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Research article

Dual threat of tidal flat loss and invasive *Spartina alterniflora* endanger important shorebird habitat in coastal mainland China

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ABSTRACT

China's coastal wetlands are critically important to shorebirds. Substantial loss of tidal flats, shorebirds' primary foraging grounds, has occurred from land claim and other processes, and is driving population declines in multiple species. Smooth cordgrass *Spartina alterniflora* was intentionally introduced to the coast of China in 1979 to promote conversion of tidal flats into dry land and has since spread rapidly. The occurrence of *S. alterniflora* reduces the availability of foraging and roosting habitat for shorebirds, and may be particularly detrimental in places that have experienced other tidal flat loss. However, the extent to which *S. alterniflora* is encroaching upon important shorebird habitat throughout coastal mainland China, and its intersection with tidal flat loss, has not been quantified. Here, we i) estimate change in the spatial extent of tidal flats between 2000 and 2015 in coastal mainland China where internationally important numbers of shorebirds have been recorded; ii) map the extent of *S. alterniflora* coverage in 2015 at the same set of sites; and, iii) investigate where these two threats to important shorebird habitat intersect. Our analysis of remote sensing data indicated a 15% net loss in tidal flat area between 2000 and 2015 across all sites, including a net loss in tidal flat area in 39 of 53 individual sites (74%). *Spartina alterniflora* occurred at 28 of 53 sites (53%) in 2015, of which 22 sites (79%) also had a net loss in tidal flat area between 2000 and 2015. Combined pressures from tidal flat loss and *S. alterniflora* invasion were most severe in eastern coastal China. Species highly dependent on migrating through this region, which include the Critically Endangered Spoon-billed Sandpiper and Endangered Nordmann's Greenshank and Far Eastern Curlew, may be particularly impacted. Our results underscore the urgent need to arrest tidal flat declines and develop a comprehensive control program for *S. alterniflora* in coastal areas of mainland China that are important for shorebirds.

1. Introduction

China's coastal wetlands are critically important for waterbirds, supporting at least 75 species in internationally important numbers (i.e. > 1% of the species' estimated flyway population; Bai et al., 2015). China's tidal flats are a critical habitat for several dozen species of shorebirds, a diverse group of waterbirds that share morphological characteristics suited to shallow water foraging. Tidal flats cover >12, 000 km^2 in China, the second-largest areal extent of tidal flats found in any country (Murray et al., 2019). Many shorebirds that occur in China are migratory and move through the East Asian-Australasian Flyway between breeding grounds in northern China, Mongolia, Russia and Alaska and non-breeding areas in southern and eastern China, Southeast Asia, Australia and New Zealand.

Land claim for agriculture, aquaculture and industrial uses has caused substantial loss of tidal flats in coastal China (Ma et al., 2014; Murray et al., 2014; Piersma et al., 2017; Choi et al., 2018; Duan et al., 2019). Reduced sediment discharge to coasts, changed hydrological

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regimes, subsidence and sea level rise are also believed to contribute to tidal flat loss (Higgins et al., 2013; Iwamura et al., 2013; Zuo et al., 2013; Murray et al., 2014; Yang et al., 2020). Loss and degradation of tidal flats has been particularly extensive in the Yellow Sea (Murray et al., 2014, 2015, 2019; Melville et al., 2016), with a 67% decrease in saltmarshes and a 49% decrease in tidal flats in the Chinese Yellow Sea over the past 30 years (Chen et al., 2019). Coastal habitat loss in the Yellow Sea has contributed to population declines in multiple species of migratory shorebirds (Clemens et al., 2016; Piersma et al., 2016, 2017; Studds et al., 2017), several of which are now threatened (IUCN, 2019a).

Invasive plants are present globally in most ecosystems and threaten biodiversity and ecosystem function (Wardle et al., 2011; Barney et al., 2015). Plant invasions can substantively modify communities and ecosystems (Pyšek et al., 2012), and generally decrease animal abundance, diversity and fitness, including that of birds (Schirmel et al., 2016).

Spartina alterniflora (smooth cordgrass) is a perennial rhizomatous grass native to the Atlantic coast of North America that expands along tidal flats. Over the past two hundred years it and related species and hybrids have been introduced both intentionally and accidentally to parts of Europe (Cottet et al., 2007; Tang and Kristensen, 2010), the Pacific coast of North America (Civille et al., 2005), New Zealand (Hayward et al., 2008), Australia (Kriwoken and Hedge, 2000), and China (An et al., 2007; Liu et al., 2016; Mao et al., 2019). *Spartina alterniflora* is considered an "ecosystem engineer" because it can alter key ecosystem processes including nutrient cycling, hydrology, and sediment deposition patterns (Crooks, 2002). It generally grows seaward from the edge of salt marshes and facilitates accumulation of sediment, eventually replacing large areas of open tidal flats with dense, elevated *S. alterniflora* marshes (Crooks, 2002; Civille et al., 2005).

In China, *S. alterniflora* was intentionally introduced to the coast of Jiangsu in 1979 to promote erosion control and create "new land" with a small number of seeds and plants imported from the United States (Qin and Zhong, 1992; An et al., 2007). From an initial planting area of 0.001 km^2 in 1981, *S. alterniflora* expanded to 2.6 km^2 by 1985 (An et al., 2007), and by 2015 covered approximately 550 km^2 across multiple regions (Liu et al., 2018), sometimes forming dense marshes over 2 m tall. In China, *S. alterniflora* occurs mostly on bare tidal flats, though it has also replaced some native saltmarshes (Li et al., 2009) and has spread both seaward and landward (Liu et al., 2017). *Spartina alterniflora* invasion is most extensive in Jiangsu, where it covered almost 200 km^2 in 2015 and accounts for >30% of the total area of *S. alterniflora* in mainland China (Liu et al., 2018).

Spartina spp. invasion into native habitats poses a direct threat to shorebirds because it reduces or eliminates the availability of tidal flats for foraging by covering them with tall, dense vegetation (Goss-Custard and Moser, 1988; Stralberg et al., 2004). In Chongming Dongtan, an important area for shorebirds in Shanghai municipality, waterbird (including shorebird) diversity and density are significantly lower in habitats invaded by *S. alterniflora* than on bare tidal flats (Gan et al., 2009). In general, the macrobenthic community has shifted towards a more large-crustacea-dominated community, as gastropod and bivalve colonization is limited by the dense roots and rhizomes in *S. alterniflora*-invaded areas. This could theoretically benefit some larger shorebirds that can feed on large prey while making the area unsuitable for many other shorebirds that prefer smaller and more digestible prey (Jing et al., 2007; Gan et al., 2009); moreover, the density of *S. alterniflora* stems and the height to which it grows makes it difficult for any shorebirds to forage within mature meadows. Significant changes to macrobenthic communities, the main prey for shorebirds, have also been recorded elsewhere following *Spartina* spp. invasion. In the Zhanjiang Mangrove National Nature Reserve, the presence of *S. alterniflora* significantly decreased the density and biomass of macrobenthic fauna in an unvegetated shoal (Chen et al., 2018); in the Wadden Sea, the diversity of macrobenthic fauna was consistently higher in open mudflat areas than *Spartina anglica.* marshes (Tang and Kristensen, 2010); and, in Australia the species richness and diversity of macrobenthic fauna was higher in bare mudflats and native saltmarsh not invaded by *S. anglica.* than in *S. anglica* marshes (Cutajar et al., 2012).

For coastal shorebird species, local-scale movements are often tide-driven with birds foraging on intertidal flats at lower tides, and roosting (an important period of sleep, rest and digestion) in nearshore and supratidal areas at higher tides (Rogers, 2003; Choi et al., 2019; Jackson et al., 2019). *Spartina* spp. impact shorebird roosting habitat by reducing the area with preferred roost site characteristics, namely shallow water or bare mud with unimpeded sight lines, which aid in predation avoidance and enable supplemental foraging opportunities (Prater, 1981; Goss-Custard and Moser, 1988; Rogers, 2003; Melville et al., 2016; Jackson et al., 2019).

The intersection of *S. alterniflora* invasion and tidal flat loss from other processes (i.e. land claim, reduced sediment discharge, etc.) presents a dual threat to coastal shorebird habitat, with both pressures narrowing the extent of tidal flats available for foraging and roosting, and *S. alterniflora* also impacting supratidal roosting habitat. Loss of tidal flats has been documented at multiple important shorebird sites in coastal China (Melville et al., 2016; Ma et al., 2019a, 2019b; Duan et al., 2020). Invasion of some important shorebird habitat in China by *S. alterniflora* has been documented, for example in the Chongming Dongtan National Nature Reserve and the Yancheng National Nature Reserve in Jiangsu, both internationally important wetlands (Gan et al., 2009; Liu et al., 2016). However, the extent to which *S. alterniflora* is encroaching upon important shorebird habitat throughout coastal mainland China, and its intersection with tidal flat loss, has not been quantified.

Here, we incorporate the latest remote sensing and ecological datasets to: i) estimate change in the spatial extent of tidal flats between 2000 and 2015 in coastal mainland China where internationally important numbers of shorebirds have been recorded; ii) map the 2015 extent of *S. alterniflora* coverage at the same set of sites; and, iii) investigate where these two threats to important shorebird habitat intersect.

2. Methods

2.1. Important shorebird sites

We generated a list of important coastal shorebird sites in mainland China (hereafter important shorebird sites) derived from Bai et al. (2015), which documents coastal sites of international importance for waterbird species (i.e. meeting Ramsar Convention listing criterion 6, >1% of the flyway population recorded at the site) in mainland China and Conklin et al. (2014), which documents sites of international importance for shorebird species in the East Asian-Australasian Flyway. We used historical imagery in Google Earth to manually map the 2015 coastline relevant to each important shorebird site for the purposes of our analysis. To determine the lateral extent of coastline at each site, we referred to either: i) the site boundaries of national nature reserves or ii) survey routes of sites from Bai et al. (2015) provided by counters from the China Coastal Waterbird Census; for additional sites from Conklin et al. (2014) not included in i) or ii) we mapped ~ 3 km of coastline on either site of the coordinates for the site, a size roughly comparable to the sites from ii). A full list of sites included in this study, the corresponding data source used to map each site, and the species that have been recorded at the site in internationally important numbers, are provided in Supplemental Materials 1.

2.2. Mapping tidal flat change at important shorebird sites

To measure tidal flat change, we compared the extent of tidal flats at each important shorebird site in 2000 and 2015. We first exported a map of tidal flats along the mainland China coast in 1999–2001 and a map of tidal flats along the mainland China coast in 2014–2016 from https://intertidal.app/ (Murray et al., 2019) and imported these two maps into

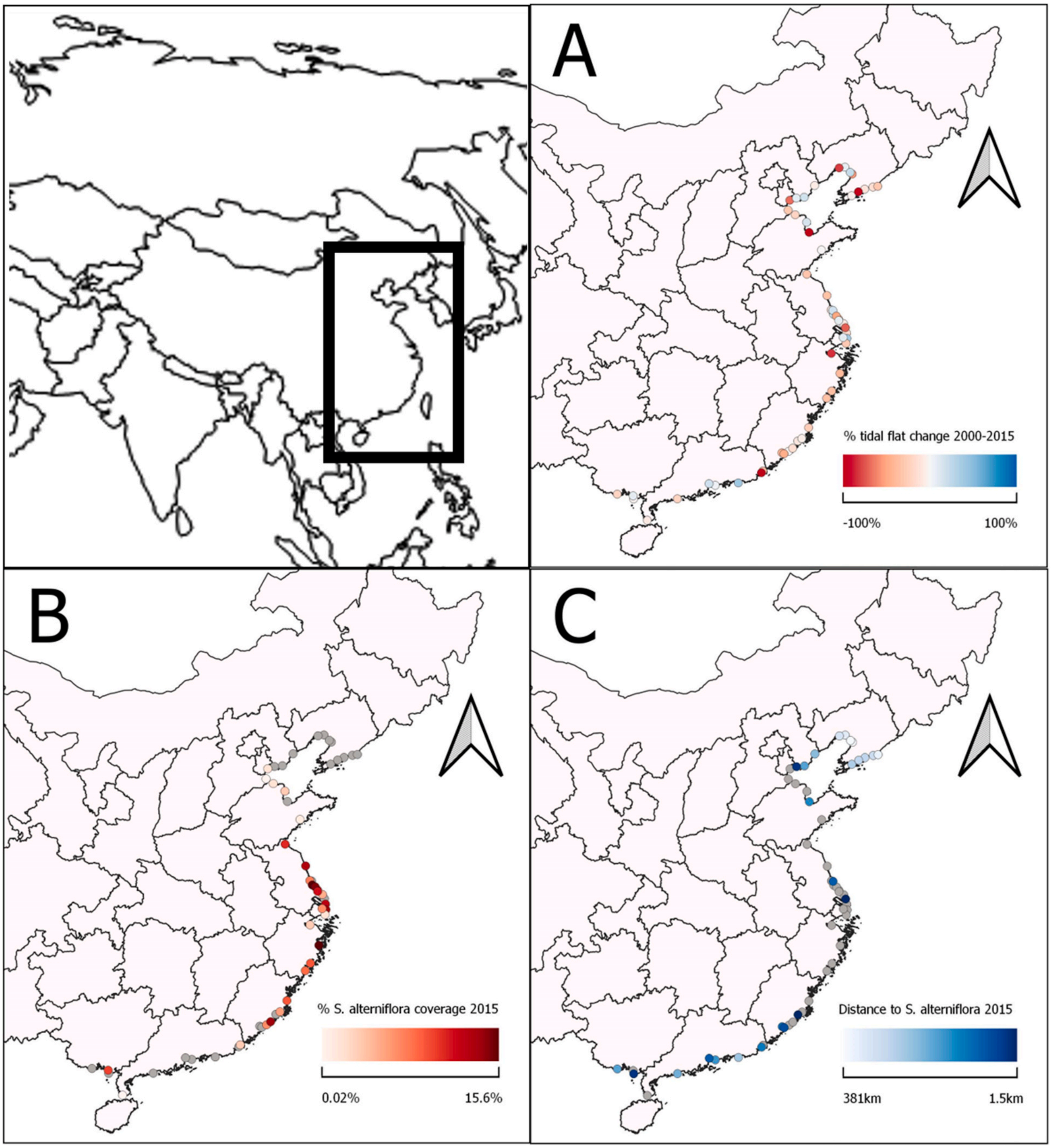

Fig. 1. Regional map showing approximate area of interest with a black rectangle (upper left panel); map of sites in mainland China where internationally important numbers of shorebirds have been recorded, showing (A) change in tidal flat area between 2000 and 2015, (B) extent of *S. alterniflora* coverage of the site in 2015 (sites with no coverage shown in grey) and (C) distance to nearest *S. alterniflora* in cases where *S. alterniflora* did not occur in the site in 2015 (sites with *S. alterniflora* coverage shown in grey).

QGIS (QGIS Development Team, 2019). We then generated an 'area of interest' for each site that extended from the coastline of the site to the seaward extent of tidal flats parallel to the coastline (which varied from several kms to > 50 km depending on the region). For each site we clipped the 1999–2001 tidal flat map layer and the 2014–2016 tidal flat map layer to the area of interest, and then calculated the area of tidal flats in 1999–2001, the area of tidal flats in 2014–2016, and the percentage change between the two.

The tidal flat maps produced by Murray et al. (2019) were generated by applying a machine learning classification model to every 30-m pixel of the coastal zone, and assigning each pixel as 'tidal flat', 'permanent water' or 'other' (the last of which represents terrestrial environments and vegetated intertidal systems including vegetated marshes and mangroves). Since *S. alterniflora* vegetates tidal flats gradually, pixels of tidal flats infested with *S. alterniflora* may be classified as either 'tidal flat' or 'other' in the Murray et al. (2019) dataset depending on the extent to which *S. alterniflora* masks underlying inundation dynamics. We therefore calculated the % total area of *S. alterniflora* detected in important shorebird sites that was also classified as tidal flats in our analysis to determine whether *S. alterniflora* invasion was reflected as tidal flat loss in our results.

Owing to extensive changes in the coastline over the study period,

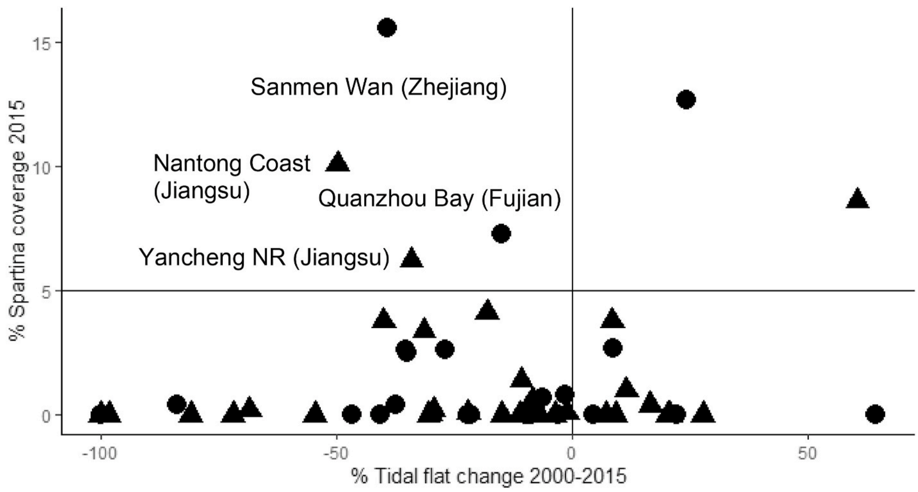

Fig. 2. Percentage tidal flat change between 2000 and 2015 and extent of *S. alterniflora* coverage in 2015 for 53 important coastal shorebird sites in mainland China, each represented by a symbol. Vertical line separates those sites where tidal flat extent (2000–2015) decreased from those sites where tidal flat extent (2000–2015) increased. Horizontal line separates those sites where *S. alterniflora* coverage was ≥5% from those sites where coverage was ≤5%. Sites with high *S. alterniflora* coverage (≥5%) where tidal flats decreased are named. Sites located in the Yellow Sea are denoted by a triangle.

often resulting from land claim activities, the 2000 coastline of a site sometimes differed from its 2015 coastline, so we manually mapped the coastline for each of the two time periods (2000 and 2015) for the purposes of calculating the area of tidal flats at the site in each year. This step helps to ensure that supratidal areas such as aquaculture ponds that may experience wetting and drying similar to tidal areas are not unintentionally represented in our map layer as tidal flats - a potential source of error in the tidal flat dataset in some locations (Murray et al., 2019; Wang et al., 2020).

In summary, tidal flat change in our analysis was identified for each site through some combination of land claim that resulted in a shift of the coastline (which we mapped manually), changes in sediment supply or other hydrological processes that affected the area of tidal flats present seaward of the coastline (reflected in the maps from Murray et al., 2019), and expansion or contraction of *S. alterniflora* marshes or other vegetated habitats in the intertidal zone (reflected in the maps from Murray et al., 2019).

For an example of how tidal flat change was mapped for i) nature reserves, ii) sites derived from the China Coastal Water Bird Census survey routes, and iii) sites identified from coordinates in Conklin et al. (2014), see Supplemental Materials 2.

2.3. Mapping *S. alterniflora* in important shorebird sites

To measure *S. alterniflora* coverage of each site, we used a map of *S. alterniflora* extent along the mainland China coast in 2015 developed from an analysis of Landsat-8 images at 30 m resolution acquired between 2014 and 2016 by Liu et al. (2018). This map was verified through field surveys and the classification had an overall accuracy of 96%, a kappa coefficient of 0.86, and producer and user accuracies greater than 0.85 (Liu et al., 2018).

Tidal flats may extend much further seaward than the plausible extent to which *S. alterniflora* could spread seaward, which is about 5 km (Liu et al., 2018). *Spartina alterniflora* also impacts supratidal shorebird habitat that occurs inland from the seawall, up to about 2 km from the coastline (Choi et al., 2019; Jackson et al., 2019). Therefore, to measure *S. alterniflora* coverage we developed an area of interest by buffering the mapped 2015 coastline for each site 2 km inland and 5 km seaward. We then clipped the 2015 *S. alterniflora* map to the area of interest for each site and calculated the area and percent coverage of *S. alterniflora* in each site. For sites identified as having no *S. alterniflora* coverage, we computed the shortest distance between the area of interest and the closest occurrence of *S. alterniflora*.

For an example of how *S. alterniflora* coverage was mapped for i) nature reserves, ii) sites derived from the China Coastal Water Bird Census survey routes, and iii) sites identified from coordinates in Conklin et al. (2014), see Supplemental Materials 2.

To test whether there was a relationship between *S. alterniflora* invasion and tidal flat loss, we used Kendall's rank and Spearman's rank correlation tests to check whether the percent coverage of *S. alterniflora* and the percentage change in tidal flat (increase or decrease) at each site were correlated. We did not use a Pearson correlation test because it measures a linear dependence between two variables, and we expected that any relationship would not be linear given that there would be multiple values of 0% for sites without any *S. alterniflora* invasion.

3. Results

We identified 53 important shorebird sites in coastal mainland China, of which 11 are national nature reserves (Supplemental Materials 1). Thirty-five species were reported in Bai et al. (2015) and/or Conklin et al. (2014) in internationally important numbers across these sites. The Critically Endangered Spoon-billed Sandpiper *Calidris pygmaea* occurred in internationally important numbers at more sites than any other species (23 sites, 43% of all sites) followed by Grey Plover *Pluvialis squatarola* (16 sites, 30% of all sites) and Dunlin *Calidris alpina* (15 sites, 28% of all sites; Supplementary Materials 1, 3).

The total area of tidal flats across all sites decreased by 15% from 3890 km^2 in 2000 to 3293 km^2 in 2015 (n = 53 sites, mean tidal flat change: −21.1%, range: −100.0% to +39.2%). There was a net loss in tidal flat area between 2000 and 2015 at 39 sites (74% of sites; mean tidal flat change: −34.5%, range: −100.0% to −1.0%), which was > −10% at 30 sites, > −50% at nine sites and −100% at two sites (Fig. 1A; Fig. 2; Supplementary Materials 1). There was a net increase in tidal flat area at 14 sites (26% of sites; mean tidal flat change: 16.5%, range: 4.3% to 39.2%, Fig. 1A; Fig. 2; Supplementary Materials 1). Loss of tidal flats at important shorebird sites between 2000 and 2015 was most severe in Zhejiang, Shanghai, Tianjin, Hebei, and Liaoning (Fig. 1A).

A known feature of the Murray et al. (2019) tidal flat dataset is that some areas of low-lying vegetation, such as pioneer *S. alterniflora*, were mapped as tidal flats. However, only 9.2% of the total area of *S. alterniflora* that we detected in important shorebird sites was also classified as tidal flats in our analysis, suggesting that our tidal flats dataset generally reflected tidal flat loss from *S. alterniflora* invasion. Note that this finding is independent of results about the area of each important shorebird site that are covered by *S. alterniflora*.

Spoon-billed Sandpiper occurred in internationally important numbers at more sites that experienced tidal flat loss than any other species (20 sites, 87% of sites where it occurred), followed by Grey Plover (12 sites, 75% of sites where it occurred) and Dunlin (9 sites, 60% of sites where it occurred; Fig. 3; Supplemental Materials 3). Other species that occurred at > 3 sites in internationally important numbers

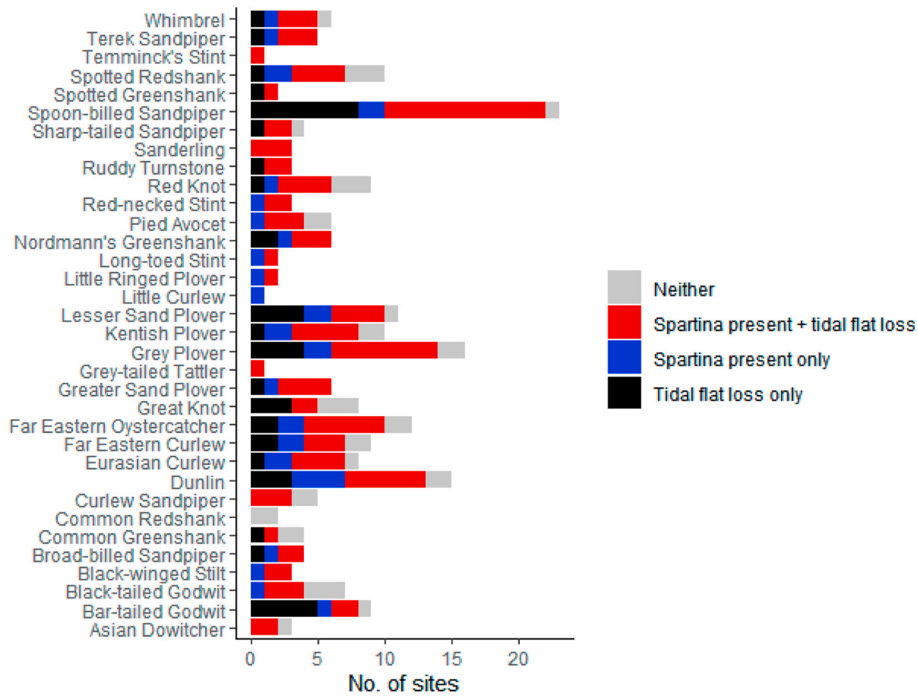

Fig. 3. Number of sites where tidal flats decreased in area (2000–2015, black) where *S. alterniflora* was present (2015, blue), where both threats occurred (red) and where neither threat occurred (grey) for each shorebird species that occurred in internationally important numbers. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and where a high proportion of those sites also experienced tidal flat loss include the Endangered Nordmann's Greenshank *Tringa guttifer*, (5 sites, 83% of sites where it occurred), Greater Sand Plover *Charadrius leschenaultii* (5 sites, 83% of sites where it occurred), Terek Sandpiper *Xenus cinereus* (4 sites, 80% of sites where it occurred) and Bar-tailed Godwit (7 sites, 78% of sites where it occurred; Fig. 3, Supplemental Materials 3).

Spoon-billed Sandpiper occurred in internationally important numbers at more sites that experienced *S. alterniflora* invasion than any other species (14 sites, 61% of sites where it occurred), followed by Grey Plover (10 sites, 63% of sites where it occurred) and Dunlin (10 sites, 67% of sites where it occurred; Fig. 3; Supplemental Materials 3).

Of the 28 sites where *S. alterniflora* occurred, 22 sites (79%) also had a net loss in tidal flat area between 2000 and 2015, while 17 of the 25 sites (68%) without *S. alterniflora* overlap had a net loss in tidal flat area between 2000 and 2015 (Fig. 2). Reflecting this result that tidal flat loss was common whether or not *S. alterniflora* was present, neither a Kendall's rank or a Spearman's rank correlation test showed a significant relationship between percent *S. alterniflora* coverage and percent tidal flat change (p-value = 0.95 and p-value = 0.98, respectively).

Four of the six sites with >5% *S. alterniflora* coverage had a net loss in tidal flat area between 2000 and 2015, including Sanmen Wan (Zhejiang province, 16% *S. alterniflora* coverage, −39% tidal flat extent), Nantong Coast (Jiangsu province, 10% *S. alterniflora* coverage, −50% tidal flat extent), Quanzhou Bay (Fujian province, 7% *S. alterniflora* coverage, −15% tidal flat extent) and Yancheng Nature Reserve (Jiangsu province, 6.2% *S. alterniflora* coverage, −34% tidal flat extent; Fig. 2).

Spoon-billed Sandpiper occurred in internationally important numbers at more sites that experienced both tidal flat loss and *S. alterniflora* invasion than any other species (12 sites, 52% of sites where it occurred). Thirty-three of 35 shorebird species occurred in internationally important numbers at least one site that experienced both threats.

4. Discussion

4.1. Distribution of threats to shorebird habitat from tidal flat loss and S. alterniflora

This analysis provides a large-scale perspective on the spatial variations of two key threats to shorebird habitat in coastal mainland China. It highlights the value of an interdisciplinary approach that combines remote sensing and ecological data to support conservation and management (Pettorelli et al., 2014). Across important shorebird sites in north-eastern coastal China including the northern Yellow Sea and the Bohai Sea (i.e. Liaoning, Hebei, Tianjin and Shandong), some sites experienced severe tidal flat loss but most were relatively free from *S. alterniflora* invasion, though worryingly *S. alterniflora* has reached the western part of this area (Fig. 1). Across important shorebird sites eastern China, including in the southern Yellow Sea (i.e. Jiangsu and Shanghai), Zhejiang and Fujian, both tidal flat loss and *S. alterniflora* invasion were widespread (Fig. 1). In contrast, important shorebird sites in south-eastern coastal China (i.e. Guangdong and Guangxi) faced relatively less pressure from both threats (Fig. 1). Thus, for the conservation of migratory shorebirds, urgent action is most needed to halt tidal flat loss in eastern and north-eastern coastal China, to control *S. alterniflora* in eastern China, and to prevent further *S. alterniflora* spread and worsening of current infestations in north-eastern China. Species highly reliant on sites in eastern coastal China include the Critically Endangered Spoon-billed Sandpiper, and Endangered Nordmann's Greenshank and Far Eastern Curlew *Numenius madagascariensis* (Conklin et al., 2014; Choi et al., 2016; Chan et al., 2019).

Among important shorebird sites that are also National Nature Reserves, which receive some of the most extensive protection among coastal habitats in China, we detected loss of tidal flats and *S. alterniflora* invasion in six of 11 sites (55%), including four sites (36%) that experienced both. This is of concern, especially given results from Ma et al. (2019b) showing that the extent of tidal flats within National Nature Reserves has decreased substantially since 2000 under the dual influence of land claim and boundary adjustments that have reduced the area of tidal flats within coastal reserves.

4.2. Managing tidal flats

Historically, loss of tidal flats from land claim has been considered one of the most pernicious threats to intertidal shorebird habitat in China (Ma et al., 2014; Murray et al., 2014; Melville et al., 2016; Piersma et al., 2017; Choi et al., 2018). A recent announcement from the Chinese government indicated that business-related land claim is to cease and decisions on future land claim activities should be made only by the central government (Melville, 2018; Stokstad, 2018). In addition, three intertidal sites (which encompass the Dongtai and Yancheng National Nature Reserve sites from this study) were inscribed onto the World Heritage list in 2019 and another ~14 sites are to be included within a second phase of this serial nomination to be considered for World Heritage Listing within the next three years, which should afford protection from major destructive and extractive activities (IUCN, 2019b).

Preventing further loss of tidal flats through protection and reduced land claim activities will slow the rapid decline in tidal flats that China has experienced over the last 50 years (Murray et al., 2012, 2014, 2019), but part of this ecosystem (tidal flats of the Yellow and Bohai Seas) is already classified as Endangered using IUCN Redlist of Ecosystems criteria (Murray et al., 2015), and land claim is not the only cause of reduced tidal flat extent. Lack of sediment delivery to coasts by rivers, changed hydrology and sea level rise may all affect the size of tidal flats (Iwamura et al., 2013; Zuo et al., 2013; Murray et al., 2014; Yang et al., 2020) and their quality is impacted by overfishing, pollution, run-off and algal blooms (Murray et al., 2015; Melville et al., 2016). Moreover, historical tidal flat loss has already had adverse effects on shorebird populations (Clemens et al., 2016; Piersma et al., 2016; Studds et al., 2017). This makes maintaining the current extent and where possible improving the condition of remaining tidal flats critically important for shorebird population recovery. A key tool in achieving this will be ongoing, large-scale monitoring of tidal flat change through publicly-available tools such as https://intertidal.app, which is expected to be updated every 3 years (Murray et al., 2019).

4.3. Managing *S. alterniflora*

Like coastal land claim, and unlike other threats including sea level rise, reduced sediment flow or changed hydrology, *S. alterniflora* is a threat to tidal flats that can be managed directly through various forms of control. In the western United States, a combination of mowing and herbicide application has had the greatest efficacy in reducing densely colonised *S. alterniflora* marshes but this method is expensive (Hedge et al., 2003), and eradication has proved difficult to achieve even with a multi-decadal control effort (Patten et al., 2017). In the South Island of New Zealand, *Spartina* spp. extent has been greatly reduced by ground-based and aerial application of herbicides, but this effort has been ongoing since the 1970s, and while eradication now seems potentially feasible it has not yet been fully achieved (Brown and Raal, 2013). These experiences demonstrate the urgency of eradicating *S. alterniflora* before it becomes well established.

In North America, chemical control has been implemented with several different chemicals including Glufosinate, Glyphosate, and Imazethapyr (Knott et al., 2013; Patten et al., 2017), while in the South Island of New Zealand, Haloxyfop has been found to be more effective than Glyphosate (which was used in earlier control efforts) and has the added benefit of being specific to Gramineae, allowing for large areas of *Spartina* spp. to be destroyed without putting native plant communities at risk (Brown and Raal, 2013).

Evans (1986) studied the response of shorebirds to chemical *Spartina* sp. control in the United Kingdom and found that they foraged more often on recently-cleared areas than on areas cleared 3–4 years before, and significantly more often than on untreated *Spartina* spp. marshes. In the western United States where *S. alterniflora* encroached on important shorebird habitat, became established, formed dense marshes, and was subsequently treated through chemical control, site usage by shorebirds following *S. alterniflora* control increased significantly within ten years (Patten et al., 2017). These results demonstrate that tidal flats can be viable as shorebird habitat following *Spartina* spp. control.

Various forms of *S. alterniflora* control have been implemented in China with mixed results (e.g. An et al., 2007; Li and Zhang, 2008). For example, in Chongming Dongtan, multiple forms of physical control and some biological control via substitution with *Phragmites australis* were implemented in 2005–2006 with limited success after the first growing season (Li and Zhang, 2008). Following this, in 2013 a large eradication and restoration project was undertaken over 24 km^2 of the Chongming Dongtan National Nature Reserve involving construction of artificial walls to encircle *S. alterniflora* (Hu et al., 2015), the stems of which were then cut and water levels manipulated to kill the rhizomes. Though costly (approximately 1.3 billion RMB), this engineering project successfully addressed the severe infestation of *S. alterniflora* inside the reserve; however, large, intact communities of *S. alterniflora* remained and continued to expand just outside the reserve, leading to sporadic re-invasions of control areas inside the reserve (Zhao et al., 2020). To test a strategy for emergency control of small patches of re-invading *S. alterniflora*, an in-situ field experiment using Haloxyfop-R-methyl (as Gallant, by Dow Chemical Company) was applied, with very high success rates recorded in July and August (Zhao et al., 2020). Nonetheless, re-invasion of the reserve by seeds brought by the sea from elsewhere will be a continuing problem and native vegetation is still highly vulnerable, highlighting the need for a concerted, regional control programme. In addition, while these results are encouraging, the original engineering approach is unlikely to be feasible on a large scale across multiple sites.

Additional herbicide trials have been recently implemented elsewhere in China. Gallant and broad-spectrum Imazapyr (as Polaris, by Nufarm) have been effective at eliminating *S. alterniflora* patches in pilot sites around Luannan (Hebei) after two years of treatment. Sulfometuron-methyl, a broad-spectrum compound herbicide (as 滩涂米草除控剂, by Xinghua Agriculture and Forestry High-tech Research Institute), has also been applied in Tianjin and Fujian and successfully removed *S. alterniflora* from tidal flats.

The environmental effects of large-scale herbicide use on intertidal ecosystems in China are not fully known, but an experimental study on Chongming Island found that Haloxyfop-R-methyl (haloxyfop) in the rhizosphere soil of *S. alterniflora* has a half-life of 2.6–4.9 days, and almost all of the haloxyfop dissipated after thirty days (Liang et al., 2020). The diversity of rhizosphere soil bacteria decreased within a week of the haloxyfop treatment but recovered after a month, and types of soil bacteria that efficiently degrade herbicides increased in abundance, suggesting that haloxyfop dissipates quickly in wetland soil, though its long-term continuous use still requires investigation (Liang et al., 2020). Further, Zhao et al. (2020) documented that there were no significant differences in the community structure of meiofauna among areas in the Chongming Dongtan National Nature Reserve treated with Gallant and the control and that no herbicide residues were detected in sediment samples collected from treatment areas, and suggested that Gallant is a high efficiency, environmentally-friendly herbicide for treating *S. alterniflora* in coastal wetlands. In New Zealand, the government currently authorises haloxyfop for *Spartina* spp. control in tidal areas following a review of multiple herbicides (Environmental Protection Authority, 2012) .

Given the clear threat that *S. alterniflora* poses to remaining shorebird habitat in coastal mainland China, controlling *S. alterniflora* at important shorebird sites with a herbicide that minimises environmental damage where it already occurs and preventing encroachment into additional sites should be undertaken as a priority for shorebird conservation. At the site-level, *S. alterniflora* management should carefully consider local waterbird roosting and foraging dynamics at a finer scale than our relatively coarse large-scale assessment, but a national-level strategy is needed given the scope of the problem across a huge area of coastline and multiple jurisdictions (Fig. 1B and C). Long-term, large-scale monitoring of *S. alterniflora* will be an important tool for monitoring management progress.

4.4. Limitations

Our list of important shorebird sites is incomplete and could be somewhat outdated. For example, Chan et al. (2019) tracked 32 Great Knot *Calidris tenuirostris* using solar-powered satellite transmitters and found that 63% of 92 stopping sites were not known as important shorebird sites, including several in southern China. Duan et al. (2020) documented sites of importance to waterbirds that may not be widely recognised based on recent data. On the other hand, Ma et al. (2019a) found that more than half of 38 Important Bird Areas studied had undergone major modification from human land use, primarily land claim. This suggests that some of the sites in our dataset (some of which, particularly from the list in Conklin et al. (2014), were identified from counts > 10 years old) may already be unsuitable for shorebirds, at least in part, due to habitat modification. Further work is needed to accurately map the current full network of important shorebird sites along the coast of mainland China and assess relative threats accordingly and regularly. In addition, the entire Yellow Sea coast, which also encompasses coastline in the Democratic People's Republic of Korea and the Republic of Korea, provides critical shorebird habitat (Conklin et al., 2014), and *Spartina* spp. may also be encroaching on shorebird habitat there (e.g. Kim et al., 2012).

Also, while tidal flats at some sites in Jiangsu did not show high rates of decline in our analysis, tidal flats in this region are some of the widest in the world and form an extremely dynamic system (Wang et al., 2002). Our analysis showed that loss of nearshore tidal flats from reclamation between 2000 and 2015 at sites in Jiangsu province was often offset or partly offset by growth in tidal flats further seaward, meaning the site did not show a net loss of tidal flat area in our results (see Supplementary Materials 2A for an example from the 'Rudong coast' site). In such cases the threat to shorebirds from tidal flat loss was underestimated, because most shorebirds spend the majority of their foraging time on the upper tidal flats (i.e. those closer to the coast; Mu and Wilcove, 2020), and shorebirds roost on areas just seaward of the seawall that do not get submerged by seawater at high tide (Goss-Custard and Moser, 1988; Choi et al., 2014), making it unlikely that loss of upper tidal flats is mitigated for shorebirds by tidal flat growth further seaward.

A further potential issue is the erosion of subtidal flats and reworking of sediments inshore, which is occurring in parts of coastal China, and causes a steeper outer edge to develop on the flats resulting in the temporary maintenance or expansion of tidal flat extent, but increased wave energy and consequent erosion that will occur at a later stage (Yang et al., 2020).

Finally, tidal flat spatial data has been shown to be variable when used at small scales due to the influence of tides (Murray et al., 2012). Nonetheless of the 39 sites where we recorded a net loss of tidal flats, loss exceeded >10% for 30 sites suggesting our results are fairly robust.

5. Conclusions

Habitat loss, particularly of tidal flats, has been the major factor behind widespread population declines in the East Asian-Australasian Flyway's migratory shorebirds, making the maintenance and improvement of remaining intertidal habitat a top priority for shorebird conservation. Controlling *S. alterniflora* at important shorebird sites where it already occurs and preventing encroachment into additional sites is required to safeguard habitat that shorebirds rely on for survival. With more than 40% of the important shorebird sites along coastal mainland China experiencing both tidal flat loss and *S. alterniflora* invasion, a national action plan to control *S. alterniflora* that considers these combined pressures is urgently needed. Failing to reduce the current extent of overlap between *S. alterniflora* and important shorebird habitat and/or prevent encroachment into additional sites will likely contribute to further population declines.

CRediT author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary Materials

Additional data tables and figures are provided in the supplementary materials.

Appendix A. Supplementary data

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