Invasion of *Spartina alterniflora* in the coastal zone of mainland China: control achievements from 2015 to 2020 towards the Sustainable Development Goals

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Abstract

The Sustainable Development Goals (SDGs) and the Convention on Biological Diversity's 15th Conference of the Parties (CBD COP15) both emphasized the urgency of protecting biological diversity. *Spartina alterniflora* (*S. alterniflora*), as an invasive species in China, has posed severe biodiversity challenges, demanding nationwide control and management. This study aims to assess the effectiveness of *S. alterniflora* management during China's SDGs implementation from 2015 to 2020. Landsat images acquired in 2015 (the beginning year of SDGs), 2018, and 2020 (the end year of SDGs' targets 6.6, 14.2, 14.5, and 15.8 related to alien invasion) were applied to quantify the spatiotemporal dynamics of *S. alterniflora* extent. The results revealed a consistent shrinkage of *S. alterniflora*, with a net areal reduction of 2,610 ha from 2015 to 2020, implying the effectiveness of control measures on *S. alterniflora* invasion. Provinces including Zhejiang, Jiangsu, and Shanghai have succeeded in controlling *S. alterniflora*, evidenced by the sharp reduction in *S. alterniflora* area by 4,908 ha, 2,176 ha, and

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1,034 ha, respectively, from 2015 to 2020. However, better management of *S. alterniflora* is needed in regions with more severe *S. alterniflora* invasion, e.g., Shandong, Fujian, and Guangdong provinces. Our results suggest that relevant policies, regulations, and ecological restoration projects implemented by national or local governments in China received satisfactory results in *S. alterniflora* control. Nevertheless, *S. alterniflora* potential utilities and its governance effectiveness should be objectively evaluated and weighed to obtain the greatest ecological benefits and promote sustainable coastal ecosystems. The results of this study are expected to provide important baseline information benefitting the formulation of coastal protection and restoration strategies in China.

Keywords: *S. alterniflora* invasion; Sustainable Development Goals (SDGs); *S. alterniflora* control; Coastal wetland; Remote sensing

1. Introduction

Invasive *Spartina alterniflora* (*S. alterniflora*), a native riparian species in the U.S. Gulf of Mexico, was introduced into China in 1979 for the purpose of ecological engineering (Liu et al., 2018). It has explosively expanded for almost 40 years and was categorized as one of the sixteen most harmful invasive plants by the Chinese Academy of Sciences and State Environmental Protection Administration of China in 2003 considering its numerous negative impacts on ecosystems, such as altering estuarine sediment dynamics (Zhou et al., 2009), outcompeting native plant species (Wang et al., 2019), and encroaching into tidal flat habitats of migratory birds (Zhang et al., 2020). The overwhelming spread of exotic *S. alterniflora* has dramatically altered China's coastal wetlands (Wang et al., 2020), which play a vital role in regulating climate and providing ecosystem services. Furthermore, in September 2015, the United Nations (UN) General Assembly adopted the 2030 Agenda for Sustainable Development, composed of 17 Sustainable Development Goals (SDGs), 169 targets, and 230 indicators (United Nations, 2015). Relevant to sustainable management of invasive alien species, a range of targets were established by the year 2020, including Target 6.6, Target 14.2, Target 14.5, and Target 15.8 (United Nations, 2015). These targets emphasize the urgency of effectively managing invasive alien species in coastal regions and promoting the stability and adaptability of coastal zones by protecting biological diversity. Therefore, mapping *S. alterniflora* in an accurate and consistent manner is essential for China's coastal sustainable management and conservation.

Given the dispersed and fragmented distribution of *S. alterniflora* in mudflats, remote sensing provides an efficient approach to monitoring and analyzing the multi-scale changes of *S. alterniflora* in near real-time. Numerous *S. alterniflora* datasets at regional or national scales were derived from remote sensing images after 2005, significantly contributing to the monitoring of *S. alterniflora* in China (Liu et al., 2018; Qing et al., 2006; Zhang et al., 2017). However, these datasets are either outdated, with limited temporal spans or restricted spatial coverages, and are unable to provide updated spatiotemporal situational awareness of *S. alterniflora's* invasion in coastal China. Recently, Mao et al. (Mao et al., 2021a) published the first long-term, multi-temporal *S. alterniflora* datasets, revealing the detailed spatiotemporal distribution characteristics of *S. alterniflora* within mainland China. Another notable effort was made by Hu et al. (Hu et al., 2021), delineating the invasive situation of *S. alterniflora* in coastal China in 2019. Nevertheless, when describing the dynamics of *S. alterniflora,* it is usually presented as part of coastal salt marsh mapping and lacks a detailed spatiotemporal analysis and systematic investigation, with few studies on *S. alterniflora* conducted over coastal China since the implementation of SDGs in 2015.

Due to its high survivability, strong adaptability, and lack of natural predators, *S. alterniflora* rampantly encroached into coastal wetlands in some ecologically sensitive estuaries, e.g., Yangtze River estuary (Liu et al., 2020), Zhangjiang Estuary (Liu et al., 2017a), and Yellow River Delta (Ren et al., 2021), and some coastal provincial administrative divisions, e.g., Zhejiang (Li et al., 2020), Jiangsu (Liu et al., 2017b), and Fujian (Wei, 2011), resulting in severe degradations in coastal wetland ecosystems. China has made extensive recent conservation progress, reflecting a broader policy realignment in China towards environmental protection and sustainable development. The Chinese government formulated China's National Plan on Implementation of the 2030 Agenda for Sustainable Development (hereinafter referred to as the National Plan) to guide the implementation of SDGs, which lays out the specific and particular arrangements for the implementation of the 17 SDGs and 169 targets. A series of management measures were formulated to restore coastal wetland ecosystems by limiting the spread of *S. alterniflora* which were ineffective. Five years after the adoption of SDGs, very few studies have been conducted to trace the progress of the SDGs by evaluating the efficacy of *S.*

alterniflora control and prevention. Such deficiency in policy evaluation greatly limits decision-making for coastal ecological restoration and regional economic development.

Therefore, the major objectives of this study include (1) quantifying the dynamics and spatial heterogeneity of *S. alterniflora* invasion from 2015-2020; (2) investigating the conversion between *S. alterniflora* and other land covers; (3) evaluating both the effectiveness of managing *S. alterniflora* invasion and challenges of China's SDGs regarding the control of its spread.

2. Materials and methods

2.1 Study area

The coastal zone of mainland China encompasses ten provinces and spans from 18°N to 41°N (Figure 1). A typical warm temperate climate and a subtropical climate prevail over the extensive coastal areas from north to south, with the mean annual temperature and precipitation ranging from 5 to 25 °C and 400 to 1800 mm, respectively. The common intertidal plants in coastal zones include *Phragmites australis*, *Suaeda salsa*, *Tamarix chinensis*, *Scirpus marquee*, *Cyperus malaccensis*, and mangrove forests (Mao et al., 2018a). *S. alterniflora* is one of the most severe invasive plants and poses significant threats to other intertidal plants and mangroves.

Figure 1 Location of the study area.

2.2 Data and preprocessing

To track the invasion of *S. alterniflora*, high-quality imagery with no cloud cover obtained in 2015, 2018, and 2020 by Landsat Operational Land Imager (OLI) was downloaded from the Geospatial Data Cloud (GDC, https://www.gscloud.cn/). Multi-temporal images in the same location were used to eliminate the interference of tidal levels and phenophase overlap on *S. alterniflora* identification. As tidal floods can greatly influence spectral reflectance and increase uncertainty in classification results, low tide images were preferred when recognizing *S. alterniflora* sited in shallow seawater. To map the extent of *S. alterniflora*, 104 image scenes (43 scenes in 2015, 29 scenes in 2018, and 32 scenes in 2020) covering the entire study area were selected. Essential image preprocessing steps, including geometric correction, atmospheric corrections, and coordinate system uniformation, were performed in ENVI 5.3 software before interpretation (Mao et al., 2019).

2.3 Mapping *S. Alterniflora*

The detailed steps for mapping *S. alterniflora* from remote sensing images were previously described (Liu et al., 2018; Mao et al., 2021a). In brief, the distribution of *S. alterniflora* was extracted using the OBIA and SVM approach built in the eCognition Developer 9.0 software. Three critical steps are summarized: 1) Segmentation; multi-band images were segmented into groups of homogeneous pixels using several parameters such as scale, compactness, and shape. The fuzzy-based segmentation parameter (FbSP) optimizer provided by the eCognition software was applied to generate optimal parameters for multiscale image segmentation and object generation. 2) Classification; the generated objects in step 1 were divided into *S. alterniflora* and non-*S. alterniflora* categories such as shallow marine water, mudflat, aquaculture pond, marsh, and mangrove using SVM classifier and training samples acquired from field survey points obtained from ground truth. 3) Manual editing; the initially extracted *S. alterniflora* distribution and other land covers were visually interpreted and manually modified to correct misclassified objects according to prior knowledge and ground survey points.

2.4 Data verification

Three rounds of field surveys were conducted to collect the reference data for imagery classification and precision validation along the shoreline of mainland China between September and November of 2015-2020. A hand-held geographic positioning system (GPS) and a digital camera were used to measure and record the geolocations and environments of *S. alterniflora* and non-*S. alterniflora* samples. Uncrewed aerial flights were conducted to assist in the detection of *S. alterniflora* patches far from shorelines. For inaccessible areas and areas under bad weather conditions during our survey missions, we supplement the limited verification points obtained from field surveys by collecting additional reference points from high-resolution images available on Google Earth. A total of 416, 382, and 499 samples were selected as validated areas with the occurrence of *S. alterniflora*, with 616, 631, and 760 samples selected for verification of other non-*S. alterniflora* land covers in 2015, 2018, and 2020, respectively. The overall landcover mapping accuracy in 2015, 2018, and 2020 was0.88±0.02, 0.89±0.02 and 0.91±0.01, respectively.

2.5 Quantifying dynamic changes of *S. alterniflora*

We analyzed *S. alterniflora's* areal changes (ΔS in the unit of ha), percentage of area change (SP in %), and annual change rate (AR in ha·a^{-1}):

$$\Delta S = S_1 - S_0 \tag{1}$$

$$SP = \frac{\Delta S}{S_1} \times 100 \tag{2}$$

$$SR = \frac{\Delta S}{\Delta T} \tag{3}$$

where S_0 and S_1 are the areas with *S. alterniflora* between any two consecutive stages; SP represents the area change ratio of *S. alterniflora*; SR represents the annual change; ΔT denotes the year gap.

Further, we performed spatial analyses, such as hotspot analysis, in ArcGIS 10.2 (Mao et al., 2021b) to describe the spatial heterogeneity of *S. alterniflora* along China's coast. The transformations between *S. alterniflora* and non-*S. alterniflora* land covers from 2015 to 2020 were quantified using a Sankey diagram.

3. Results

3.1 Differential areal change of *S. alterniflora* along China's coast

Our results indicate that *S. alterniflora* in China were clustered in the mid-latitude intertidal zones and estuaries. Provinces with severe *S. alterniflora* invasion mainly include Shandong, Jiangsu, Shanghai, Zhejiang, and Fujian. In 2020, the area of *S. alterniflora* in these regions was over 48,661 ha, occupying about 94% of the total area of invasive *S. alterniflora* in the study area. Among all coastal provinces, Jiangsu had the largest area of *S. alterniflora* (16,183 ha), accounting for more than thirty percent of the total *S. alterniflora*. However, small clusters of *S. alterniflora* in the northmost (i.e., Tianjin and Hebei) and southmost (i.e., Guangdong and Guangxi) provinces were also present.

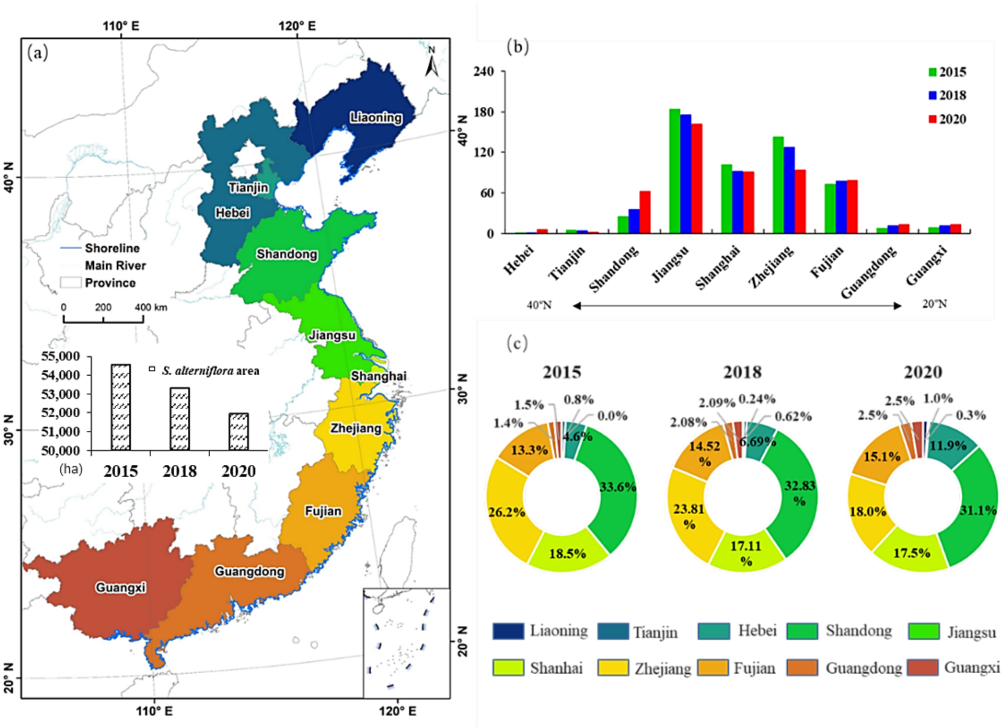

Figure 2 Invasion situation (a), total area (b), and areal portion (c) of *S. alterniflora* in coastal provinces of mainland China in 2015, 2018, and 2020.

Figure 2 (a) shows the variable areas of exotic *S. alterniflora* during the investigated years, i.e., a notable, consistent shrinkage of *S. alterniflora* from 54,580 ha in 2015 to 53,324 ha in 2018 to 51,970 ha in 2020. From 2015 to 2020, *S. alterniflora* declined by 2,610 ha, suggesting an average annual decrease of 522 ha and a change rate of 4.78%. Specifically, from 2015 to 2018, *S. alterniflora* had an evident shrinkage of 1,256 ha, an annual change of 419 ha·a^{-1}, while in the latter period, from 2018 to 2020, *S. alterniflora* decreased by 1,354 ha with an accelerated reduction rate of 677 ha·a^{-1}.

The dynamics of *S. alterniflora* was spatially heterogeneous in coastal China (Figure 2). *S. alterniflora* declined by 852 ha from 2015 to 2018, then declined by 1,324 ha in the next two years in Jiangsu, with an annual change rate of -435.2 ha·yr^{-1}. Having the second-largest area of *S. alterniflora*, Zhejiang experienced the most dramatic reduction by 1,586 ha during 2015-2018 and by 3,322 ha during 2018-2020, with an annual change rate of -981.6 ha·yr^{-1}. The continuous decrease of *S. alterniflora* also occurred in Shanghai and Tianjin, with a net areal reduction of 1,034 and 247 ha, respectively. Alarmingly, *S. alterniflora* expanded in the other coastal provinces. For example, the most significant expansion in *S. alterniflora* occurred in Shandong with explosive areal growth of 3,718 ha and the highest increase rate of 743.5 ha·yr-

[1]. *S. alterniflora* only covered 25 ha in Hebei in 2015 but expanded to 518 ha in 2020 with a dramatic growth rate of 1988%. Moreover, Guangdong and Guangxi experienced *S. alterniflora* expansion, with a growth rate of 65.87% and 56.22%, respectively.

Table 1 Coverage and changing rate of *S. alterniflora* over the investigated period 2015-2020.

Province	Periods(ha)			Change Rate
	2015-2018	2018-2020	2015-2020	ha·yr^{-1}
Hebei	103	391	493	98.7
Tianjin	-94	-153	-247	-49.3
Shandong	1,081	2,636	3,718	743.5
Jiangsu	-852	-1,324	-2,176	-435.2
Shanghai	-983	-51	-1,034	-206.8
Zhejiang	-1,586	-3,322	-4,908	-981.6
Fujian	478	78	556	111.2
Guangdong	326	187	514	102.8
Guangxi	271	203	474	94.8

3.2 Hotspots showing evident invasion and shrinkage of *S. alterniflora*

Figure 3 illustrates the areal changes of *S. alterniflora* at the city level within the study region during the periods of 2015-2018, 2018-2020, and 2015-2020. The areal reductions of *S. alterniflora* were notable in central coastal cities such as Taizhou, Wenzhou, Yancheng, Ningbo, and Shanghai from 2015 to 2020. Our results suggest that economically highly-developed cities in the central coastal provinces of China made remarkable achievements in controlling *S. alterniflora*. For example, in Zhejiang Province, the *S. alterniflora* coverage decreased by 1,909 ha in Taizhou, 1,523 ha in Wenzhou, and 1,359 ha in Ningbo. In Jiangsu Province, the *S. alterniflora* coverage decreased in Yancheng by 614 ha from 2015 to 2018 and by 829 ha from 2018 to 2020, with a total reduction rate of nearly 12% during the 5-year period.

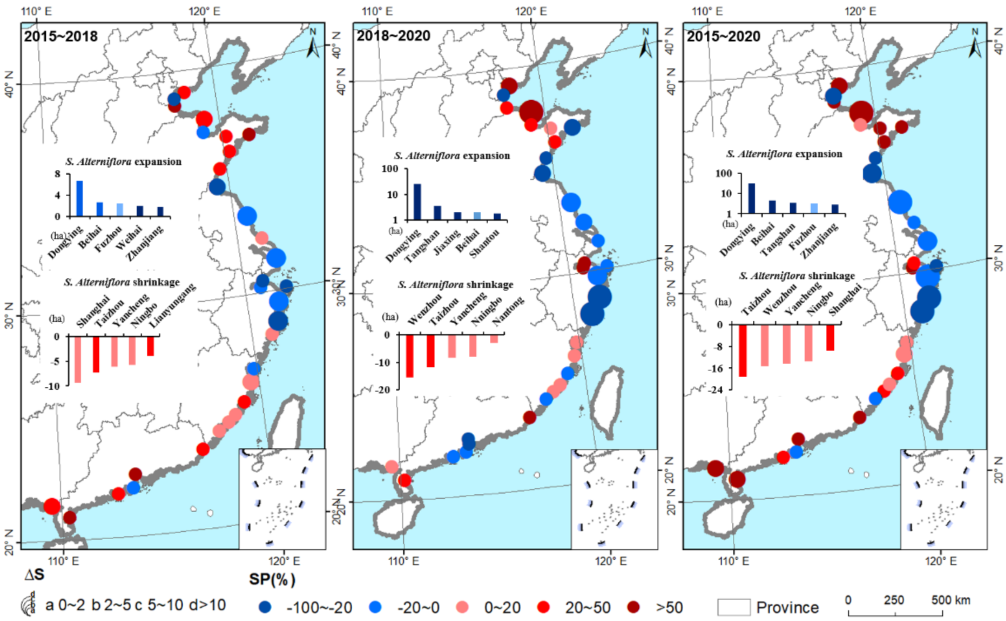

Figure 3 Areal changes of *S. alterniflora* at the city level along the coast of mainland China.

In comparison, *S. alterniflora* expanded in 19 cities. Dongying City in Shandong province, located in the Yellow River Estuary, had the most *S. alterniflora* expansion among all selected cities during the entire 5-year period and two separated periods. *S. alterniflora* was concentrated in the northern edge of the Yellow River Delta estuary in 2015 (1,533 ha), extended to the entire north and northeast edge in 2018 (2200 ha), and then continued to expand inland and along both sides of the river in 2020 (4,733 ha), with a total growth rate of 208.7% from 2015 to 2020. Beihai City, situated on the east coast of Beibu Gulf and in the south of Guangxi province, had 843 ha of *S. alterniflora* (2015), accounting for 100% of *S. alterniflora* coverage in the entire Guangxi Province. *S. alterniflora* was distributed in the intertidal zones of the Dandou Sea and Beihai Port of the Beibu Gulf. Moreover, *S. alterniflora* further expanded towards inner lands and spread along the coast of Beihai City, a city with the second-largest increase of all the coastal cities in *S. alterniflora* coverage of 459 ha from 2015 to 2020. Two other cities, Tangshan in Hebei Province and Fuzhou in Fujian Province had a net areal increase of over 300 ha.

3.3 Conversion between *S. alterniflora* and *non-S. alterniflora* land covers

To further investigate the dynamics of *S. alterniflora*, the conversions between *S. alterniflora* and *non-S. alterniflora* land covers were analyzed (Figure 4). As illustrated in Figure 4(a), from 2015 to 2020, invasive *S. alterniflora* of around 15,648 ha was mainly converted to shallow marine water, mudflat, aquaculture pond, marsh, and mangrove in the high to low conversion sequence. The converted *S. alterniflora* was 7,398 ha for shallow marine water, representing 47% of the *S. alterniflora* decrease, followed by 20% and 17% for aquaculture pond and marsh, respectively. In addition, about 833 ha of *S. alterniflora* was converted into mudflats. On the other hand, different land cover types were extensively encroached by *S. alterniflora* during the period of 2015-2020. They are mainly shallow marine water (5,204 ha) and mudflats (3,398 ha), accounting for 39% and 26% of all *S. alterniflora* converted from other land cover types. Almost 984 ha of mangrove forests were invaded by *S. alterniflora*, the invasion mainly occurred in Beihai (742 ha). *S. alterniflora* also encroached into marsh and aquaculture ponds by 2,095 ha and 1,571 ha, respectively.

Figures 4 (b) and (c) show the percentages of different land cover types converted to or from *S. alterniflora* in China's coastal provinces. Marsh restoration in Jiangsu (43%) and Shandong (42%) was greatly attributed to the reduction of *S. alterniflora*. However, the shrinkage of *S. alterniflora* due to marsh restoration was less than 15% in Tianjin, Fujian, Guangdong, and Guangxi provinces. Moreover, the conversion of *S. alterniflora* to aquaculture ponds was evident in Hebei, followed by Jiangsu and Zhejiang. The proportions of *S. alterniflora* submerged into marine water were higher in Shanghai (91%), Zhejiang (54%), and Tianjin (53%) than in other provinces.

On the other hand, mudflat was severely encroached by *S. alterniflora,* with Shandong being the most severe case during the five years (over 50%). Extensive marshes were transformed into *S. alterniflora* in Jiangsu, Shandong, Zhejiang, and Shanghai, accounting for 43%, 42%, 29%, and 27% of the total increased *S. alterniflora*, respectively. In addition, shallow marine water lost to *S. alterniflora* was obvious in Jiangsu, Shandong, Zhejiang, and Shanghai, accounting for 43%, 42%, 29%, and 27% of the total *S. alterniflora* expansion, respectively. The conversion of mangrove to *S. alterniflora* mainly occurred in Guangxi, Guangdong, and Fujian.

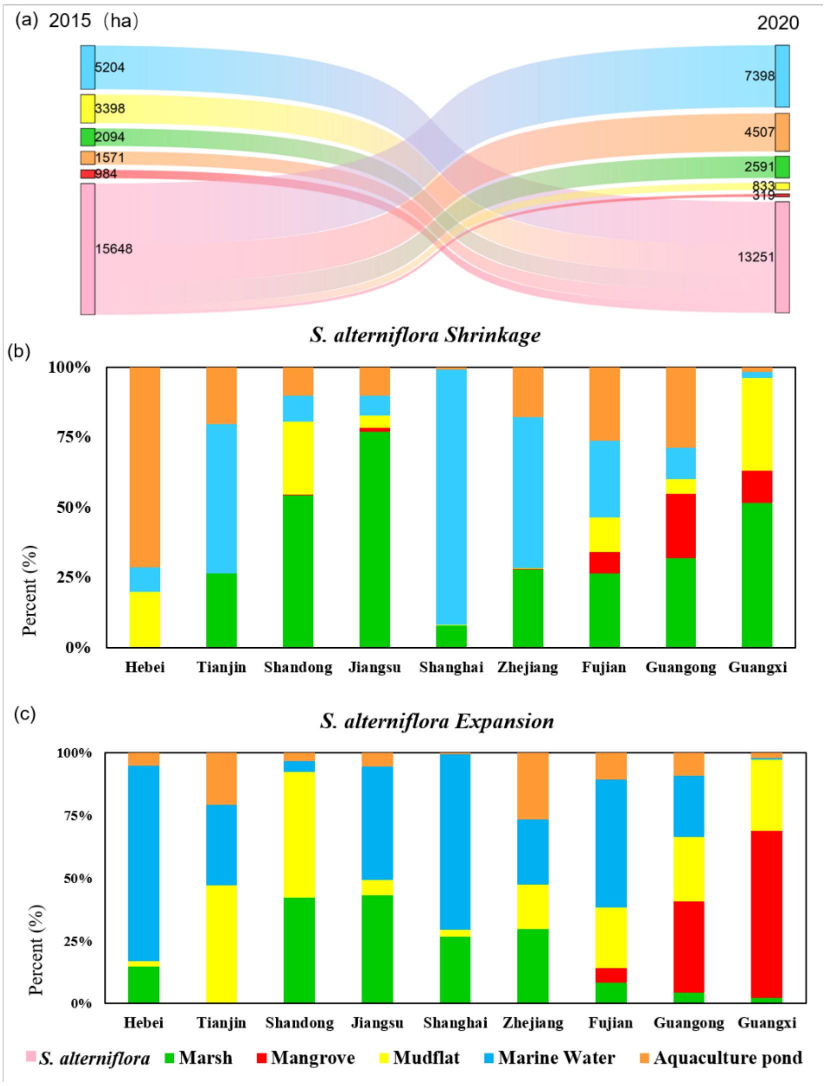

Figure 4 Conversions between *S. alterniflora* and *non-S. alterniflora* land covers from 2015 to 2020. (a) a Sankey diagram of landcover conversions; (b) percentages of *non-S. alterniflora* land covers converted to *S. alterniflora*; (c) percentages of land cover types converted from *S. alterniflora* in China's coastal provinces.

4. Discussion

4.1 SDG targets related to alien invasions in terms of exotic *S. alterniflora*

Aiming towards sustainable marine resources and controlling invasive species, a range of targets were established by the year 2020 (Appendix 1). At present, we are only able to find one study on *S. alterniflora* control for SDGs, i.e., the chapter on Spatiotemporal Distribution of China's Vegetated Wetlands of the Big Earth Data in Support of the Sustainable Development Goals issued by the Chinese Academy of Sciences in 2020 (Guo, 2021). However, as a case of

Target 6.6, this chapter presented the distribution of *S. alterniflora* and its dynamics from 2015 to 2018 while failing to analyze the *S. alterniflora* control in China for SDGs systematically. Our study is expected to fill this gap.

According to the Global Indicator Framework (GIF) for the SDGs adopted by the United Nations in 2017, the indicators for monitoring and tracking the progress of Target 6.6 are documented in Indicator 6.6.1 (Appendix 1). For Target 6.6, China's National Plan proposed establishing a nationwide ecological safety scheme to conserve and rebuild aquatic ecosystems and gradually restore their functions. In this study, the areal change of *S. alterniflora* was used as an indicator to evaluate the progress of Target 6.6 in China. Our results indicate that, since the implementation of SDGs (2015-2020), the area of *S. alterniflora* within China has decreased by 25%, revealing the effectiveness of China's coastal protection and restoration. Moreover, the significant conversions of the invasive *S. alterniflora* (around 15,648 ha) to other wetland types, such as shallow marine water, mudflat, aquaculture pond, marsh, and mangrove, notably contributed to the restoration and improvement of the coastal wetland ecosystem.

In the GIF for SDGs, the Indicator 14.2.1 documents the "Number of countries using ecosystem-based approaches to managing marine areas is applied to evaluate the progress of Target 14.2". For SDG target 14.2, China's National Plan proposes creating a national, real-time, and automatic supervision system for the marine environment to promote the implementation of SDGs. Considering that our study area belongs to such a national monitoring system, we complied the cities that use ecosystem-based approaches to managing *S. alterniflora* in this study and those that do not, the results are shown in Appendix 2. Appendix 2 indicates that 23 cities took single or integrated measures to prevent the spread of *S. alterniflora*, accounting for over 65% of all coastal cities. The cities that use multiple treatment measures and have made outstanding achievements in controlling the spread of *S. alterniflora* are Wenzhou, Taizhou, Yancheng, and Shanghai (Figure 3). In contrast, the coastal cities in Shandong have barely taken action to reduce the impact of *S. alterniflora* invasion since 2015, explaining the severe invasion of *S. alterniflora* (Figure 2b).

For SDG Target 14.5, China's National Plan suggests greatly expanding coastal and maritime protected areas. The Chinese government has strengthened the protection of coastal wetlands from the invasion of *S. alterniflora* through the establishment of nature reserves. Given the focus of this study, we quantitatively assess the progress towards Target 14.5 using "the ratio of the area of coastal wetland reserves containing *S. alterniflora* to the suitable distribution area of *S. alterniflora*." Following a current study by Jia et al. (Jia et al., 2021a), we considered the 1 km buffer area of *S. alterniflora* to be *S. alterniflora's* suitable area. According to the National Directory of Nature Reserves released in 2015 and the newly-built nature reserves from 2015 to 2020 investigated in this study, the total area of China's coastal wetland nature reserves to which *S. alterniflora* has invaded is 465,214 ha, accounting for above 20% of the *S. alterniflora* suitable area (2,300,831 ha). This is a much higher percentage than the requirement from Target 14.5, implying the management of *S. alterniflora* has met Target 14.5.

For SDG Target 15.8, China's National Plan emphasizes the importance of participating in the international prevention of exotic invasive species introduction, improving the list of exotic invasive species, and making biodiversity protection plans. In this study, the national laws relevant to *S. alterniflora* controls were queried to evaluate the progress towards Target 15.8 in China in terms of Indicator 15.8, "Proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of invasive alien species." The results on the progress of *S. alterniflora* introduction, invasion, shrinkage, and relevant regulations and policies are presented in Figure 5.

The List of China's Invasive Alien Species (First Batch in 2003) and the List of National Key Management of Invasive Alien Species (First Batch in 2012) identified *S. alterniflora* as a key invasive species that needs consistent attention. The Ministry of Ecology and Environment issued the "Technical Guidelines for Environmental Risk Assessment of Alien Species" in 2012, providing technical standards for performing environmental risk assessments of alien species, including *S. alterniflora*. A series of technical standards such as the Guidelines for Eradication of Invasive Weeds and Technical Specifications for Alternative Control of Invasive Plants have been implemented to strengthen technical guidance on preventing and controlling invasive *S. alterniflora*. In 2021, five national ministries jointly issued the "Work Plan for Further Strengthening the Prevention and Control of Invasive Alien Species," aiming to detail the status of *S. alterniflora*, improve the creation of relevant laws, regulations, and policy systems, form multi-departmental joint efforts, effectively restrain the spread of *S. alterniflora* by the year 2025, and eventually control *S. alterniflora* invasion by the year 2035.

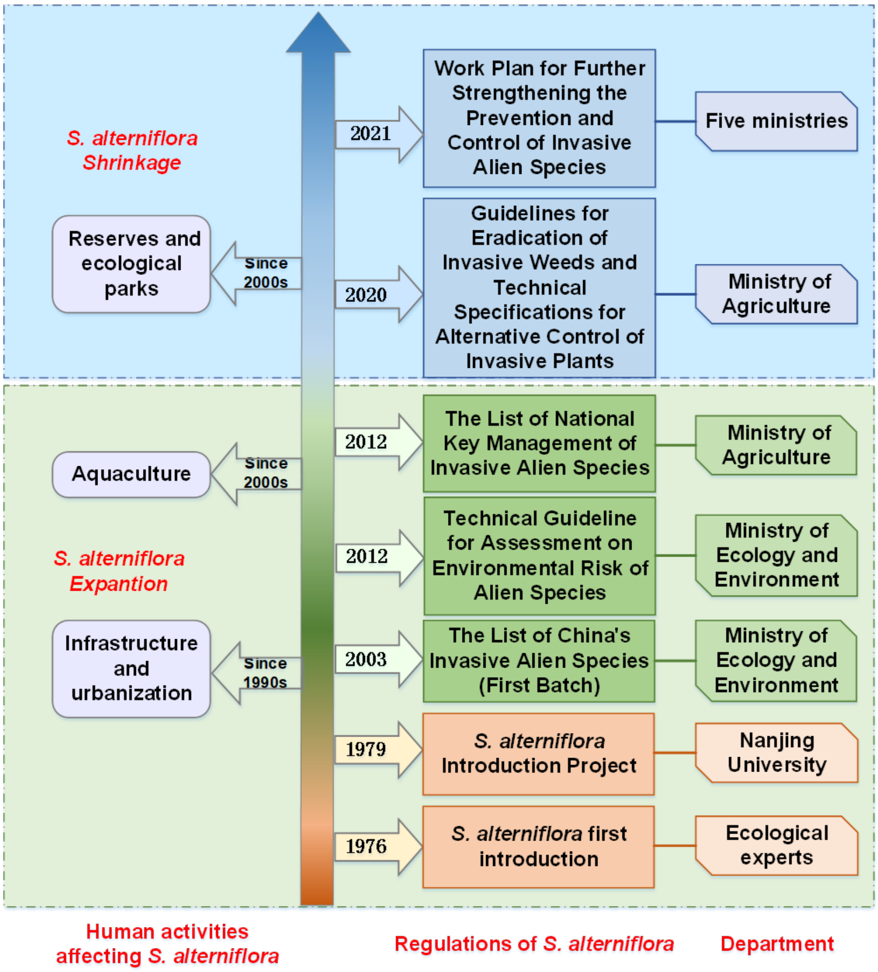

Figure 5 National policies on *S. alterniflora's* introduction and management.

4.2 Policies and measures to control *S. alterniflora* invasion on province scales

Besides substantial attention from the central government to the issue of *S. alterniflora* invasion (mentioned in section 4.1.4), provincial governments have established a series of practical measures and programs to control the proliferation of *S. alterniflora* (Appendix 3). The provinces, i.e., Jiangsu, Zhejiang, and Shanghai, witnessed the most severe invasions of *S. alterniflora* early, and their local governments have been paying attention to *S. alterniflora* management since 2010. However, other provinces, which have relatively small areas of *S. alterniflora* (compared to Zhejiang and Jiangsu), delayed developing the management policies of *S. alterniflora* control.

The Thirteenth Five-Year Plan for forestry development in Jiangsu Province implemented multiple ecological measures on wetland restoration and *S. alterniflora* control, including ten coastal wetland restoration projects aiming to restore a total of 3000 ha of coastal wetlands. Our study suggests that three coastal cities in Jiangsu, Yancheng, Lianyungang, and Nantong, have witnessed *S. alterniflora* shrinkage by 1,443 ha, 612 ha, and 181 ha, respectively, indicating the effectiveness of coastal wetland protection and restoration. The Development Plan of Wenzhou and Taizhou Coastal Industrial Belt (2009), the Twelfth Five-Year Plan for Zhejiang Province Environmental Protection (2010), as well as the Environmental Protection Plan of Taizhou Coastal Industrial Zone (2012) all pointed out the importance of promoting nature reserves and biodiversity conservation, paying specific attention to the risk assessment of *S. alterniflora* invasion and developing effective control measures. As shown in Figure 5, the cities that include Ningbo, Taizhou, and Wenzhou, where *S. alterniflora* was once extensively distributed since the 1990s (Mao et al., 2021), have made notable achievements in *S. alterniflora* control, evidenced by a total reduction of 4,791 ha from 2015 to 2020, accounting for more than 30% of *S. alterniflora* reduction within mainland China.

As the core area of the Yangtze River Estuary, Chongming Island experienced a rapid spread of *S. alterniflora* in the mid-1990s, resulting in a severe local ecological crisis (Chen et al., 2004). Since 2006, continuous efforts on the environmental management of *S. alterniflora* have been made in Chongming Dongtan thanks to the cooperating efforts of the Shanghai Forestry Bureau and more than 20 other departments (Song et al., 2020). The management plan of "enclosing, cutting, flooding, drying, planting, and regulating" was also adopted in the Chongming Dongtan Ecological Restoration Project implemented in 2013, responsible for the dramatic reduction in *S. alterniflora* with a net areal decrease of 1,034 ha from 2015 to 2020 (Figure 6).

Previous research has revealed the invasion of *S. alterniflora* in China's north coast (Jia et al., 2021b), with *S. alterniflora* identified as the most severe invasive alien species in Bohai Bay, threatening the ecological balance of its coastal areas (Zhang et al., 2017). In 2015, the Agriculture Committee of Tianjin Binhai New Area issued the Implementary Program for the Protection of Wetland and Wildlife and further invested a special fund of 1 million Yuan for the removal of *S. alterniflora*. From 2015 to 2018, about 94 ha of *S. alterniflora* coverage was detected in Tianjin Binhai New Area. To further restore the wetland ecology, Tianjin Binhai New Area launched a project to control the invasion of *S. alterniflora* from the Yongding River estuary to the adjacent Hebei in 2017, leading to a net decrease of *S. alterniflora* coverage by 152 ha from 2018 to 2020, accounting for 46% of the total area of *S. alterniflora* in Tianjin (Figure 6).

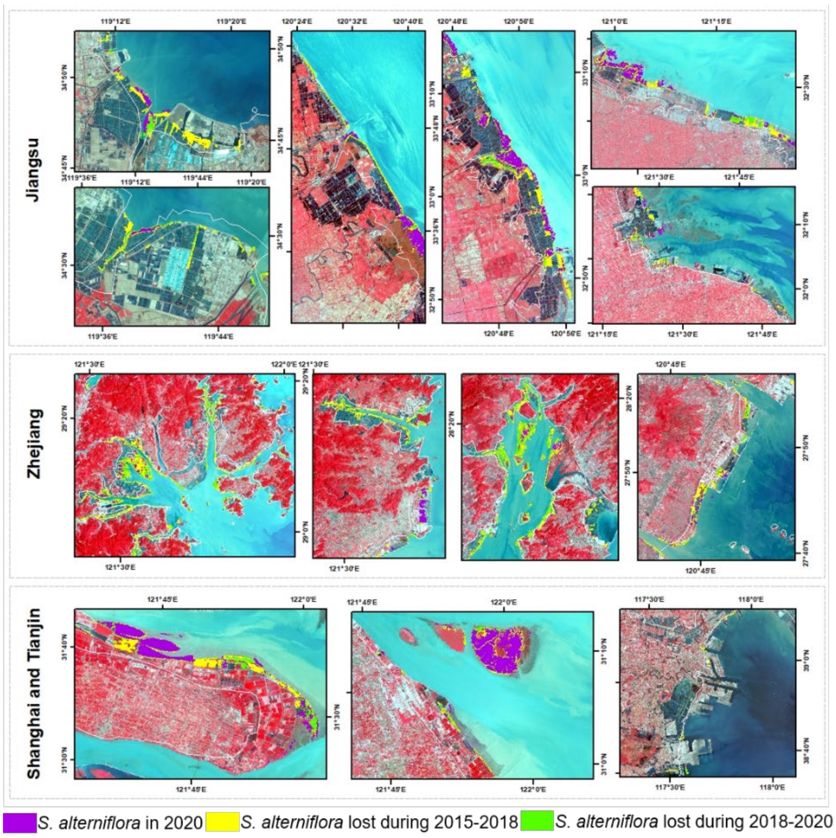

Figure 6 Areas with a notable reduction in *S. alterniflora* coverage.

Despite the success of controlling *S. alterniflora* in many provinces, the expansion of *S. alterniflora* was observed in some regions, especially in Shandong. From 2015 to 2020, Shandong has seen a dramatic increase of *S. alterniflora* by 3718 ha (see Figure 2a and Table 1). In 2020, the Oceanic Bureau of Shandong Province established the Expert Committee on Comprehensive Management of *S. alterniflora* and developed the Implementation Plan of *S. alterniflora* Control and *S. alterniflora* Management Technical Manual. These plans stated that existing *S. alterniflora* invasion issues are expected to be mitigated by curbing *S. alterniflora*'s spread from 2021-2024. Strict and consistent monitoring should be conducted to supervise and evaluate the effectiveness of *S. alterniflora* management.

4.3 Scientific management of *S. alterniflora* benefits the sustainable development of coastal zones

This study shows that the effectiveness of *S. alterniflora* control exhibited significant spatial heterogeneity within coastal mainland China. East China made remarkable achievements in *S. alterniflora* control using physical control, chemical herbicides, and biological substitution or integrated measures (Appendix 2). Physical control is common in all regions of East China, transforming this harmful invasive plant into a potential bioenergy plant and further into fertilizer (Lu and Zhang, 2013). However, this approach might cause potential air pollution (Syed et al., 2021) and can't stop subsequent *S. alterniflora* re-invasion. Herbicides such as Imazapyr (Zhao et al., 2020) and Haloxyfop-R-methyl (Chen et al., 2012) were also confirmed to be effective in *S. alterniflora* emergency control and re-invasion prevention in Chongming, Shanghai, East China (Figure 7a). A potential risk is herbicide residue in the test area's sediment samples, though herbicides' adverse effect on ecological security remains unclear (Zhao et al., 2020). The development of aquaculture and construction of wetland parks are win-win approaches to address the invasion of *S. alterniflora* and benefit ecological restoration and tourism development (Mao et al., 2018b), i.e., in Ningbo (Figure 7b) and Xuanmen Bay (Figure 7c) of Zhejiang Province. In coastal East China, seawall construction in salt marshes invaded by *S. alterniflora* significantly reduced soil organic carbon and nitrogen accumulation in marshes, which could greatly contribute to the shrinkage of residual *S. alterniflora* and prevent *S. alterniflora* from entering the soil and reducing soil humidity and salinity (Yang et al., 2017). In addition, the succession of *S. alterniflora* community to reed community has been adopted to control *S. alterniflora* on Chongming Island (Gan et al., 2009). Similarly, native mangrove species, i.e., *Kandelia obovate* (Xu et al., 2021) and *Sonneratia caseolaris* (Zhou et al., 2015), as well as exotic *Sonneratia apetala* (Chen et al., 2014), were commonly mixed-planted to replace invasive *S. alterniflora* and restore the typical complex food web of mature mangrove ecosystems (Chen et al., 2014). Such mangrove substitution significantly reduced *S. alterniflora* biomass (Wang et al., 2021), optimized the nutritional status of soil (Feng et al., 2019), improved physicochemical properties influencing the sequential food chain, and thus recovered regional habitat and biodiversity (Feng et al., 2018). With the implementation of the Key Bay Ecological Restoration and Demonstration Projects in Zhejiang, a large amount of *S. alterniflora* (over 200 ha) was eliminated and replaced by *S. apetala* and *S. caseolaris* in Leqing Bay. A noticeable improvement in the food web is recognized in the coastal ecosystems of East China under deliberate reduction of *S. alterniflora*, as it positively affects the diversity and density of native flora and fauna (Syed et al., 2021).

Conversely, most of the coastal areas in North China and South China failed to effectively deal with *S. alterniflora* invasion from 2015 to 2020. With its gradual domination and elimination of the local native plant species, *S. alterniflora* caused a severe loss of local biodiversity (Yue et al., 2021), weakened the stability in the wetlands (Zhang et al., 2021), and altered the soil characteristics (Zhang et al., 2018) in the Yellow River Delta, the area subjected to the most severe invasion of *S. alterniflora* in mainland China from 2015 to 2020. Nevertheless, *S. alterniflora* is an ideal plant species to grow at a wide range of pH and salinity (Li et al., 2010) and is resilient to hydrocarbon compounds and heavy metal contaminations (Lian et al., 2018) as well as sea-water flooding for utilizations such as biomass production, phytoremediation, soil remediation (Wan et al., 2009), and carbon sink restoration in coastal marshes and their maintenance (Liu et al., 2021). The introduction of *S. alterniflora* into degraded salt marshes such as *Sueda salsa* (Zhang et al., 2010), *Cyperus malaccensis* (Yang et al., 2013), and sparse mangroves significantly increased soil organic carbon, improved the soil quality, and enhanced the soil productivity in the Bohai Gulf (Lian et al., 2018) and Yellow River Delta of North China (Zhang et al., 2021) as well as the Beibu Gulf of South China (Wang et al., 2016). However, the invasion of *S. alterniflora* into healthy mangrove ecosystems may be counterproductive in the Fujian province of South China (Zhang et al., 2012). Furthermore, *S. alterniflora* is also tolerant to both organic (Su et al., 2016) and inorganic (Chai et al., 2014) contaminants, and is thus efficient in phytoremediation programs of Bohai Bay with severe heavy metal and organic pollutions. Obviously, given the multiple potential applications that *S. alterniflora* has, we need to improve our technology for monitoring its spread in the fragile coastal ecological environment in North and South China while maximizing the positive effect of this spread to enhance the stability of the coastal wetland ecosystem (Mao et al., 2020).

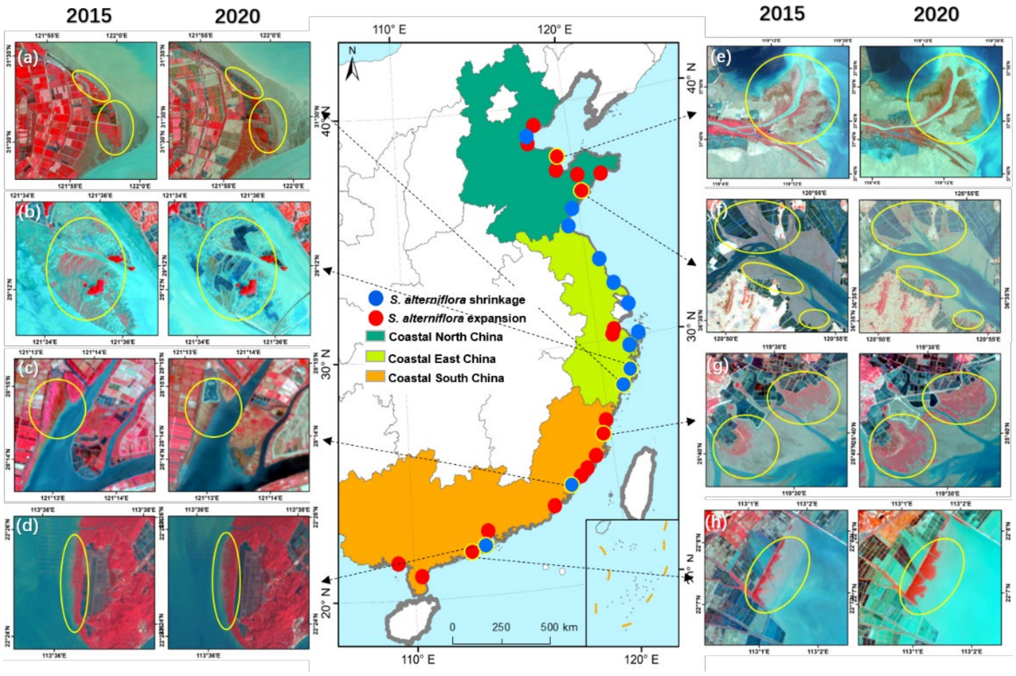

Figure 7 The effectiveness of *S. alterniflora* control in different coastal regions of China, (a) chemical control in Chongming, Shanghai; (b) aquaculture in Ningbo, Zhejiang; (c) construction of wetland parks in Xuanmen Bay, Zhejiang; (d) the succession of *S. alterniflora* community to mangroves in Qiao island, Guangdong; typical *S. alterniflora* expansion areas: (e) Yellow River Delta, Shandong; (f) Yantai, Shandong; (g) Fuqing Bay, Fujian; (h) Jiangmen, Guangdong.

4.4 Partial vs. complete eradication of *S. alterniflora*

Landmark achievements have been made in controlling *S. alterniflora* over coastal mainland China as indicated by an areal decrease of 25% since the SDGs were adopted in 2015. In the next decade, *S. alterniflora* will very likely continue decreasing in China because of the government's current attitude towards invasive *S. alterniflora* and the established *S. alterniflora* governance policies. Effective *S. alterniflora* managements benefit the regional habitat and biodiversity and contribute to restoring and improving the coastal wetland ecosystem. Nevertheless, *S. alterniflora* was broadly employed in the remediation of coastal zones vulnerable to environmental deterioration, sea-water inundation, and anthropogenic pollution. In addition, *S. alterniflora* also provides such applications as biomass production for multiple purposes, phytoremediation, soil remediation, and carbon sink restoration in coastal marshes. However, once large-scale elimination of extensive exotic *S. alterniflora* within coastal China is implemented, the positive ecological effects of *S. alterniflora* would be weakened, implying a site-specific protection approach is necessary for sustainable coastal development wetland management in China. Utilization technologies are also needed to guarantee the positive effects of *S. alterniflora* in most regions exceed the negative ones when employed under control. Nevertheless, such treatments might contribute to unintentional *S. alterniflora* spread into adjacent areas. Besides native reed community and mangrove species, we should identify more native species that might serve similar functions as *S. alterniflora* so as not to alter the traditional landscape, threaten biodiversity, or degrade ecosystem functions. The potential impacts of *S. alterniflora* invasion and the effectiveness of *S. alterniflora* treatment should be objectively assessed to allow scientific measures of coastal ecosystem promotion to improve local conditions.

4.5 Potential sources of uncertainties in the Spartina alterniflora maps of China

The accuracy and uncertainty of *S. alterniflora* mapping of coastal China are mainly affected by several factors. Landsat OLI imagery's 30 m spatial resolution has clearly limited accessibility to capture small *S. alterniflora* patches. A group of *S. alterniflora* with a spatial extent of 50 m × 50 m would just be covered by approximately four pixels, which could be either neglected or identified as other types since a coarser resolution pixel may be a mixture of different surface features. With frequent cloud cover in the coastal zone and a 16-day repeat cycle of Landsat satellites, it is impossible to obtain cloud-free images that cover the entire area in the same season or same tidal level period. Although low tide images were selected when recognizing *S. alterniflora* located in shallow seawater, tidal variations within scenes also inevitably induce some errors in the *S. alterniflora* maps. In this study, object-based information analysis (OBIA) was used to perform *S. alterniflora* extractions, resulting in satisfactory overall accuracies of *S. alterniflora* mapping, over 87%. However, with the limited resolution of Landsat images and the segmentation scale (80) in OBIA, the smallest unit of objects identified from the image segmentation was determined as 0.072 km^2, indicating that *S. alterniflora* groups smaller than 0.072 km^2 failed to be captured. In addition, the extracted *S. alterniflora* were visually interpreted to manually modify the misclassified objects, with the accuracy greatly depending on personal experience.

5. Conclusions

The analysis of the Landsat image series for 2015, 2018, and 2020 revealed that the *S. alterniflora* area had a net decrease of 2,610 ha, mainly in coastal provinces of East China such as Zhejiang, Shanghai, Jiangsu, and Tianjin. However, consistent and notable expansions of *S. alterniflora* occurred in North and South China, especially in Shandong, with an areal increase of 3,718 ha from 2015 to 2020. Our results suggest that relevant policies, regulations, and ecological restoration projects implemented by national or local governments in China led to satisfactory outcomes in controlling *S. alterniflora*. In mainland China, the control and management of *S. alterniflora* have met Targets 6.6, 14.2, 14.5, and 15.8 of the SDGs. Meanwhile, more effective management of *S. alterniflora* is needed in regions where *S. alterniflora* invasion is more severe, such as Shandong, Fujian, and Guangdong. Strict and consistent monitoring should be coordinated with constant improvements to *S. alterniflora* utilization to maintain the effectiveness of *S. alterniflora* management in East China and restore the fragile coastal ecological environment of North and South China. The results presented in this study are expected to benefit the formulation of coastal protection and restoration strategies in China.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Huiying Li: Conceptualization, Data curation, Investigation, Methodology, Software, Writing - original draft, Funding acquisition, Writing - review & editing. Dehua Mao: Conceptualization, Methodology, Resources, Writing - review & editing, Funding acquisition. Zongming Wang: Writing - review & editing, Funding acquisition. Mingming Jia: Writing - review & editing. Xiao Huang: Writing - review & editing, Lin Li: Writing - review & editing.

References

Chai, M., Shi, F., Li, R., Shen, X., 2014. Heavy metal contamination and ecological risk in Spartina alterniflora marsh in intertidal sediments of Bohai Bay, China. Mar. Pollut Bull. 84: 115-124.

Chen L., Gao J, Zhu Q, Wang Y. Yang Y., 2018. Accumulation and output of heavy metals by the invasive plant Spartina alterniflora in a coastal salt marsh. Pedosphere. 28: 884-894.

Chen, H., Liao, B., Liu, B., Peng, C., Zhang, Y., Guan, W., Zhu, Q., Yang, G., 2014. Eradicating invasive Spartina alterniflora with alien Sonneratia apetala and its implications for invasion controls. Ecol Eng. 73: 367-372.

Chen, J., Wang, L., Li, Y., Zhang, W., Fu, X., Le, Y., 2012. Effect of Spartina alterniflora invasion and its controlling technologies on soil microbial respiration of a tidal wetland in Chongming Dongtan, China. Ecol Eng. 41: 52-59.

Chen, Z., Li, B., Zhong, Y., Chen, J., 2004. Local competitive effects of introduced Spartina alterniflora on Scirpus mariqueter at Dongtan of Chongming Island, the Yangtze River estuary and their potential ecological consequences. Hydrobiologia. 528: 99-106.

Feng, J., Huang, Q., Chen, H., Guo, J., Lin, G., 2018. Restoration of native mangrove wetlands can reverse diet shifts of benthic macrofauna caused by invasive cordgrass. J Appl Ecol. 55: 905-916.

Feng, J., Wang, S., Wang, S., Ying, R., Yin, F., Jiang, L., Li, Z., 2019. Effects of Invasive Spartina alterniflora Loisel. and Subsequent Ecological Replacement by Sonneratia apetala Buch.-Ham. on Soil Organic Carbon Fractions and Stock. Forests. 10: 171.

Gan, X., Cai, Y., Choi, C., Ma, Z., Chen, J., Li, B., 2009. Potential impacts of invasive Spartina alterniflora on spring bird communities at Chongming Dongtan, a Chinese wetland of international importance. Estuar. Coast Shelf S. 83: 211-218.

Guo, H., 2021. Big Earth data in support of the sustainable development goals (2020). EDP Sciences.

Hu, Y., Tian, B., Yuan, L., Li, X., Huang, Y., Shi, R., Jiang, X., Wang, L., Sun, C., 2021. Mapping coastal salt marshes in China using time series of Sentinel-1 SAR. ISPRS J Photogramm. 173: 122-134.

Jia M., Wang Z., Mao D., Huang C., Lu C., 2021. Spatial-temporal changes of China's mangrove forests over the past 50 years: An analysis towards the Sustainable Development Goals (SDGs). Chinese Sci Bull. 66: 3886-3901.

Jia, M., Wang, Z., Mao, D., Ren, C., Wang, C., Wang, Y., 2021. Rapid, robust, and automated mapping of tidal flats in China using time series Sentinel-2 images and Google Earth Engine. Remote Sens Environ. 255: 112285.

Li N., Li L., Zhang Y., Wu M., 2020. Monitoring of the invasion of Spartina alterniflora from 1985 to 2015 in Zhejiang Province, China. BMC Ecol. 20: 1-12.

Li, R., Shi, F., Fukuda, K., 2010. Interactive effects of various salt and alkali stresses on growth, organic solutes, and cation accumulation in a halophyte Spartina alterniflora (Poaceae). Environ Exp Bot. 68: 66-74.

Liu, J., Deng, D., Zou, C., Han, R., Xin, Y., Shu, Z., Zhang, L., 2021. Spartina alterniflora saltmarsh soil organic carbon properties and sources in coastal wetlands. J Soil Sediment. 21: 1-10.

Liu, J., Han, R., Su, H., Wu, Y., Zhang, L., Richardson, C., Wang, G., 2017. Effects of exotic Spartina alterniflora on vertical soil organic carbon distribution and storage amount in coastal salt marshes in Jiangsu, China. Ecol Eng. 106: 132-139.

Liu, M., Li, H., Li, L., Man, W., Jia, M., Wang, Z., Lu, C., 2017. Monitoring the invasion of Spartina alterniflora using multi-source high-resolution imagery in the Zhangjiang Estuary, China. Remote Sens. 9: 539.

Liu, M., Mao, D., Wang, Z., Li, L., Man, W., Jia, M., Ren, C., Zhang, Y., 2018. Rapid invasion of Spartina alterniflora in the coastal zone of mainland China: new observations from Landsat OLI images. Remote Sens. 10: 1933.

Liu, Y., Ma, J., Wang, X., Zhong, Q., Zong, J., Wu, W., Wang, Q., Zhao, B., 2020. Joint Effect of Spartina alterniflora Invasion and Reclamation on the Spatial and Temporal Dynamics of Mudflats in Yangtze River Estuary. Remote Sens. 12: 1725.

Lu, J., Zhang, Y., 2013. Spatial distribution of an invasive plant Spartina alterniflora and its potential as biofuels in China. Ecol Eng. 52: 175-181.

Mao, D, Wang, Z, Wang, Y, Choi, C., Jia, M., Jackson, M.V., Fuller, R.A., 2021. Remote Observations in China's Ramsar Sites: Wetland Dynamics, Anthropogenic Threats, and Implications for Sustainable Development Goals. J Remote Sens. 2021.

Mao, D., He, X., Wang, Z., Tian, Y., Xiang, H., Yu, H., Man, W., Jia, M., Ren, C., Zheng, H., 2019. Diverse policies leading to contrasting impacts on land cover and ecosystem services in Northeast China. J Clean Prod. 240: 117961.

Mao, D., Liu, M., Wang, Z., Li, L., Man, W., Jia, M., Zhang, Y., 2019. Rapid invasion of Spartina Alterniflora in the coastal zone of mainland China: spatiotemporal patterns and human prevention. Sensors. 19: 2308.

Mao, D., Luo, L., Wang, Z., Wilson, M.C., Zeng, Y., Wu, B., Wu, J., 2018. Conversions between natural wetlands and farmland in China: A multiscale geospatial analysis. Sci Total Environ. 634: 550-560.

Mao, D., Wang, Z., Du, B., Li, L., Tian, Y., Jia, M., Zeng, Y., Song, K., Jiang, M., Wang, Y., 2020. National wetland mapping in China: A new product resulting from object-based and hierarchical classification of Landsat 8 OLI images. ISPRS J Photogramm. 164: 11-25.

Mao, D., Wang, Z., Wu, J., Wu, B., Zeng, Y., Song, K., Yi, K., Luo, L., 2018. China's wetlands loss to urban expansion. Land Degrad Dev. 29: 2644-2657.

Ministry of Foreign Affairs of the People's Republic of China, 2016. China's National Plan on Implementation of the 2030 Agenda for Sustainable Development (English version).

Ren, G., Zhao, Y., Wang, J., Wu, P., Ma, Y., 2021. Ecological effects analysis of Spartina alterniflora invasion within Yellow River delta using long time series remote sensing imagery. Estuari Coast Shelf S. 249: 107111.

Song, S., Zhang, C., Gao, Y., Zhu, X., Wang, R., Wang, M., Zheng, Y., Hou, L., Liu, M., Wu, D., 2020. Responses of wetland soil bacterial community and edaphic factors to two-year experimental warming and Spartina alterniflora invasion in Chongming Island. J Clean Prod. 250: 119502.

Su, J., Ouyang, W., Hong, Y., Liao, D., Khan, S., Li, H., 2016. Responses of endophytic and rhizospheric bacterial communities of salt marsh plant (Spartina alterniflora) to polycyclic aromatic hydrocarbons contamination. J Soil Sediment. 16: 707-715.

Syed, S., Xu, M., Wang, Z., Yu, C., Lian, B., 2021. Invasive Spartina alterniflora in controlled cultivation: environmental implications of converging future technologies. Ecol Indic. 130: 108027.

United Nations, 2015. Transforming Our World, the 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda. (accessed 2021 Oct 31).

Wan, S., Qin, P., Liu, J., Zhou, H., 2009. The positive and negative effects of exotic Spartina alterniflora in China. Ecol Eng. 35: 444-452.

Wang, D., Huang, W., Liang, R., Li, F., 2016. Effects of Spartina alterniflora invasion on soil quality in coastal wetland of Beibu Gulf of South China. PLoS One. 11: e0168951.

Wang, L., Jia, M., Yin, D., Tian, J., 2019. A review of remote sensing for mangrove forests: 1956–2018. Remote Sens Environ. 231: 111223.

Wang, Q., An, S., Ma, Z., Zhao, B., Chen, J., Li, B., 2006. Invasive Spartina alterniflora: biology, ecology and management. J Sys Evol. 44: 559-588.

Wang, Q., Duarte, C., Song, L., Christakos, G., Agusti, S., Wu, J., 2021. Effects of Ecological Restoration Using Non-Native Mangrove Kandelia obovata to Replace Invasive Spartina alterniflora on Intertidal Macrobenthos Community in Maoyan Island (Zhejiang, China). J Mar Sci Eng. 9: 788.

Wang, X., Xiao, X., Zou, Z., Chen, B., Ma, J., Dong, J., Doughty, R.B., Zhong, Q., Qin, Y., Dai, S., Li, X., Zhao, B., Li, B., 2020. Tracking annual changes of coastal mudflats in China during 1986–2016 through analyses of Landsat images with Google Earth Engine. Remote Sens Environ. 238: 110987.

Wei, P., 2011. Dynamic monitoring analysis of expansion of Spartina alterniflora in Fujian. Chinese J Agrometeorol. 32: 174.

Xu, Y., Liao, B., Jiang, Z., Xin, K., Xiong, Y., Zhang, Y., 2021. Examining the Differences between Invasive Sonneratia apetala and Native Kandelia obovata for Mangrove Restoration: Soil Organic Carbon, Nitrogen, and Phosphorus Content and Pools. J Coastal Res. 37: 708-715.

Yang, W., Qiao, Y., Li, N., Zhao, H., Yang, R., Leng, X., Cheng, X., An, S., 2017. Seawall construction alters soil carbon and nitrogen dynamics and soil microbial biomass in an invasive Spartina alterniflora salt marsh in eastern China. Appl Soil Ecol. 110: 1-11.

Yang, W., Zhao, H., Chen, X., Yin, S., Cheng, X., An, S., 2013. Consequences of short-term C4 plant Spartina alterniflora invasions for soil organic carbon dynamics in a coastal wetland of Eastern China. Ecol Engin. 61: 50-57.

Yue, S., Zhou, Y., Xu, S., Zhang, X., Liu, M., Qiao, Y., Gu, R., Xu, S., Zhang, Y., 2021. Can the non-native salt marsh halophyte Spartina alterniflora threaten native seagrass (Zostera japonica) habitats? a case study in the Yellow River Delta, China. Front Plant Sci. 12: 734.

Zhang X., Zhang Z., Li Z., Li M., Wu H., Jiang M., 2021. Impacts of Spartina alterniflora invasion on soil carbon contents and stability in the Yellow River Delta, China. Sci Total Environ. 775: 145188.

Zhang, D., Hu, Y., Liu, M., Chang, Y., Yan, X., Bu, R., Zhao, D., Li, Z., 2017. Introduction and spread of an exotic plant, Spartina alterniflora, along coastal marshes of China. Wetlands. 37: 1181-1193.

Zhang, G., Bai, J., Jia, J., Wang, X., Wang, W., Zhao, Q., Zhang, S., 2018. Soil organic carbon contents and stocks in coastal salt marshes with Spartina alterniflora following an invasion chronosequence in the Yellow River Delta, China. Chinese Geogr Sci. 28: 374-385.

Zhang, X., Xiao, X., Wang, X., Xu, X., Chen, B., Wang, J., Ma, J., Zhao, B., Li, B., 2020. Quantifying expansion and removal of Spartina alterniflora on Chongming island, China, using time series Landsat images during 1995–2018. Remote Sens Environ. 247: 111916.

Zhang, Y., Ding, W., Luo, J., Donnison, A., 2010. Changes in soil organic carbon dynamics in an Eastern Chinese coastal wetland following invasion by a C4 plant Spartina alterniflora. Soil Biol Biochem. 42: 1712-1720.

Zhang, Y., Huang, G., Wang, W., Chen, L., Lin, G., 2012. Interactions between mangroves and exotic Spartina in an anthropogenically disturbed estuary in southern China. Ecology. 93: 588-597.

Zhao, Z., Xu, Y., Yuan, L., Li, W., Zhu, X., Zhang, L., 2020. Emergency control of Spartina alterniflora re-invasion with a chemical method in Chongming Dongtan, China. Water Sci Eng. 13: 24-33.

Zhou T., Liu S., Feng Z., Liu G., Gan Q., Peng S., 2015. Use of exotic plants to control Spartina alterniflora invasion and promote mangrove restoration. Sci Rep. 5: 1-13.

Zhou, H., Liu, J., Qin, P., 2009. Impacts of an alien species (Spartina alterniflora) on the macrobenthos community of Jiangsu coastal inter-tidal ecosystem. Ecol Eng. 35: 521-528.