray’s study, would be classified as permanent water in this study. Considering the global product, a detailed revision for more representative samples should be conducted in YRE.

Although we use adequate Landsat images, annual good-quality observations of pixels showed great spatial and inter-annual variation, and 66% of the pixels had fewer than 15 good-quality observations annually (Figure 3). The variation in Landsat images may lead to uncertainty in annual tidal flats mapping [38], but it is still useful to track inter-annual dynamics.

Besides image data and algorithms, the background environment of three sample areas in the past 30 years were not exactly the same, especially the coastal surface water salinity, which may result in the different growth rate of wetland vegetation and affect tidal flat development. According to the data of YRE in the comprehensive investigation of the coastal zone and tidal resources and the project of sediment resources and utilization in 2012, the surface salinity of both CG and JDS was around 10 PSU in winter [64]. However, after construction of the YRE deep water channel, a higher level of saltwater encroachment occurred in the south passage (south of JDSI) and north branch (between CMI and Jiangsu Province), leading to higher surface salinity of JDS and DT. The surface salinity of CG was around 2PSU lower than JDS during the neap tide. The salinity differences of wetland cause divergent S. alterniflora competitive capacity, as it grows better in higher salinity wetlands [3], which is also why it leads to faster sediment accumulation in JDS and DT.
4.2. Impact of S. alterniflora Invasion on Tidal Flats Expansion Patterns

With a great capacity for decreasing tidal velocity, mitigating erosion, and trapping sediments, S. alterniflora has been introduced to many coastal regions in the world to protect dikes and promote silting for natural reclamation [65], which turned out to be successful to some extent. The plant did reduce the influence of typhoons and protect the coastal environment of Zhejiang against typhoons in 1990 and 1994 [66]. Also, S. alterniflora is responsible for the rapid sediment accretion in CMI and JDSI besides anthropogenic reclamation. Even though deposits from the Yangtze River are decreasing, YRE is still expanding overall. S. alterniflora has larger stem and rhizome density compared with S. mariqueter and P. australis, so it intercepts more suspended particles with smaller sizes, which helps make it an ecosystem engineer [3,15]. Enhanced net primary production by S. alterniflora strengthened the carbon sink of the wetland [67]. In addition, S. alterniflora provided compatible habitats for native crab S. dehaani in YRE [68], and crab increased the competition ability of S. alterniflora by increasing soil nitrogen [69]. However, S. alterniflora replaced S. mariqueter in YRE and occupied mangrove zones in Southern China [22,23], reducing the food resources and habitat of local wetland animals. Invasive S. alterniflora homogenized and lowered the species diversity of the nematode
community and altered the diets and community structure of local arthropods and macro-benthonic invertebrates [3,70–73], leading to further impact on migratory birds [19]. According to the growth features of *S. alterniflora* and clustered plantation by human introduction, small patches first formed on the low-tide areas of tidal flats, and then merged and formed larger patches sprawling toward higher tidal flats and competing with native vegetation. Thus, tidal flats with *S. mariqueter* at the front experienced much slower *S. alterniflora* expansion than tidal flats [74]. Moreover, human disturbances to native vegetation left gaps for *S. alterniflora* to colonize and suppress native vegetation recruitment [22], which provided the environmental conditions for *S. alterniflora* expansion [75]. On the other hand, larger patches of *S. alterniflora* filled in the tidal creeks toward the sea and occupied the area of tidal flats, which resulted in the smaller expansion area of tidal flats in one year and larger expansion area in previous years.

### 4.3. Impact of Ecological Engineering on Tidal Flats Expansion Patterns

A dike with elevation above sea level can control the ecological consequences of previous *S. alterniflora* invasions [25], and meet the needs of the land in cities and keep the expansion of tidal flats. The construction of dikes on Dongtan promoted the outward expansion of tidal flats, in that the dikes intercepted the route of the flood tide, leading to decreased tidal velocity and causing a large amount of sediment deposit on the tidal flats outside the dike [76]. The promotion effect is obvious in the first year and is weakened over time until the sediment flux of upper and lower tidal flats reaches a new balance. During the construction of dikes, the sediment environment of neighboring tidal flats was disturbed, the supply of which reduced tremendously in a short time due to large-scale sand borrowing, leading to erosion that year. However, the sediment concentration after construction was higher than pre-construction [77], which resulted in the expansion of tidal flats in the following years. However, the dike constructed below sea level in northern CMI block the tide from entering tidal flats inside the dike, leading to a tremendous reduction in and even disappearance of Polychaeta species and increased insect larvae and mollusks species [78]. The disappearance of important benthic animals because of habitat loss is direct evidence of excessive reclamation [79].

### 4.4. Joint Effect of *S. alterniflora* Invasion and Reclamation on Tidal Flats

Land reclamation played an important role on CMI. Anthropogenic reclamation was dispersed and small scale in 1985–1990. Two large dikes, dike 1992 and dike 1998, were constructed in the 1990s [80], leading to a rapid decline in tidal flats at that time. The reclamation dike of the *S. alterniflora* invasion control project, which replaced *S. alterniflora* with *S. mariqueter*, was carried out in 2013. A large area of bare land was identified for tidal flats, which was covered by *S. alterniflora* during the gap between *S. alterniflora* cutting and *S. mariqueter* replantation, leading to a tremendous increase in tidal flats in 2013 and a low growth rate in the following years after replantation [42]. The control project is the vital reason for *S. alterniflora* shrinkage. Liu et al. [22] provided a similar result, proving that land reclamation on tidal flats or *S. alterniflora* vegetation to aquaculture ponds and mangrove replantation led to *S. alterniflora* shrinkage.

The control project was effective in the controlled region, but there were still *S. alterniflora* patches dispersed outside the dike and quite a large area observed along the northern CMI shoreline [23]. Since *S. alterniflora* was proved to be robust in promoting silting, it would be time consuming and labor intensive to completely remove them without large construction. It is strongly recommended that the *S. alterniflora* patches on the eastern part of island be removed, otherwise, the tragedy would be repeated. However, for the land ascertained as a reclamation region for fields, ponds, or building areas in the near future, we suggest retaining *S. alterniflora* to promote silting in the diked region. The outline dikes were important because *S. alterniflora* must be under control. After the reclamation project is complete, it should be removed if the region will no longer be wetland, in case of its fast spread in the surrounding area.
4.5. Future Tidal Flats in YRE

Besides river sediment deposits, the main factor that affected CXI and HSI tidal flat areas was reclamation, and their shorelines were both solidified. The Yangtze estuary deep-water channel was located along the northern shoreline of the two islands. There is a nearly 20 km deep shoreline with little sediment deposit along southern CXI, which is an ideal place for a port. The largest shipyard in China, Shanghai South of Yangzi River Changxing Shipyard, is located at the southern shoreline, while Qingcaosha reservoir was located at the northern shoreline. There was a large area of reclamation along eastern HSI during 2006–2017, which is nearly the same area as CXI. We can predict that both the tidal flats and island areas of CXI and HSI will be stable in the future, since their shorelines have been smoothed and solidified by man-made shorelines.

*S. alterniflora* was the main factor that promoted tidal flats in JDSI. One reason to introduce *S. alterniflora* to JDSI was to attract migratory birds and draw them away from the nearby Pudong International Airport [10]. Shanghai Jiuduansha Wetland National Nature Reserve covers all of JDSI, so no reclamation project could be easily conducted there. Although *S. alterniflora* has been proved to be harmful to migratory bird habitats, the focus of the JDS nature reserve is to protect the wetlands rather than the bird habitats. To a large extent, *S. alterniflora* would be kept in the future. The situation in CMI would be more complicated. Sediment deposits had a much larger contribution than *S. alterniflora* and reclamation. Contrary to the JDS nature reserve, Chongming Dongtan National Nature Reserve only covers eastern CMI, not the whole island, so the control project discussed above was only conducted there for bird habitat protection. However, there was still *S. alterniflora* left outside the dike. If the management suggestions we provided above had been accepted, the tidal flats and island areas of CMI and JDSI would still increase. The tidal flat area of JDSI would keep its present speed with the help of *S. alterniflora*, and eastern CMI would increase rather more slowly with several sudden increases as most *S. alterniflora* is removed, but more reclamation projects may be conducted in the northern island.

5. Conclusions

This paper demonstrated the spatial and temporal dynamics of tidal flats in YRE during 1996–2018 using the GEE cloud computing platform, analyzing the effects of invasion by *S. alterniflora* and reclamation on the expansion and erosion of tidal flats. Three typical sample areas in YRE, CG, JDS, and DT, represent the control group, *S. alterniflora* invasion, and joint controls, respectively, which reduce the background interference and allow the comparison of comprehensive disturbance at the same time. The results illustrate the joint effect of *S. alterniflora* invasion and reclamation by comparing the three sample areas and point out the main driving factors of tidal flats in four islands. Due to the decreasing river deposits in the Yangtze River, the expansion speed of tidal flats in YRE is getting slower, but the trend of expansion is still obvious. River sediment concentration had the largest contribution in CMI and HSI, while reclamation and *S. alterniflora* invasion were the most vital factor in CXI and JDSI, respectively. *S. alterniflora* has a robust capability of silting and can accelerate tidal flat expansion by 2.54 times. Further monitoring of *S. alterniflora* on Dongtan is necessary for migratory birds, and retaining the remaining *S. alterniflora* in northern CMI would be an effective approach to accelerate reclamation if carefully enclosed in a limited region. Therefore, our findings could be used to support coastal zone management and biodiversity conservation of the YRE in the future.

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