Environmental Science & Technology
pubs.acs.org/est
Article

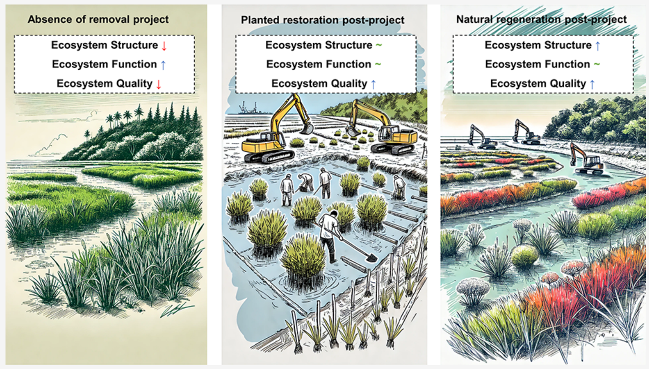
Ecological Effects of the Huge Invasive Species Removal Project in Coastal China

Guanpu Qi, Lanxuan Li, Haiyang Li, Ya Liu, Tiewei Xie, Haiqiang Guo, Zhijun Ma, Jihua Wu, Bo Li, and Jun Ma*

Cite This: https://doi.org/10.1021/acs.est.4c05253
Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Saltmarsh wetlands are recognized as some of the most ecologically valuable yet vulnerable ecosystems globally. However, since the 1970s, saltmarsh wetlands in coastal China have been seriously threatened by the invasive *Spartina alterniflora*. Although the Chinese government has initiated a nationwide *S. alterniflora* removal project, the potential benefits and risks of this project remain unknown. Here, we focus on the Yangtze River Estuary Saltmarsh Wetland (YRESW) and simulate its future ecosystem structure, function, and quality under three scenarios based on remote sensing and field investigation data. The simulation scenarios include the absence of a removal project, natural regeneration postproject (NRP), and planted restoration postproject. The results show that the removal project will reverse the escalating invasion trend of *S. alterniflora* in the YRESW. Compared to the baseline year of 2022, there is a remarkable increase in ecosystem structure (composition: +107%, configuration: +27%) and ecosystem quality (+10.5%) under the NRP scenario. Although blue carbon storage sharply decreases under both scenarios involving project implementation, planted restoration can restore YRESW's carbon sequestration capacity to 0.19 Tg C per year, achieving 87% of the carbon storage present before the project. This study underscores the necessity of comprehensive and detailed risk assessments in ecological projects, particularly when dominant species are involved. Our findings hold significant implications for stabilizing coastal wetland ecosystems and promoting sustainable development in coastal areas.



KEYWORDS: *Ecological project, Coastal saltmarsh, Biological invasion, Ecosystem assessment, Bioremediation*

1. INTRODUCTION

Saltmarsh wetlands in the land-sea transition zone are characterized as saline or brackish mudflats covered with halophytes, periodically influenced by tides, ranking among the most ecosystem-service-rich ecosystems.[1] Saltmarsh wetlands are pivotal in providing biological habitats, fisheries production, carbon sequestration, storm surge defense, and cultural benefits.[2,3] However, globally, estuarine coastal zones featuring saltmarsh wetlands are also characterized by high human population density and developed economies.[4,5] This geographical location not only causes saltmarsh wetlands to endure the impacts of frequent human activities like urban expansion and coastal modifications but also renders them vulnerable to global changes such as biological invasions, climate change, and extreme weather events.[6,7] Therefore, saltmarsh wetlands are also recognized as ecologically fragile areas.

China has an extensive coastline interspersed with numerous coastal wetlands, accounting for 25% of the world's total.[8] However, since the introduction of *Spartina alterniflora* in the 1970s for coastline defense,[9] it has become a threatening, invasive species within China's coastal wetlands owing to its advantages over native species in resource competition and disturbance resistance.[10] As of 2019, *S. alterniflora* was distributed across all coastal provinces in China, covering 61,565 ha and accounting for 48.29% of China's saltmarsh vegetation.[11] The invasion of *S. alterniflora* has significantly impacted the saltmarsh ecosystems in multiple dimensions.[12] On the one hand, the invasion of *S. alterniflora* has reshaped soil functions by modifying soil physicochemical properties and the structure of the microbial community through root exudates, plant litter, and sediment accretion.[13,14] On the other hand, the invasion of *S. alterniflora* has supplanted native saltmarsh species, altered their native community structure, and influenced inherent succession trajectory.[15,16] Further-

Received: May 27, 2024
Revised: September 19, 2024
Accepted: September 20, 2024

Figure 1. Hotspots of saltmarsh distribution in Yangtze River Estuary Saltmarsh Wetland. The Yangtze River Estuary region and the portions covering salt marshes are pale yellow and green, respectively. Chongming Dongtan is labeled in bright red. Sampling points and areas are marked with brown points. The approval number of the administrative vector boundary map of China is [GS(2023)2767], which comes from the National Geomatics Center of China.

more, the invasion has also impacted intertidal animals (e.g., birds, fish, and zoobenthos) by reducing their suitable habitat and food resources.[17−19] Considering the severe threat to the ecological security of coastal China, *S. alterniflora* has been listed as one of the first 16 invasive species by the Ministry of Environmental Protection of China.[9] Effective containment of *S. alterniflora*'s invasion has emerged as a crucial objective for protecting China's saltmarsh ecosystems.[20]

As early as 2006, many research institutions began to study the removal of *S. alterniflora* in the Yangtze River Estuary Saltmarsh Wetland (YRESW) to combat its invasion. Various physical, chemical, and biological methods were proposed to eradicate *S. alterniflora* effectively.[21] In 2023, the Chinese government implemented a nationwide ecological project to eliminate over 90% of *S. alterniflora* in China by 2025. This project aims to fundamentally reconstruct China's coastal saltmarsh ecosystems invaded by exotic species, restoring their functions, and enhancing their quality.[22] This unprecedented ecological intervention is anticipated to significantly impact severely invaded saltmarsh ecosystems in China, and thus necessitates a thorough and timely evaluation of the ecological consequences caused by the project to formulate strategies that ensure ecosystem health and promote regional ecological sustainability. However, few studies have comprehensively assessed the potential impacts of this large-scale ecological project.

Here, we focused on the YRESW (Figure 1), which hosts the largest expanse of salt marshes in China.[11] Utilizing remote sensing data and machine learning-based land cover prediction models, we mapped the dynamics of vegetation succession in the YRESW from 2019 to 2022 and simulated the vegetation succession dynamics under three scenarios (Table 1), the absence of the removal project (ARP), natural regeneration postproject (NRP), and planted restoration postproject (PRP).

Table 1. Simulation Scenarios of Different Coastal Restoration Methods Postproject

Scenarios	Description
Absence of a removal project (ARP)	No anthropogenic intervention on the YRESW since 2022
Natural regeneration postproject (NRP)	No further restoration approach postproject
Planted restoration postproject (PRP)	Planted restoration as the proportion of native species in 2022 postproject

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Based on the vegetation dynamics, we further integrated up-to-date environmental and biological data, primarily using the InVEST model, and assessed the ecosystem structure, function, and quality of the YRESW. We aimed to identify the risks and benefits associated with the removal project, provide feasible guidance for maintaining the health of coastal ecosystems, and offer scientific evidence to support policy formulation for the effective management and sustainable development of saltmarsh ecosystems in coastal China.

2. MATERIALS AND METHODS

2.1. Study Area. Our study area encompassed the entire YRESW, extending across 30.819°−31.919°N and 120.810°−122.190°E (Figure 1). The YRESW has a typical northern subtropical monsoon climate, experiencing an average annual temperature of 17.7 °C and an average annual rainfall of 1389 mm. More than 25% of China's salt marshes are distributed across Chongming Island, Hengsha Island, Changxing Island, Jiuduansha, Nanhui Wetlands, and Qidong Wetlands within the YRESW. The saltmarsh vegetation consists of native species such as *Phragmites australis*, *Bolboschoenoplectus mariqueter*, and *Carex scabrifolia*, as well as the invasive *Spartina alterniflora Loisel.*[23] The intertidal zones of the YRESW harbor a rich diversity of animal species, including 133 zoobenthos and 63 fish species, constituting a vital biological resource repository. The Chongming Dongtan National Nature Reserve in the YRESW has recorded 290 bird species, including numerous endangered species.[24]

2.2. Saltmarsh Vegetation Classification. The YRESW before 2018 was influenced by historical modifications and regional ecological projects (Figure S2). Therefore, to explore the natural succession patterns of the YRESW, we selected annual remote sensing data after the completion of these projects and conducted vegetation classification mapping. The remote sensing data used in this study, spanning from January 1, 2019, to December 31, 2022, included all the Landsat-8 Collection 2 Level-2 OLI surface reflectance data and Sentinel-2 Level-2A MSI surface reflectance data covering the study area.[25,26] These remote sensing data underwent atmospheric correction, radiometric calibration, and terrain correction to improve accuracy.

To ensure consistency in reflectance values across different satellite sensors, we first aligned Landsat-8 data to match Sentinel-2 data using linear correction.[27] We removed low-quality pixels using quality assessment bands and the s2cloudless algorithm.[28] We calculated various vegetation indices representing plant spectral characteristics, ultimately selecting the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Normalized Difference Water Index (NDWI), and the Modified Red Edge Chlorophyll Index (MRECl) for classification. Finally, we obtained a long-term series of vegetation index data sets from 2019 to 2022, with a 15-day cycle, using bimonthly composites and Savitzky−Golay (S-G) filtering functions.

We collected geographic locations of various saltmarsh land covers using a DJI Drone Phantom-4 RTK and conducted field surveys annually in October from 2019 to 2022 at multiple sample sites across the YRESW (Figure 1). By matching the vegetation index time series in remote sensing image pixels with these ground samples, we successfully captured the phenological traits of different saltmarsh land cover in the YRESW. Using the Google Earth Engine (GEE) cloud platform,[29] we developed a semiautomated, decision-tree supervised algorithm for saltmarsh classification based on a threshold judgment approach. The China coastal intertidal zone vector delineation demarcated the intertidal extent within the YRESW.[30] Validation results demonstrated that the model's classification accuracy was ideal (Table S1), rendering it suitable for further analysis. More details about classification samples, data preprocessing, and the classification algorithm can be found in the Supporting Information.

2.3. Prediction of Saltmarsh Vegetation Dynamics. To obtain the vegetation structural characteristics of the YRESW, we simulated the succession dynamics of its vegetation community from 2023 to 2032. The simulation encompassed two aspects: the dynamics of saltmarsh vegetation's community composition and spatial configuration.

Regarding saltmarsh community composition, we used the Markov model to simulate its dynamics from 2023 to 2032 based on the succession pattern from 2019 to 2022.[31] The Markov model assumes that the land cover change is characterized by the principle that the subsequent state S_{t+1} depends only on its current state S_t, rather than the entire historical process preceding the current state. This assumption aligns closely with the characteristic of rapid succession in saltmarsh vegetation.

$$S_{t+1} = P \times S_t$$

where S_t and S_{t+1} are the saltmarsh land cover vector matrices, representing the ecosystem's composition at times t and t+1; P is the transition probability matrix for each land cover.

For spatial configuration, we predominantly utilized the Cellular Automata model for patch-scale land cover change simulation (PLUS) to forecast the spatial distribution of each saltmarsh land cover.[32] PLUS consists of two main modules: the LEAFS module and the CARS module. Based on the random forest model, the LEAFS module uses environmental data to analyze potential expansion zones for each saltmarsh land cover. By integrating the community dynamics from the Markov model with the potential expansion areas determined by the LEAFS module, the CARS module accurately predicts the spatial distribution of each saltmarsh land cover using roulette selection rules driven by self-adaptive coefficients and neighborhood weights.

For validation, we compared the saltmarsh classification result with the actual distribution of saltmarsh land cover, showing a mean overall accuracy of 0.847 and a mean Kappa value of 0.749, indicative of highly reliable predictions.

Since PLUS is based on a scenario-driven model mechanism characterized by "top-down" and "bottom-up" features, we can simulate potential changes in the YRESW under various scenarios. By manipulating the neighborhood weights and each species' expansion area in the CARS module, we established three scenarios in this study: absence of a removal project (ARP), natural regeneration postproject (NRP), and planted restoration postproject (PRP) (Table 1). Details about the PLUS model and setting scenarios can be found in the Supporting Information.

2.4. Assessment of Ecological Effects. Ecosystem structure, function, and quality are three essential aspects in assessing the consequences of ecological projects. These aspects reflect the ecosystem's resilience to disturbances and its ability to provide valuable services to humankind. Therefore, evaluating these aspects is essential for predicting the project's effectiveness and formulating specific removal strategies.

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

2.4.1. Ecosystem Structure Assessment. We evaluated the ecosystem structure of the YRESW under various scenarios, emphasizing vegetation spatial configuration and community composition. Landscape metrics, including Edge Density (ED), Mean Patch Area (MPA), and Patch Density (PD), collectively form the Modified Fragmentation Index (MFI)[33] to assess the integrity of the saltmarsh ecosystem in the YRESW. The CONNECT index evaluates the spatial structural connectivity of the ecosystem. Shannon's Diversity Index (SHDI) and Modified Simpson's Diversity Index (MSDI) ascertain the species diversity of the YRESW, while Shannon's Evenness Index (SHE) and Modified Simpson's Evenness Index (MSEI) detect species evenness. We compared all metrics to those of 2022, creating dimensionless and comparable parameters ranging between 0 and 1. Higher values of these metrics indicate a healthier ecosystem structure. The definitions and calculations of these metrics are detailed in the Supporting Information.

2.4.2. Ecosystem Function Assessment. Carbon sequestration is one of the most essential ecosystem functions of salt marshes, making them known as "blue carbon" ecosystems. This function is indispensable for achieving China's "carbon peak and neutrality" goals and is considered by the IPCC in its "Special Report on the Ocean and Cryosphere in a Changing Climate" as a primary pathway for marine natural ecosystems to mitigate climate change.[34] Considering the significant disturbance to soil carbon stocks of the YRESW during the removal project, we primarily focused on carbon sequestration as a representative ecosystem function.

We utilized the InVEST Coastal Blue Carbon model to simulate carbon storage dynamics in the YRESW.[35] This model conceptualizes coastal wetland carbon storage into three components: carbon in aboveground biomass, litter, and soil. It uses a bookkeeping-type approach to simulate the carbon cycling process for efficiency. The model depends on three key parameters: the initial carbon storage of different saltmarsh land covers both above and below ground, the annual carbon sequestration capacity of various land covers, and the proportion of carbon storage lost due to land cover changes.

Initial carbon storage data were collected in hotspots of salt marshes within the YRESW during October and November from 2021 to 2022, including Chongming Dongtan, Hengsha Island, and Nanhui Wetlands (Figure 1). We established a transect perpendicular to the seawall at each sampling site. Along these transects, several 1 m^2 plots ($n = 101$) were set at intervals of 100 m from the seawall, where the saltmarsh land cover was recorded, and samples were collected from both the aboveground parts and the soil (0−50 cm depth). The aboveground parts and soil samples were dried at 75 °C to a constant weight to measure biomass and bulk density. The soil organic carbon in acidified samples was determined using a Flash Smart Elemental Analyzer. The annual carbon sequestration rate, carbon emission rate, and soil organic matter half-life for different saltmarsh land covers were sourced from previous research and long-term monitoring data from the Chongming Dongtan field station.[36] Employing these key carbon cycling parameters (Table S4) and the spatial dynamics of saltmarsh land covers under different scenarios, we applied the InVEST Coastal Blue Carbon model to evaluate carbon storage in the YRESW. By subtracting the carbon storage in 2022 from that in 2032, we calculated the carbon sequestration potential of the YRESW under various scenarios.

2.4.3. Ecosystem Quality Assessment. We employed the InVEST Habitat Quality model to assess the ecosystem quality of the YRESW.[35] This assessment integrated the supportive capacities of various land covers for organisms and the associated threats from human activities. In this study, these two terms refer to the biocapacity for intertidal animals of each saltmarsh land cover and the relative impact of coastal human infrastructure on each land cover, respectively.

Different indicators (e.g., abundance, richness, and frequency of occurrence) of intertidal animals, such as birds, fish, and zoobenthos, within each saltmarsh land cover, were used to represent relative biocapacity. We conducted annual field investigations in October from 2015 to 2022 in the YRESW. Ten long-term transects were established along nine principal tidal channels in Chongming Dongtan, covering the northern, eastern, and southern regions (Figure 1, Figure S4). At each transect, sample points included different saltmarsh land covers, and the corresponding biological samples were collected. In a single sampling event, for fish, nets were set at the central bottom of the principal tidal channels, and catches were collected after each complete ebb tide, preserved in formalin, and then enumerated and weighed. For zoobenthos, two soil cores, one meter apart and 10 cm deep, were extracted using a 15 cm diameter PVC pipe and combined along each transect. Zoobenthos were then sieved through a 0.5 mm mesh, identified at the species level, and quantified. For birds, leveraging previous research on bird observations in the YRESW and long-term monitoring data from the Chongming Dongtan Bird National Nature Reserve, the frequency of bird occurrence in different saltmarsh land covers was compiled.[37−40] Following the normalization and aggregation of these indicators, the dimensionless biocapacity ranging from 0 to 1 for each saltmarsh land cover was determined (Figure S5). More details about the indicators are provided in the Supporting Information.

Regarding threats from human activity to biocapacity, we initially calculated the Euclidean distance of all coastal human infrastructure to each saltmarsh pixel as human impact factors (Table S2). We used a random forest model to regress the expansion of different saltmarsh land covers from 2019 to 2022 with these human impact factors and other environmental data. The contribution of each human impact factor from the model was considered the relative threat to salt marshes, excluding the influence of environmental factors (Table S6). The proportion of the total contribution of human impact factors to the regression was quantified as the vulnerability of salt marshes to human activities. These indices are dimensionless, ranging from 0 to 1.

Finally, integrating these key parameters, we parametrized the InVEST Habitat Quality model to evaluate YRESW's ecosystem quality under various scenarios. This approach facilitated identifying specific changes in habitat quality before and after the project under multiple scenarios.

2.5. Software Used and Statistical Analysis. Indices assessing ecosystem structure were calculated using Fragstats 4.2 software.[41] The Mann−Whitney test was utilized separately in each scenario due to the non-normality of the results to determine the statistical differences in carbon storage and sequestration potential across various scenarios. Differences in biocapacity across various vegetation species were assessed by ANOVA with Scheffe's posthoc analysis after normality and homogeneity of variance tests. All statistical tests were two-

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

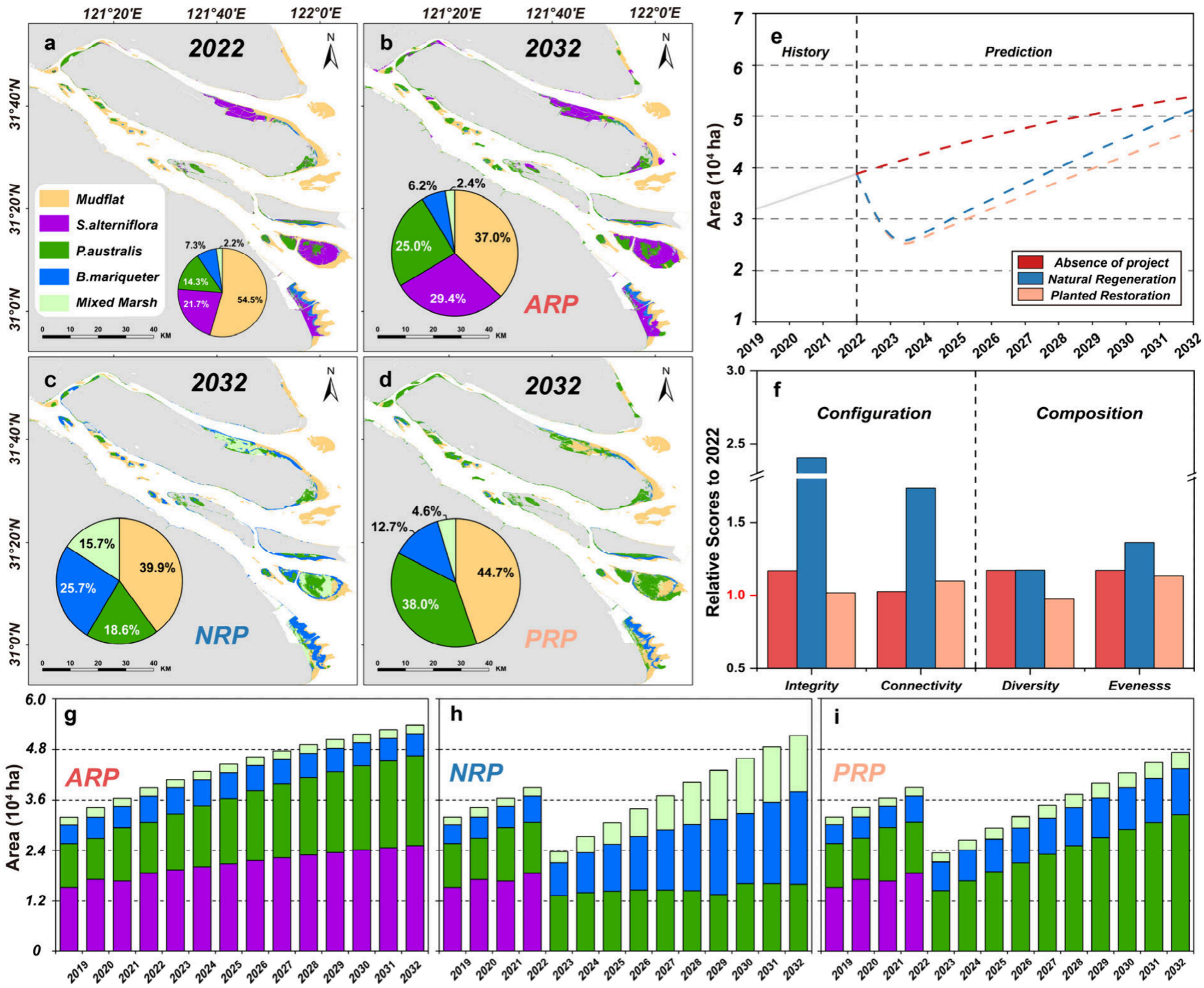


Figure 2. Community composition and spatial distribution of salt marshes under different scenarios in the Yangtze River Estuary Saltmarsh Wetland. (a–d) The specific spatial distribution and community composition. (e) Saltmarsh wetland area dynamics in different scenarios. (f) Multiple quantifying indicators of community composition and spatial configuration. These indices are divided using the value for the year 2022 as the baseline. A higher index indicates better performance. (g–i) Saltmarsh vegetation community structure and quantity dynamics under different scenarios.

tailed, and a P-value of less than 0.05 was considered statistically significant.

The software used for modeling was R Version 4.3.1. The packages included randomForest for random forest analysis, contribution statistics, and bruceR for variance analysis and significance testing.[42] The software used for graphics included Origin Pro 2023 (Version 9.0.0.87), ArcMap Desktop Version 10.8 (Esri), Adobe Photoshop (Version 25.0, 2023), and Adobe Illustrator (Version 27.9, 2023).

3. RESULTS

3.1. Ecosystem Structure under Different Scenarios.

The YRESW comprised 38,851 ha of saltmarsh vegetation and 46,528 ha of mudflats in 2022. From 2019 to 2022, the total area of vegetation expanded by 6,911 ha (121.6% of the 2019 total), primarily due to the expansion of *S. alterniflora* (49.7%) (Figure 2e). Under the ARP scenario, this expansion will continue, with the total vegetation area expected to reach 53,812 ha by 2032, the highest among all scenarios. However, the area of *S. alterniflora* is projected to increase by 6,583.38 ha, while the area of native species *B. mariqueter* is expected to decrease by 919.89 ha, reducing from 16% to 9.8% of the total vegetation area (Figure 2g). Despite these changes, an increase in diversity and evenness of the community composition by 17% is expected.

Following the removal project, by 2023, the total vegetation area is estimated to decrease by 23,685 ha (61% of the 2022 total). By planted restoration (Figure 2i), the vegetation area is estimated to recover to 47,229 ha by 2032, with *P. australis* becoming the dominant species. The area of *B. mariqueter* and mixed marsh is anticipated to grow by 4,640 ha (174.7% of the 2022 total) and 2,020 ha (205.7% of the 2022 total), respectively.

In the NRP scenario (Figure 2h), by 2032, it is envisaged that the total area of vegetation will exceed the 2022 level, reaching 51,277 ha (132.0% of the 2022 total). *B. mariqueter* is anticipated to become the dominant species for the first time, expanding to 3.54 times its 2022 area. Additionally, the mixed

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

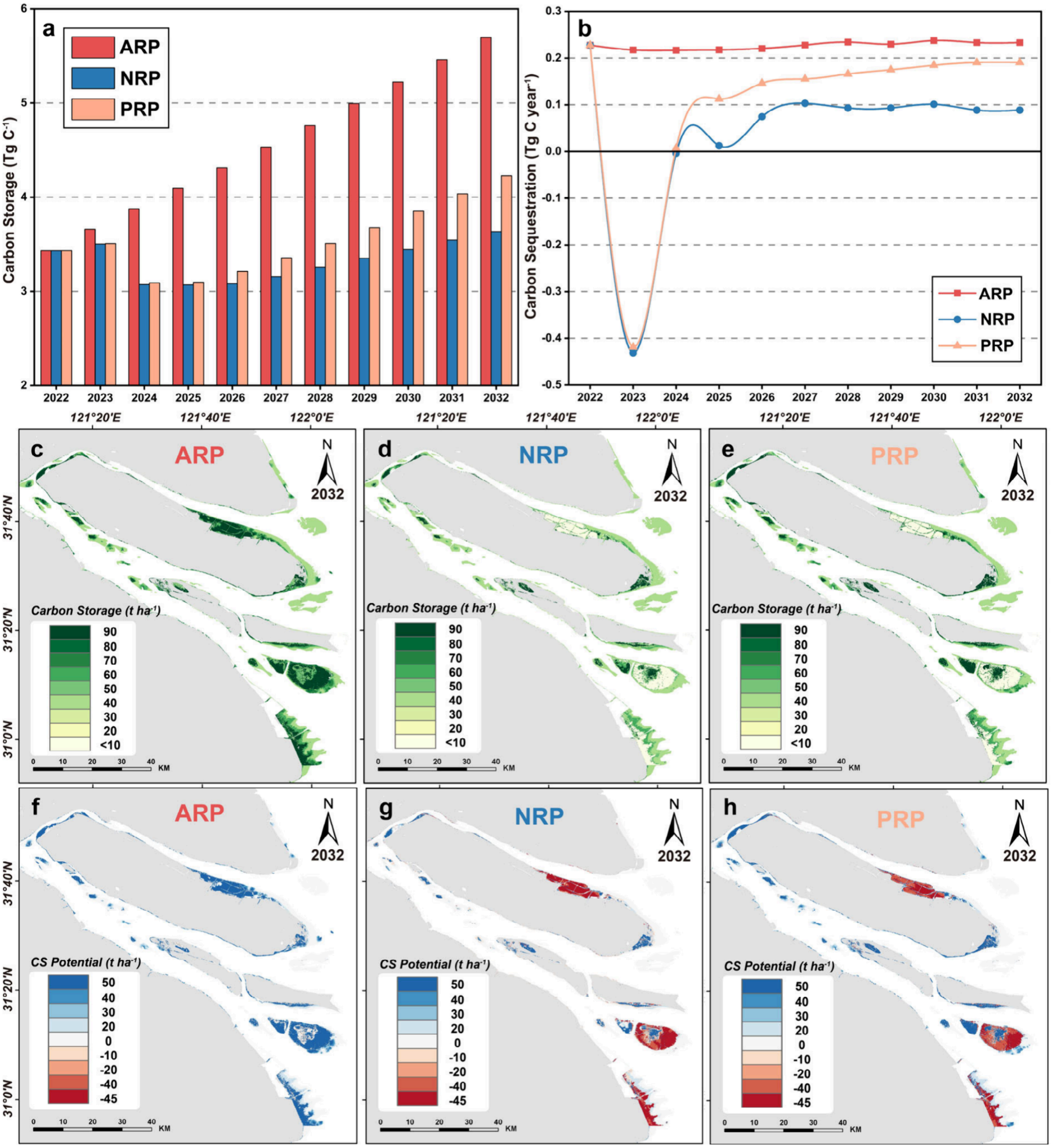


Figure 3. Spatiotemporal dynamics of carbon sequestration function in the Yangtze River Estuary Saltmarsh Wetland. (a–b) The dynamic of carbon storage and sequestration rate in different scenarios. (c–h) Spatial distribution of carbon storage and carbon sequestration potential.

marsh area is projected to expand to 13,407 ha, about seven times its 2022 area. The NRP scenario is expected to yield the most remarkable improvement in species diversity (17%) and evenness (36%) across all scenarios (Figure 2f).

Regarding the spatial configuration of vegetation in the YRESW, from 2019 to 2022, vegetation expansion primarily occurred in regions heavily invaded by *S. alterniflora*, such as the Nanhui wetlands and Jiuduansha Island. As of 2022, only Chongming Dongtan and Hengsha Island had not been extensively invaded (Figure 2a). In the ARP scenario, *B. mariqueter*'s presence in Chongming North Lake is forecasted to vanish (Figure 2b), yet the spatial configuration of the YRESW will not worsen (Integrity: + 17%, Connectivity: + 3%) by 2032.

Under the PRP scenario, *P. australis* is anticipated to emerge as the dominant species distributed throughout the YRESW (Figure 2d). By 2032, the coverage of saltmarsh vegetation in Chongming North Lake, Nanhui Wetlands, and Jiuduansha is

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

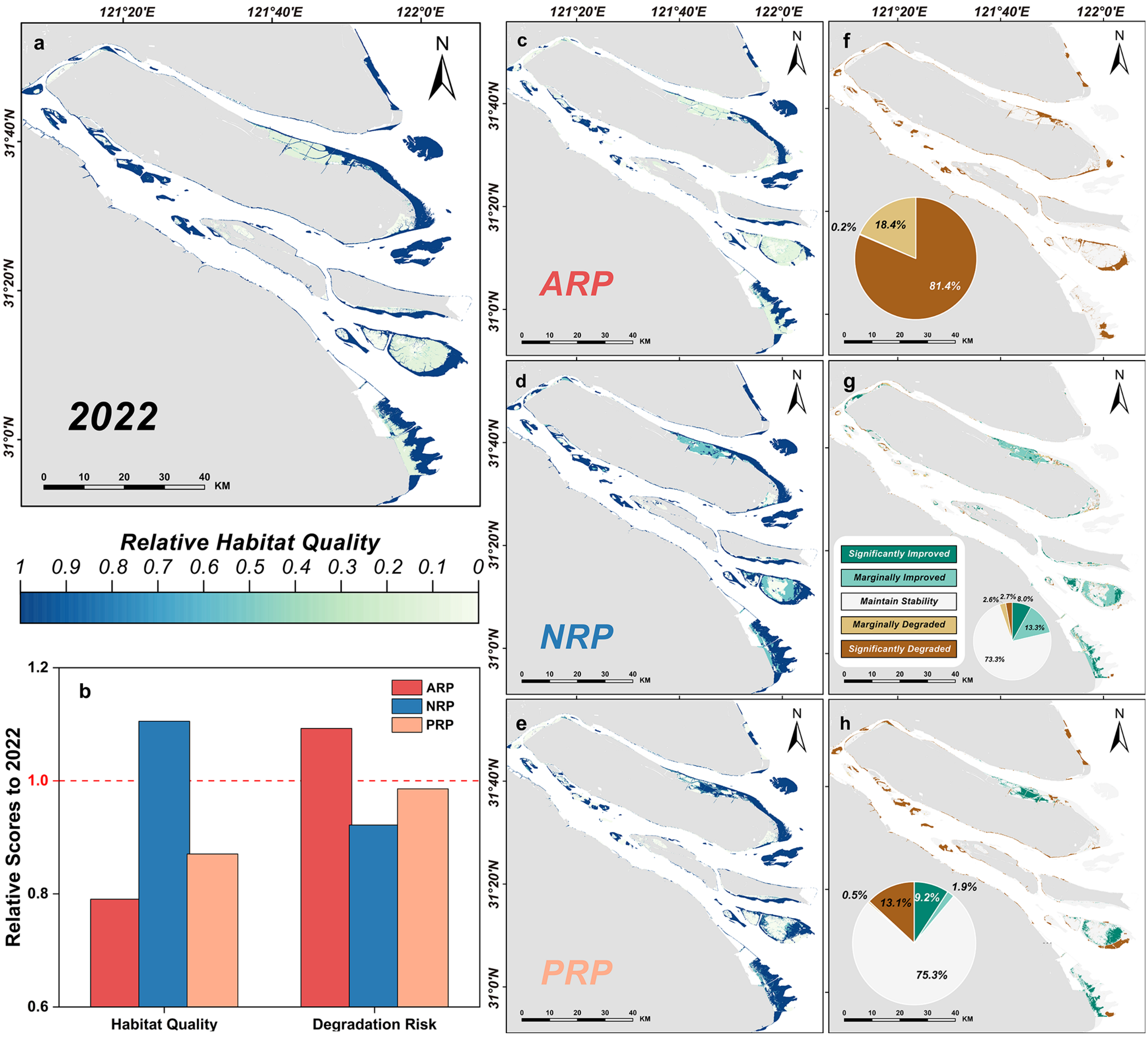


Figure 4. Habitat quality and degradation risk of Yangtze River Estuary Saltmarsh Wetland under different scenarios. (a) Spatial distribution of habitat quality in 2022. (b) The relative value of habitat quality and degradation risk compared to 2022 in different scenarios. The red dashed line represents whether the value is greater than that of 2022. These indices were divided using the 2022's value as the baseline. The higher habitat quality and lower degradation risk mean better performance. The a,b and c above the bars indicate significant difference among different groups. (c−e) The spatial distribution of habitat quality in 2032 under different scenarios. (f−h) The restoration effect of habitat quality relative to 2022 in various scenarios, with a decrease higher than 60% indicating significant degradation, a decrease of 60% to 20% indicating marginal degradation, a decrease of 20% to an increase of 20% indicating maintained stability, an increase of 20% to 60% indicating marginal improvement, and increase higher than 60% indicating significant improvement.

estimated to be lower than in 2022, with improvement mainly in Connectivity (+10%).

In the NRP scenario, *B. mariqueter* will re-emerge throughout Chongming and Hengsha Island, becoming the dominant species in Nanhui Wetlands (Figure 2c). Furthermore, it exhibits the most substantial improvement in spatial configuration among the three scenarios (Integrity: +141%, Connectivity: +73%).

3.2. Ecosystem Function under Different Scenarios. In 2022, the YRESW exhibited a total carbon storage of 3.43 Tg (Figures 3a and 3b). Under the ARP scenario, it is projected that by 2032, the total carbon sequestration will rise from 0.21 Tg C year^{-1} to 0.25 Tg C year^{-1}, and the total carbon storage is estimated to increase by 64.5%, reaching 5.65 Tg C, thereby producing a carbon sequestration potential of 2.26 Tg C. In 2023, the YRESW's carbon sequestration is anticipated to decrease to −0.42 Tg C year^{-1}, returning to being a carbon sink region by 2025.

Under the PRP scenario, the YRESW's total carbon sequestration will recover to 0.19 Tg C year^{-1} by 2032, approaching preproject levels (87.6% of 2022). The total carbon storage is anticipated to increase to 4.226 Tg C (23.1%), yielding a carbon sequestration potential of 0.794 Tg C, which is significantly lower than that in the ARP scenario (*P*

< 0.001). However, under the NRP scenario, it is projected that by 2032, the carbon sequestration of the YRESW will be only 0.089 Tg C year^{-1} (42.7% of 2022), with carbon storage estimated at 3.462 Tg C. This results in the lowest carbon sequestration potential among all scenarios, at merely 0.201 Tg C ($P < 0.001$).

Regarding spatial distribution patterns (Figures 3c–h), differences in carbon storage and sequestration potential of the YRESW by 2032 are significant among scenarios. Under the ARP scenario, areas with high carbon storage (>80 t C ha^{-1}) and carbon sequestration potential (>40 t C ha^{-1}) will be predominantly located in the center of Chongming North Lake, the offshore side of Jiuduansha, and the landward regions of the Nanhui wetlands, with almost the entire YRESW region serving as an effective carbon sink (96.9%).

After the project, the spatial distribution patterns of carbon storage and sequestration potential in the YRESW under both restoration scenarios will exhibit similarities. High carbon storage (>80 t C ha^{-1}) and sequestration potential (>40 t C ha^{-1}) areas will be the converse of the ARP scenario, situated in the center of Jiuduansha and the landward regions of Chongming Dongtan. In comparison, other areas will predominantly feature low carbon storage (0–10 t C ha^{-1}) and low sequestration potential (<-40 t C ha^{-1}). Most areas of the YRESW will continue to function as carbon sinks (PRP: 78.3%, NRP: 73.6%).

Additionally, in all scenarios, the east and west sides of Chongming Island will consistently maintain high carbon storage (>80 t C ha^{-1}) and robust carbon sequestration potential (>40 t C ha^{-1}), remaining nearly undisturbed by the project.

3.3. Ecosystem Quality under Different Scenarios.

Under the ARP scenario, a significant decline in habitat quality of the YRESW compared to 2022 is expected, amounting to 21%, with an increase in degradation risk of 9.3% (Figure 4b). It is projected that 164.5 ha (0.2%) will undergo marginal degradation, while 15,281.8 ha (18.4%) will experience significant degradation in habitat quality (Figure 4f).

Under the PRP scenario, a decrease in the YRESW's habitat quality compared to 2022 is anticipated, amounting to 13%, with a 1.4% reduction in degradation risk. Significant degradation of habitat quality is expected in 10,866.7 ha (13.08%) of the YRESW, while 7,647.75 ha (9.21%) will experience a significant improvement in habitat quality (Figure 4h).

Under the NRP scenario, an improvement in habitat quality is estimated at 10.5%, with a 7.8% decrease in degradation risk. An area of 6,644.43 ha (8%) will exhibit a significant improvement in habitat quality. In contrast, the YRESW will display a decline in habitat quality, amounting to only 4,422.69 ha (5.32%). Additionally, 11,090.07 ha (13.35%) of the YRESW will show a marginal improvement in habitat quality (Figure 4g).

Regarding spatial distribution in 2022, regions with high habitat quality (HQ > 0.8) in the YRESW, primarily mudflats, were located on the eastern and northern sides of Chongming Island, Jiuduansha, and the Nanhui wetlands. The landward side of these regions was widely covered by *S. alterniflora* and *P. australis* and had low habitat quality (HQ < 0.2, Figure 4a).

Under the ARP scenario, saltmarsh hotspots of high habitat quality will experience a reduction in area, with declines in habitat quality primarily occurring on the southeastern sides of Jiuduansha and the northeastern landward side of Chongming North Lake (Figures 4c and 4f).

Under the PRP scenario, improvements in habitat quality will be observed in the landward areas of Nanhui wetlands, the eastern and northern sides of Chongming Island, and the center of Jiuduansha. However, substantial reductions in habitat quality will be observed on the northwestern side of Chongming Island and the landward regions of Jiuduansha (Figures 4e and 4h).

In the NRP scenario, while stability will be maintained in the spatial distribution of habitat quality in the majority, low-quality areas in Chongming North Lake and the center of Jiuduansha will experience improvements in habitat quality. By 2032, areas of low habitat quality in the YRESW are expected to be confined to the center of Jiuduanshaand landward areas in Chongming Dongtan (Figures 4d and 4g).

4. DISCUSSION

4.1. Benefits from the *S. alterniflora* Removal Project.

We predicted that the *S. alterniflora* removal project would have an overall positive impact on the YRESW. The NRP scenario demonstrated the most optimal status for the ecosystem structure of the YRESW, featuring the highest vegetation recovery rate, significant biodiversity improvement, and robust spatial configuration (Figure 2). Native saltmarsh species are projected to rapidly colonize the mudflats exposed after the project, even without plant restoration. This phenomenon is attributed to the YRESW's comprehensive native species composition in most saltmarsh vegetation hotspots, indicating this ecosystem's strong recovery potential. The rapid recovery suggests that the YRESW remains in a stage of rapid succession and exhibits decent resilience. The removal of *S. alterniflora* alleviates competitive pressure on native salt marshes, facilitating their expansion by utilizing abundant environmental resources.[43] This ideal recovery has also been observed in the YRESW following local pioneer removal projects.[44]

However, inappropriate planted restoration could prevent the YRESW from reaching the ecological structure restoration level observed in the NRP (Figure 2). Due to the NRP, native saltmarsh vegetation species can reclaim their original ecological niches previously invaded by *S. alterniflora* via natural selection and interspecies competition, circumventing the "mismatch" phenomenon commonly observed in ecological projects. Similarly, this phenomenon has been corroborated in the restoration of degraded forests.[45]

The key ecosystem function of carbon sequestration in the YRESW is also projected to recover rapidly after the project (Figure 3). Despite the weaker carbon sequestration ability of native saltmarsh species compared to *S. alterniflora*,[46] the rapid recovery of native salt marshes (Figure 2e) is expected to mitigate the loss in carbon sequestration capacity. The PRP, primarily through planting *P. australis*, is expected to enhance carbon sequestration capacity significantly. Consequently, by 2032, the carbon storage in the YRESW is projected to surpass the 2022 level.

Following the removal project, substantial recovery in the YRESW's ecosystem quality is expected, notably under the NRP scenario. This recovery can be attributed to the strength of naturally recovered plant communities in terms of community composition and spatial configuration, offering better habitats and resources for intertidal animals. The interspecies interactions among them will ensure the stability

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

of the YRESW, thereby enhancing the sustainability of its carbon sequestration capacity.[47]

Additionally, the predictions of this study align with outcomes observed after similar *S. alterniflora* removal projects worldwide. Projects conducted in the Siuslaw Bay Estuary and San Francisco Bay, USA, have effectively protected shorebird habitats.[48,49] Projects in Willapa Bay, USA, and Northern Ireland estuaries have facilitated the post-control succession of affected tidelands to native saltmarsh species.[50,51] These cases and our results collectively indicate the potential benefits of restoring the valuable coastal ecosystem through the removal project.

4.2. Ecological Risks under the *S. alterniflora* Removal Project. Despite recognizing the adverse impacts of *S. alterniflora* on saltmarsh ecosystems in China, removing this dominant species from these fragile ecosystems still poses significant ecological risks. In the YRESW, *S. alterniflora* exhibits a prolonged colonization period, significant biomass, and extensive distribution.[52] Studies have revealed its substantial biocapacity and disturbance resistance (Table S6, Figure 5[18,53,54]), highlighting its crucial role in the local ecosystem's energy flow and material cycling.[55] According to the mass ratio hypothesis,[56] the abrupt removal of a long-established dominant species could lead to species loss, potentially impacting multiple ecosystem functions and causing instability throughout the entire ecosystem. The loss of such an optimally adapted species could intensify the risk of ecosystem collapse,[57,58] particularly under global changes such as rising sea levels and more frequent extreme weather events.[4,59] This risk is also noted in the "*Technical guideline for ecological restoration in smooth cordgrass removal and management area*" issued by the Chinese government and observed in some areas where removal projects have been implemented (Figure S6).

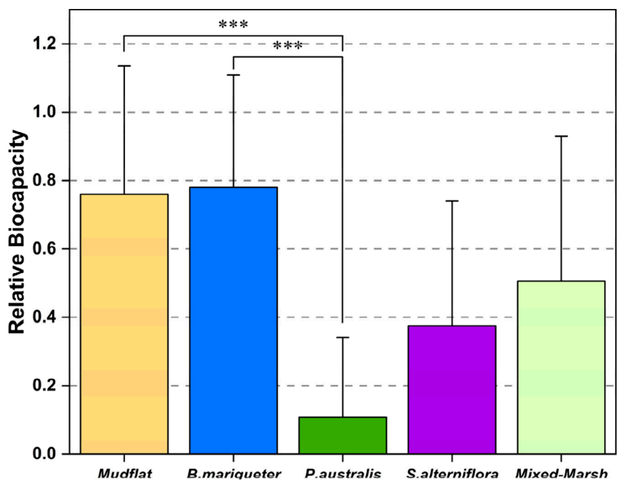


Figure 5. Biocapacity of different saltmarsh land covers. Avian data were derived from bird observation data at the Chongming Dongtan National Nature Reserve and previous research, while fish and benthic organisms originate from the sampling conducted in this study.[38−40] Regarding different saltmarsh land covers, we assessed overall observation frequency for birds, and for fish and benthic organisms, we calculated their abundance and diversity. Data for different organisms were initially subjected to individual standard normalization procedures in separate observations, followed by the overall sum and standard deviation computation in the final analysis. Significance levels of 1%, 5%, and 10% were denoted by ***, **, and *, respectively.

Also, the recovery of native plants postproject may encounter unforeseen challenges. Our simulation presupposes ideal conditions where soil physicochemical properties will not deteriorate (except for carbon storage), and *S. alterniflora* will not reinvade, with a 100% survival rate of planted native salt marshes. However, due to limitations in balancing efficiency and costs, chemical removal techniques known to aggravate soil physicochemical properties have been widely employed to prevent the extensive reinvasion of *S. alterniflora*.[21] Additionally, most saltmarsh ecosystems in coastal China lack the recovery potential seen in the YRESW for the loss of native species caused by the severe invasion of *S. alterniflora* and coastal modification projects.[11] The loss of *S. alterniflora* will also diminish the storm surge defense and sediment accretion ability of coastal ecosystems,[5] thus heightening the risks for the survival of the planted native salt marshes in the following restoration (Figure S7).

Lastly, the pivotal ecosystem function of carbon sequestration, influenced by these factors, faces an amplified risk of degradation. *S. alterniflora*'s formidable carbon sequestration and sediment interception capabilities contribute significantly to carbon sequestration benefits.[14] Our study estimated that the direct potential loss in YRESW's carbon sequestration due to the removal of *S. alterniflora* ranges from 1.466 to 2.059 Tg (Figure 3a). Furthermore, *S. alterniflora*'s robust sediment capability expands suitable areas for vegetation in the YRESW, indirectly enhancing carbon sequestration.[60] Its storm surge defense also maintains the long-term stability of YRESW's carbon sequestration. Considering these aspects collectively sustaining YRESW's carbon sequestration capacity, the potential loss stemming from the removal project might surpass our prediction.

4.3. Future Fates of Salt Marshes in the YRESW. In the absence of the removal project, following the succession trends of the YRESW since 2019, the area of vegetation is projected to continue increasing, albeit at a reduced rate. The primary reason for this deceleration is the reduction of human activity impact, facilitating the transition of the saltmarsh wetlands from rapid expansion to a natural succession rate. Over the past decade, Shanghai has embarked on several coastal development projects,[61] specifically the Lingang New City reclamation project (Figure S2). The reclamation in the Nanhui Wetlands has significantly accelerated the sedimentation of mudflats on the offshore side of the newly constructed seawall. These emerging mudflats are conducive to the rapid growth of saltmarsh vegetation, resulting in an anomalous rate of vegetation expansion from 2019 to 2022 (Figure 2a). These areas, created by anthropogenic activities with potential for vegetation expansion, are anticipated to be gradually colonized by saltmarsh vegetation.

With China adopting stricter policies limiting coastal reclamation after 2018, coastal ecosystems tend toward increased stability. The rate of vegetation expansion also gradually normalizes. Notably, this kind of recuperation process is prone to be misconstrued as a manifestation of ecosystem degradation in direct observations. Overall, our findings suggest that large-scale coastal projects not only influence the vegetation community and spatial configuration of saltmarsh ecosystems directly but also indirectly cause prolonged impacts on the rates and direction of ecosystem succession by unintentionally fostering suitable habitats and supplying extra resources. Such anomalies introduce height-

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

ened uncertainty into current assessments of saltmarsh ecosystems.

Our findings also indicated that the invasion of *S. alterniflora* in the YRESW will likely escalate. Apart from the previously invaded regions, areas like Chongming Dongtan, which have undergone *S. alterniflora* removal efforts,[53] still face reinvasion risk. Though the scant presence of *S. alterniflora* was noted in 2022 in these areas, it might evolve into a severe wave of reinvasion by 2032. This reinvasion risk is due to the removal methods mainly employing physical means, making it challenging to remove *S. alterniflora*'s seeds and roots in the soil,[62] which are used for reproduction. At the same time, *S. alterniflora* between different areas can migrate through tidal channels and rivers.[63] These two factors could collectively result in the reinvasion of *S. alterniflora*.[64] In our prediction, the reinvasion (i.e., ARP) will cause a continuous decline in habitat quality to the YRESW and a substantial rise in degradation risk (Figure 4b). Contributing factors include that *S. alterniflora* cannot provide enough resources for native intertidal organisms (Figure 5) and its proliferation displacing *B. mariqueter*, a species offering critical resources like food and habitat.[15,17,18] Previous studies found that *S. alterniflora* not only directly supersedes *B. mariqueter* during expansion but also modifies soil conditions,[13] thereby accelerating the expansion of native *P. australis*, which provides relatively limited resources. In this case, a collective "strangulation" of *B. mariqueter* is expected to occur on the northeastern sides of Chongming Island, similarly observed in other saltmarsh wetlands before.[16]

In the ARP scenario, the invasion of *S. alterniflora* is projected to relocate the primary distribution of the *B. mariqueter* community from the minimally human-impacted Chongming Island to the substantially human-influenced areas of the Nanhui wetlands (Figure 2b). The heightened vulnerability of *B. mariqueter* to anthropogenic disturbances (Table S6) will significantly increase the degradation risk across the YRESW (Figure S5).

4.4. Limitations and Uncertainty. Although our study provides a predictable blueprint for the benefits of *S. alterniflora* removal projects, it is also necessary to acknowledge its limitations. From the implementation of projects in other provinces, the removal process is generally promoted in steps across different regions and is often accompanied by reinvasion.[64] Our study maximized the project's effectiveness and speed, assuming that no reinvasion would occur. For postproject restoration methods, most local governments only replant a single saltmarsh species. The selected species and spatial replanting order have not yet been well planned. However, the simulation in this study is based on the best planting area of plants for proportional restoration, and the predicted results represent the most ideal outcomes.

Moreover, our study did not take multiple global change scenarios into account. Studies have found that climate change, such as the fertilization effect and photosynthesis compensation brought about by rising carbon dioxide concentration and warming environments, will enhance the production capacity of saltmarsh vegetation.[65−67] Simultaneously, rising sea levels and frequent extreme weather will also increase the risks of severe storms to coastal ecosystems.[68] This complex interaction calls for further study to determine the ultimate potential impact. Therefore, this study represents a unified and ideal result, reflecting the different impacts the removal project may bring when supplemented by various restoration methods, thereby providing guidance and warnings for regional governments to carry out this project effectively.

5. ENVIRONMENTAL IMPLICATIONS

Our study highlights the multifaceted response of fragile ecosystems to large-scale human disturbances, providing a deeper understanding of the rapid succession characteristics of saltmarsh ecosystems. While our research affirms the necessity of undertaking removal projects to protect invaded coastal ecosystems in China, it also unveils the conflict between enhancing the ecosystem's carbon sequestration capacity and optimizing its structure and quality. For the implementation of the project, we have the following suggestions. During the removal process, different restoration methods should be used based on local governments' capabilities and the geographical environment's characteristics. Physical methods should be employed where possible while minimizing soil disturbance in terms of spatial extent and relative severity. After removal, when the local saltmarsh ecosystem maintains good resilience, appropriate amounts of native plants can be replanted in the most suitable areas to accelerate the restoration of the saltmarsh ecosystem's structure and function based on succession prediction results.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.4c05253.

Additional details about saltmarsh classification, sample description, modeling details, and discussion support (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Jun Ma − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China;* orcid.org/0000-0003-3412-7766; Email: ma_jun@fudan.edu.cn

Authors

Guanpu Qi − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China*

Lanxuan Li − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China*

Haiyang Li − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China*

Ya Liu − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China*

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Tiewei Xie − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China*

Haiqiang Guo − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China*

Zhijun Ma − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China*

Jihua Wu − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China; State Key Laboratory of Herbage lmprovement and Grassland Agro-Ecosystems, College of Ecology, Lanzhou University, Lanzhou 730000, China*

Bo Li − *Ministry of Education Key Laboratory for Biodiversity Science and Ecological Engineering, National Observations and Research Station for Wetland Ecosystems of the Yangtze Estuary, School of Life Sciences, Fudan University, Shanghai 200438, China; Ministry of Education Key Laboratory for Transboundary Ecosecurity of Southwest China, Yunnan Key Laboratory of Plant Reproductive Adaptation, Evolutionary Ecology and Centre for Invasion Biology, Institute of Biodiversity, School of Ecology and Environmental Science, Yunnan University, Kunming 650504, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.4c05253

Author Contributions

Conceptualization: J.M. Methodology: J.M. Data collection: G.P.Q., H.Y.L., Y.L., T.W.X., L.X.L., H.Q.G., Z.J.M., J.H.W., B.L. Art design: T.W.X. Visualization: G.P.Q., L.X.L. Writing—original draft: G.P.Q. Writing—review and editing: G.P.Q., J.M.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was supported by the Natural Science Foundation of China (U2106209, J.M.), the National Key Research and Development Program of China (2022YFC2601100, J.M.), National Forestry and Grassland Administration Emergency Leading the Charge with Open Competition Project (202302), the Scientific Research Program of Shanghai Science and Technology Commission (21ZR1405600, 23DZ1202700, J.M.), and CURE (Hui-Chun Chin and Tsung-Dao Lee Chinese Undergraduate Research Endowment, 22939).

REFERENCES

(1) Costanza, R.; d'Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'neill, R. V.; Paruelo, J.; et al. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387* (6630), 253−260.

(2) Macreadie, P. I.; Costa, M. D.; Atwood, T. B.; Friess, D. A.; Kelleway, J. J.; Kennedy, H.; Lovelock, C. E.; Serrano, O.; Duarte, C. M. Blue carbon as a natural climate solution. *Nat. Rev. Earth Environ.* **2021**, *2* (12), 826−839.

(3) Temmerman, S.; Meire, P.; Bouma, T. J.; Herman, P. M.; Ysebaert, T.; De Vriend, H. J. Ecosystem-based coastal defence in the face of global change. *Nature* **2013**, *504* (7478), 79−83.

(4) Kirwan, M. L.; Megonigal, J. P. Tidal wetland stability in the face of human impacts and sea-level rise. *Nature* **2013**, *504* (7478), 53−60.

(5) Ward, N. D.; Megonigal, J. P.; Bond-Lamberty, B.; Bailey, V. L.; Butman, D.; Canuel, E. A.; Diefenderfer, H.; Ganju, N. K.; Goni, M. A.; Graham, E. B.; Hopkinson, C. S.; Khangaonkar, T.; Langley, J. A.; McDowell, N. G.; Myers-Pigg, A. N.; Neumann, R. B.; Osburn, C. L.; Price, R. M.; Rowland, J.; Sengupta, A.; Simard, M.; Thornton, P. E.; Tzortziou, M.; Vargas, R.; Weisenhorn, P. B.; Windham-Myers, L. Representing the function and sensitivity of coastal interfaces in Earth system models. *Nat. Commun.* **2020**, *11* (1), 2458.

(6) Gedan, K. B.; Silliman, B. R.; Bertness, M. D. Centuries of human-driven change in salt marsh ecosystems. *Annu. Rev. Mar. Science* **2009**, *1*, 117−141.

(7) Sage, R. F. Global change biology: A primer. *Global Change Biol.* **2020**, *26* (1), 3−30.

(8) McOwen, C. J.; Weatherdon, L. V.; Bochove, J. V.; Sullivan, E.; Blyth, S.; Zockler, C.; Stanwell-Smith, D.; Kingston, N.; Martin, C. S.; Spalding, M.; Fletcher, S. A global map of saltmarshes. *Biodivers. Data J.* **2017**, *5* (5), No. e11764.

(9) Qing, W.; Shu-Qing, A.; Zhi-Jun, M.; Bin, Z.; Jia-Kuan, C.; Bo, L. Invasive Spartina alterniflora: biology, ecology and management. *J. Syst. Evol.* **2006**, *44* (5), 559.

(10) Gao, S.; Du, Y.; Xie, W.; Gao, W.; Wang, D.; Wu, X. Environment-ecosystem dynamic processes of Spartina alterniflora salt-marshes along the eastern China coastlines. *Sci. China Earth Sci.* **2014**, *57*, 2567−2586.

(11) Wang, X.; Xiao, X.; Zou, Z.; Hou, L.; Qin, Y.; Dong, J.; Doughty, R. B.; Chen, B.; Zhang, X.; Chen, Y.; Ma, J.; Zhao, B.; Li, B. Mapping coastal wetlands of China using time series Landsat images in 2018 and Google Earth Engine. *ISPRS J. Photogramm. Remote Sens.* **2020**, *163* (C), 312−326.

(12) Ren, J.; Chen, J.; Xu, C.; van de Koppel, J.; Thomsen, M. S.; Qiu, S.; Cheng, F.; Song, W.; Liu, Q. X.; Xu, C.; Bai, J.; Zhang, Y.; Cui, B.; Bertness, M. D.; Silliman, B. R.; Li, B.; He, Q. An invasive species erodes the performance of coastal wetland protected areas. *Sci. Adv.* **2021**, *7* (42), No. eabi8943.

(13) Sheng, Y.; Luan, Z.; Yan, D.; Li, J.; Xie, S.; Liu, Y.; Chen, L.; Li, M.; Wu, C. Effects of Spartina alterniflora Invasion on Soil Carbon, Nitrogen and Phosphorus in Yancheng Coastal Wetlands. *Land* **2022**, *11* (12), 2218.

(14) Wang, D.; Zhang, R.; Xiong, J.; GUO, H.-Q.; Zhao, B. Contribution of invasive species Spartina alterniflora to soil organic carbon pool in coastal wetland: Stable isotope approach. *Chin. J. Plant Ecol.* **2015**, *39* (10), 941.

(15) Jones, C. G.; Lawton, J. H.; Shachak, M. Positive and negative effects of organisms as physical ecosystem engineers. *Ecology* **1997**, *78* (7), 1946−1957.

(16) Wang, B.; Zhang, K.; Liu, Q. X.; He, Q.; van de Koppel, J.; Teng, S. N.; Miao, X.; Liu, M.; Bertness, M. D.; Xu, C. Long-distance facilitation of coastal ecosystem structure and resilience. *Proc. Natl. Acad. Sci. U.S.A.* **2022**, *119* (28), No. e2123274119.

(17) Gan, X.; Cai, Y.; Choi, C.; Ma, Z.; Chen, J.; Li, B. Potential impacts of invasive Spartina alterniflora on spring bird communities at Chongming Dongtan, a Chinese wetland of international importance. *Estuarine Coastal Shelf Sci.* **2009**, *83* (2), 211−218.

(18) Lu, K.; Han, G.; Wu, H. Effects of Spartina alterniflora invasion on the benthic invertebrate community in intertidal wetlands. *Ecosphere* **2022**, *13* (3), No. e3963.

(19) Zhou, X.; Wang, T.; Ge, Z.; Shi, W.; Zhou, L. Impact of Spartina alterniflora invasion on the macrobethos community of

Jiuduansha's intertidal mudflat in the Yangtze River estuary. *Biodivers. Sci.* **2006**, *14* (2), 165−171.

(20) Li, B.; Liao, C.-h.; Zhang, X.-d.; Chen, H.-l.; Wang, Q.; Chen, Z.-y.; Gan, X.-j.; Wu, J.-h.; Zhao, B.; Ma, Z.-j.; Cheng, X.-l.; Jiang, L.-f.; Chen, J.-k. Spartina alterniflora invasions in the Yangtze River estuary, China: An overview of current status and ecosystem effects. *Ecol. Eng.* **2009**, *35* (4), 511−520.

(21) Bao-hua, X.; Guang-xuan, H. Control of invasive Spartina alterniflora: A review. *Ying Yong Sheng Tai Xue Bao* **2018**, *29* (10), 3464−3476.

(22) Quanqin, S.; Jiangwen, F.; Jiyuan, L.; Fan, Y.; Hua, L.; Xiuchun, Y.; Mingxiang, X.; Peng, H.; Xingjian, G.; Lin, H. Approaches for Monitoring and Assessment of Ecological Benefits of National Key Ecological Projects. *Adv. Earth Sci.* **2017**, *32* (11), 1174.

(23) Ping, Z.; Chang-an, L.; Shu-he, Z.; Chun-hong, W.; Yu-bo, L. Distribution of Spartina plantations along the China's coast. *Acta Oceanolog. Sin.* **2009**, *31* (5), 101−111.

(24) Yang, J.; Yu, H.-g.; Xu, F.-j.; Ma, M.-r.; You, W.-h. Species composition and diversity of herb communities in Dongtan reclamation areas of Chongming Island, Shanghai. *Chin. J. Ecol.* **2013**, *32* (7), 1748.

(25) Drusch, M.; Del Bello, U.; Carlier, S.; Colin, O.; Fernandez, V.; Gascon, F.; Hoersch, B.; Isola, C.; Laberinti, P.; Martimort, P.; et al. Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sens. Environ.* **2012**, *120*, 25−36.

(26) Irons, J. R.; Dwyer, J. L.; Barsi, J. A. The next Landsat satellite: The Landsat data continuity mission. *Remote Sens. Environ.* **2012**, *122*, 11−21.

(27) Roy, D. P.; Kovalskyy, V.; Zhang, H. K.; Vermote, E. F.; Yan, L.; Kumar, S. S.; Egorov, A. Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity. *Remote Sens. Environ.* **2016**, *185* (1), 57−70.

(28) Frantz, D.; Haß, E.; Uhl, A.; Stoffels, J.; Hill, J. Improvement of the Fmask algorithm for Sentinel-2 images: Separating clouds from bright surfaces based on parallax effects. *Remote Sens. Environ.* **2018**, *215*, 471−481.

(29) Gorelick, N.; Hancher, M.; Dixon, M.; Ilyushchenko, S.; Thau, D.; Moore, R. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* **2017**, *202*, 18−27.

(30) Zhang, Z.; Xu, N.; Li, Y.; Li, Y. Sub-continental-scale mapping of tidal wetland composition for East Asia: A novel algorithm integrating satellite tide-level and phenological features. *Remote Sens. Environ.* **2022**, *269*, 112799.

(31) Davis, M. H. *Markov Models & Optimization*; Routledge, 2018.

(32) Liang, X.; Guan, Q.; Clarke, K. C.; Liu, S.; Wang, B.; Yao, Y. Understanding the drivers of sustainable land expansion using a patch-generating land use simulation (PLUS) model: A case study in Wuhan, China. *Comput. Environ. Urban Syst.* **2021**, *85*, 101569.

(33) Ma, J.; Li, J.; Wu, W.; Liu, J. Global forest fragmentation change from 2000 to 2020. *Nat. Commun.* **2023**, *14* (1), 3752.

(34) IPCC. *Special Report on the Ocean and Cryosphere in a Changing Climate*. IPCC Geneva, Switzerland, 2019.

(35) Stanford University, U. o. M., Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience Centre and the Royal Swedish Academy of Sciences. *Natural Capital Project InVEST 3.14.1*. 2024. https://naturalcapitalproject.stanford.edu/software/invest, accessed 2023−03−11.

(36) Ge, Y.; Zhen-ming, G.; Li-quan, Z. Distribution of soil carbon storage in different saltmarsh plant communities in Chongming Dongtan wetland. *Ying Yong Sheng Tai Xue Bao* **2014**, *25* (1), 85−91.

(37) Sun, C.; Li, J.; Liu, Y.; Zhao, S.; Zheng, J.; Zhang, S. Tracking annual changes in the distribution and composition of saltmarsh vegetation on the Jiangsu coast of China using Landsat time series-based phenological parameters. *Remote Sens. Environ.* **2023**, *284*, 113370.

(38) Liu, J.; Niu, J.; Zou, Y.; Lu, S.; Wang, T. Changes in the waterbird community of the ecological restored wetlands in Pudong Dongtan, Shanghai. *Resources and Environment in the Yangtze Basin* **2015**, *24*, 219−226.

(39) Zou, Y.-a.; Niu, J.-y.; Tang, C.-d.; Pei, E.-l.; Tang, S.-x.; Lu, S.; Wang, T.-h. Shorebird habitat changes in the East Asian Australasian Flyway: A case study of the stopover site in Chongming Dongtan. *Chin. J. Ecol.* **2014**, *33* (12), 3300.

(40) Xu, Z.; Dong, B.; Wei, Z.; Lu, Z.; Liu, X.; Xu, H. Study on habitat suitability change and habitat network of rare wintering cranes in important international wetlands. *Ecol. Indic.* **2023**, *154*, 110692.

(41) McGarigal, K. *FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure*; US Department of Agriculture, Forest Service, Pacific Northwest Research Station, 1995.

(42) R Team. *R: A Language and Environment for Statistical Computing*, 2010.

(43) Hernandez, D. L.; Antia, A.; McKone, M. J. The ecosystem impacts of dominant species exclusion in a prairie restoration. *Ecol. Appl.* **2022**, *32* (5), No. e2592.

(44) Xie, B.; Han, G.; Qiao, P.; Mei, B.; Wang, Q.; Zhou, Y.; Zhang, A.; Song, W.; Guan, B. Effects of mechanical and chemical control on invasive Spartina alterniflora in the Yellow River Delta, China. *PeerJ.* **2019**, *7*, No. e7655.

(45) Kamp, J.; Trappe, J.; Dübbers, L.; Funke, S. Impacts of windstorm-induced forest loss and variable reforestation on bird communities. *For. Ecol. Manage.* **2020**, *478*, 118504.

(46) He, S.; Lin, J.; Liu, X.; Jia, S.; Chen, S. Cordgrass Spartina alterniflora acts as a key carbon source to support macrozoobenthos in the salt marsh and nearby mudflat communities. *Ecol. Indic.* **2023**, *148*, 110052.

(47) Mahaut, L.; Choler, P.; Denelle, P.; Garnier, E.; Thuiller, W.; Kattge, J.; Lemauviel-Lavenant, S.; Lavorel, S.; Munoz, F.; Renard, D.; Serra-Diaz, J. M.; Viovy, N.; Violle, C. Trade-offs and synergies between ecosystem productivity and stability in temperate grasslands. *Global Ecol. Biogeogr.* **2023**, *32* (4), 561−572.

(48) Pickering, D. Covering the Spartina threat: An alternative control method for non-native Spartina patens in a west coast salt marsh. In *Conference on Invasive Spartina*, 2004.

(49) Strong, D. R.; Ayres, D. A. Control and consequences of Spartina spp. invasions with focus upon San Francisco Bay. *Biol. Invasions* **2016**, *18*, 2237−2246.

(50) Patten, K.; O'Casey, C.; Metzger, C. Large-scale chemical control of smooth cordgrass (Spartina alterniflora) in Willapa Bay, WA: towards eradication and ecological restoration. *Invasive Plant Sci. Manage.* **2017**, *10* (3), 284−292.

(51) Hammond, M.; Cooper, A. Spartina anglica eradication and inter-tidal recovery in Northern Ireland estuaries. *Turning the Tide: The Eradication of Invasive Species* **2002**, 124−131.

(52) Zhang, X.; Xiao, X.; Wang, X.; Xu, X.; Qiu, S.; Pan, L.; Ma, J.; Ju, R.; Wu, J.; Li, B. Continual expansion of Spartina alterniflora in the temperate and subtropical coastal zones of China during 1985−2020. *Int. J. Appl. Earth Obs. Geoinf.* **2023**, *117*, 103192.

(53) Cui, B.-s.; He, Q.; An, Y. Spartina alterniflora invasions and effects on crab communities in a western Pacific estuary. *Ecol. Eng.* **2011**, *37* (11), 1920−1924.

(54) Wang, J.-q.; Zhang, X.-d.; Nie, M.; Fu, C.-z.; Chen, J.-k.; Li, B. Exotic Spartina alterniflora provides compatible habitats for native estuarine crab Sesarma dehaani in the Yangtze River estuary. *Ecol. Eng.* **2008**, *34* (1), 57−64.

(55) Yang, R. M.; Guo, W. Invasive Spartina strengthens soil resilience in wetlands of the east-central China coast. *Land Degrad. Dev.* **2018**, *29*, 2846−2853.

(56) Grime, J. P. Benefits of plant diversity to ecosystems: immediate, filter and founder effects. *J. Ecol.* **1998**, *86* (6), 902−910.

(57) Avolio, M. L.; Forrestel, E. J.; Chang, C. C.; La Pierre, K. J.; Burghardt, K. T.; Smith, M. D. Demystifying dominant species. *New Phytol.* **2019**, *223* (3), 1106−1126.

(58) Loreau, M.; Naeem, S.; Inchausti, P.; Bengtsson, J.; Grime, J. P.; Hector, A.; Hooper, D. U.; Huston, M. A.; Raffaelli, D.; Schmid, B.; Tilman, D.; Wardle, D. A. Biodiversity and ecosystem functioning: current knowledge and future challenges. *Science* **2001**, *294* (5543), 804−808.

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

(59) Kintisch, E. Can Coastal Marshes Rise Above It All? *Science* **2013**, *341* (6145), 480−481.
(60) Xia, S.; Wang, W.; Song, Z.; Kuzyakov, Y.; Guo, L.; Van Zwieten, L.; Li, Q.; Hartley, I. P.; Yang, Y.; Wang, Y.; Andrew Quine, T.; Liu, C.; Wang, H. Spartina alterniflora invasion controls organic carbon stocks in coastal marsh and mangrove soils across tropics and subtropics. *Global Change Biol.* **2021**, *27* (8), 1627−1644.
(61) Qiao, G.; Mi, H.; Wang, W.; Tong, X.; Li, Z.; Li, T.; Liu, S.; Hong, Y. 55-year (1960−2015) spatiotemporal shoreline change analysis using historical DISP and Landsat time series data in Shanghai. *Int. J. Appl. Earth Obs. Geoinf.* **2018**, *68*, 238−251.
(62) Tang, L.; Gao, Y.; Wang, C.-h.; Zhao, B.; Li, B. A plant invader declines through its modification to habitats: A case study of a 16-year chronosequence of Spartina alterniflora invasion in a salt marsh. *Ecol. Eng.* **2012**, *49*, 181−185.
(63) Ning, Z.; Li, D.; Chen, C.; Xie, C.; Chen, G.; Xie, T.; Wang, Q.; Bai, J.; Cui, B. The importance of structural and functional characteristics of tidal channels to smooth cordgrass invasion in the Yellow River Delta, China: Implications for coastal wetland management. *J. Environ. Manage.* **2023**, *342*, 118297.
(64) Zhao, Z.; Yuan, L.; Li, W.; Tian, B.; Zhang, L. Re-invasion of Spartina alterniflora in restored saltmarshes: Seed arrival, retention, germination, and establishment. *J. Environ. Manage.* **2020**, *266*, 110631.
(65) Coldren, G.; Barreto, C.; Wykoff, D.; Morrissey, E.; Langley, J. A.; Feller, I.; Chapman, S. Chronic warming stimulates growth of marsh grasses more than mangroves in a coastal wetland ecotone. *Ecology* **2016**, *97* (11), 3167−3175.
(66) McKee, K.; Rogers, K.; Saintilan, N. Response of salt marsh and mangrove wetlands to changes in atmospheric CO2, climate, and sea level. In *Global Change and the Function and Distribution of Wetlands*; Springer, 2012; pp 63−96.
(67) Kirwan, M. L.; Mudd, S. M. Response of salt-marsh carbon accumulation to climate change. *Nature* **2012**, *489* (7417), 550−553.
(68) Sun, B.; Jiang, M.; Han, G.; Zhang, L.; Zhou, J.; Bian, C.; Du, Y.; Yan, L.; Xia, J. Experimental warming reduces ecosystem resistance and resilience to severe flooding in a wetland. *Sci. Adv.* **2022**, *8* (4), No. eabl9526.

https://doi.org/10.1021/acs.est.4c05253
Environ. Sci. Technol. XXXX, XXX, XXX−XXX