Areal Extent, Species Composition, and Spatial Distribution of Coastal Saltmarshes in China

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***Abstract*—Coastal saltmarshes are key ecosystems with important ecological functions. Yet, they have experienced a widespread decline. Due to their importance, the conservation and restoration of saltmarshes are globally shared objectives, including China. Despite multiple local studies, nationwide information about saltmarshes in China is scarce. Thus, we used remote sensing to delineate the spatial distribution and areal extent of saltmarshes along coastal China and resolve their species composition. By interpreting 10 m spatial resolution Sentinel-2 images on Google Earth Engine, assisted with field survey and literature search, a total of 118 010 ha of saltmarshes were delineated in coastal China in 2019. Seven typical saltmarsh species were identified, with *Phragmites australis*, *Spartina alterniflora,* and *Scirpus mariquater* as dominant species, accounting for 95.5% of total saltmarsh extent, while *Suaeda salsa*, *Tamarix chinensis*, *Cyperus malaccensis,* and *Sesuvium portulacastrum* were present in limited abundance. The *P. australis* and exotic species *S. alterniflora* grow along almost all coastal provinces, but *P. australis* dominates in the north while *S. alterniflora* dominates in the middle part of coastal China. *Suaeda salsa* occurs mainly in the north and has suffered large losses. *Tamarix chinensis* is abundant in Shandong province, *S. mariquater* in the Yangtze River delta, *C. malaccensis* in Guangdong and Guangxi provinces, and *S. portulacastrum* in Taiwan. The exotic species *S. alterniflora* expanded extensively along the coast and its expansion rate continues to increase. The results provided conform a much-needed baseline for future monitoring efforts and the assessment of progress in the conservation and restoration projects toward recovering saltmarshes in China.**

***Index Terms*—Distribution, remote sensing, saltmarsh, sentinel-2.**

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I. Introduction

SALTMARSHES are coastal ecosystems formed by herbaceous communities growing in saltwater or brackish mudflats that are periodically or intermittently flooded by tides [1]. Saltmarshes are highly productive ecosystems and provide a suite of ecosystem services, such as coastal protection by attenuating waves [2], [3], provision of food, shelter, and habitat for wildlife [4], [5], especially for migratory seabirds [6]–[8] and early life stages of fish and invertebrates [9], nutrient removal [3], and carbon sequestration [10]. Hence, saltmarshes rank among Blue carbon ecosystems [11]–[13], and their conservation and restoration contribute to climate change mitigation and adaptation [11], [12], [14]–[16]. As regards humans, saltmarshes can offer a variety of commercial, recreational, and aesthetic values [17].

Saltmarshes are major components of coastal ecosystems in China, being present across all the coastal provinces and municipalities. As one of the major Blue carbon habitats, saltmarshes play a significant role in Blue carbon strategies in China due to their broad distribution and high carbon sequestration potential [18]. Recently, China has been vigorously developing a blue carbon program for climate change mitigation and adaptation, including the improvement of wetland carbon sequestration capacity as a strategy to reduce greenhouse gas emissions among China's Nationally Determined Contributions submitted under the Paris Agreement [19]. This requires quantification of the magnitude of carbon stocks in Chinese saltmarshes, including accurate information on the extent, species composition, and distribution of coastal saltmarshes, as well as threats and drivers of changes. Understanding the present and historical extent and distribution of saltmarshes can help set targets for saltmarsh restoration projects to mitigate climate change [20]. Additionally, regular monitoring of saltmarshes can help update the estimation of their carbon sequestration capacity [21].

So far, various local studies of saltmarsh dynamics have been conducted in some hotspot areas in China, such as the Liao River Delta [22], [23], the Yellow River Delta [24], [25], the middle coast of Jiangsu province [26]–[28], Shanghai [29]–[31], and the Yangtze River Estuary [32], [33]. The distribution of exotic *Spartina alterniflora* across China's coastline has been reported in a number of studies [34]–[37], and its spatiotemporal patterns was also studied [38]. A nationwide assessment of saltmarshes is, however, still pending. Thus, this study aims to identify and map the spatial distribution of different saltmarsh species along coastal China to provide a 2019 nationwide baseline for coastal saltmarshes, which is beneficial to saltmarsh conservation and restoration.

II. Materials and Methods

A. Study Area

The coastline of China extends over approximately 32 000 km, including 14 000 km island coastline, starting from the Yalu River mouth in the north of Liaoning and extending to the Beilun River mouth of Guangxi in the south as well as Hainan. From north to south along the coast, the 14 provinces and municipalities are Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Taiwan, Guangdong (include Hong Kong and Macau), Guangxi, and Hainan. Our study area covers the entire coastal China from 18°10´N to 39°50´N, containing tropical, subtropical, and temperate climate zones. Hangzhou Bay (30° N) in Zhejiang is a dividing point for the entire coastline [39] as China's coast north of Hangzhou Bay is dominated by sandy/muddy shores, while the coast south of Hangzhou Bay is mainly rocky shores, unsuitable to support saltmarshes.

Saltmarshes usually grow in sandy or muddy shorelines and are stratified, in terms of community structure, with elevation relative to mean sea level, into low marshes, middle marshes, and high marshes. Along coastal China, native saltmarsh species *Phragmites australis* and *Tamarix chinensis* are dominant in high marshes; *Suaeda salsa* and *Cyperus malaccensis* are dominant in middle marshes; and *Scirpus mariqueter* and *Scirpus triqueter* dominate in low marshes [36]. Exotic *Spartina alterniflora* are encroaching seaward into low marshes and landward into high marshes [40].

B. Field Survey

We conducted a field survey along the national coastal zone in 2019, recorded the positions using a handheld GPS device, and taken aerial photos by a Hasselblad L1D-20c of DJI Mavic-2 Pro and DJI 4 P4 drone. These aerial photos (R, G, B) could help identify and verify saltmarsh species and distributions within a large extent far away from the coast. The information of field survey sites was recorded in Supplement Table SI and detailed information of aerial photoshoots could be seen in Gu [41].

C. Remote Sensing Method

Remote sensing is beneficial to mapping blue carbon ecosystems [42]. Abundant remote sensing images, such as Landsat series and Sentinel series images, are publicly available. We selected Sentinel 2 L1C data with a spatial resolution of 10 m as the main source to identify and map coastal saltmarsh distributions in China. The analyses were conducted on the Google Earth Engine, a cloud-based analysis platform that comprises a large archive of publicly available geospatial data, including analysis-ready Sentinel 2 data, and high-performance parallel computation services [43]–[45].

TABLE I
Overall Accuracy (OA) and Kappa Index of SVM Training and Validation

Region	Training		Validation	
	OA (%)	Kappa	OA (%)	Kappa
Liaoning	91.4	0.88	96.1	0.95
Hebei & Tianjin	97.8	0.97	96.3	0.94
Shandong	91.1	0.89	88.6	0.86
Jiangsu	97.1	0.96	93.7	0.92
Shanghai	89.3	0.87	88.7	0.86
Zhejiang	94.3	0.93	95.2	0.94
Fujian	93.7	0.92	96.9	0.96
Guangdong	89.4	0.86	94.3	0.92
Guangxi	95.4	0.94	95.7	0.95
Average	93.3	0.91	93.9	0.92

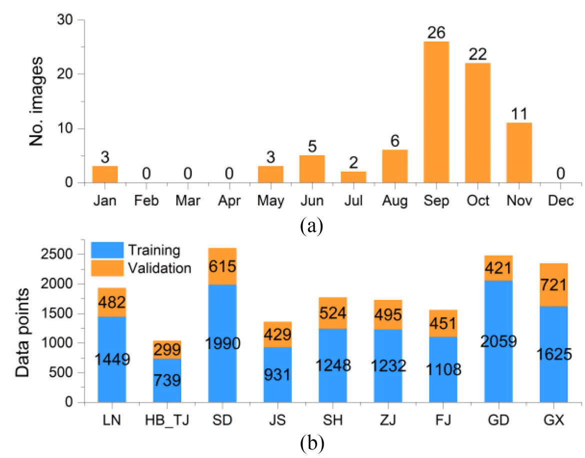

Fig. 1. Information about remote sensing classification data (a: number of used Sentinel 2 images acquired in each month; b: Training and validation data points used in SVM classification model in each region; LN: Liaoning, HB_TJ: Hebei and Tianjin, SD: Shandong, JS: Jiangsu, SH: Shanghai, ZJ: Zhejiang; FJ: Fujian, GD: Guangdong, GX: Guangxi).

Since coastal saltmarshes are only distributed in coastal intertidal zones, land masks, updated with visual interpretation based on publicly available natural and man-made coastline data of open street map, were applied to eliminate land information while retaining coastal zone information. Sentinel 2 images acquired on low-tide and cloud-free dates from September to November were selected to effectively identify different landscapes and saltmarsh vegetation species. Although we selected images that had the cloud cover less than 10% to get high quality data, best available images for some areas still had thin clouds, which would influence the surface reflectance of different land covers. Thus, pixels that were identified as cloud or cloud shadow by the FMask algorithm [46] were excluded from the image stacks to avoid errors. As tidal stages affect saltmarsh interpretation of remote sensing images [47], we looked through all the cloud-free scenes and manually selected relative low-tide scenes by overlaying the scenes. Totally 78 Sentinel 2 images were applied for the whole coastal China to identify saltmarsh species, in which 59 images were acquired during late growing seasons (September to November) while other 19 images were not [see Fig. 1(a)]. In some regions, such as Hainan, Macau,

TABLE II
SALTMARSH SPECIES AND AREAL EXTENTS ALONG COASTAL CHINA IN 2019 (UNIT: HA)

	PA	SS	SA	SM	CM	Other	Total
Liaoning	3717	1431	33				5181
Hebei & Tianjin	204	27	430				661
Shandong	10144	1653	6989			1281[a]	20067
Jiangsu	7592	461	16919	53			25025
Shanghai	11372		16228	6486			34086
Zhejiang	1063		14877	3869			19809
Fujian	145		10217	121[b]			10483
Taiwan	28		149			87[c]	264
Guangdong	337[d]		557		19		913
Guangxi			1133		387[d]		1520
Hainan	1						1
Total	34603	3572	67532	10529	406	1368	118010

Note: PA: *Phragmites australis*; SS: *Suaeda salsa*; SA: *Spartina alternilfora*; SM: *Scirpus mariqueter*; CM: *Cyperus malaccensis*; [a]mix growing of *Tamarix chinensis, Phragmites australis* and *Suaeda salsa*; [b]*Scirpus triqueter*; [c]*Sesuvium portulacastrum*; [d]mix growing of *Phragmites australis* and *Cyperus malaccensis*.

Hong Kong, and Taiwan, the spatial resolution of Sentinel 2 is too coarse to identify the saltmarshes due to their limited distribution there. As a result, we used higher spatial resolution images available in Google Earth during the late growing seasons at the same year to manually map the saltmarsh distribution using visual interpretation and expert classification. Google Street views also helped identify saltmarsh species in these small regions.

The training data and validation data used in the classification were all randomly selected pixels from the Sentinel 2 images based on field survey, aerial photos, and very-high-resolution images on Google Earth. Total 16 818 samples were selected as training and validation data, but the former covered 74% (12 381) and the latter covered 26% (4437) of the whole dataset [see Fig. 1(b)]. These training data and validation data were stratified by region and class (Supplement Table SII). Specifically, in each province, the data classes included water, tidal flat, 1–4 kinds of saltmarsh species, or mangrove. We used the support vector machine (SVM), an advanced machine learning method, to implement the classification of saltmarshes. This supervised machine-learning model was trained using input data from randomly selected pixels of Sentinel 2 images. To better identify different land covers, we computed 7 predictor variables to be used in the SVM classification, including Sentinel 2 Near Infrared band, Short-wave Infrared 1 band (SWIR1), the normalized differenced water index (NDWI) [48], modified NDWI (MNDWI) [49], automated water extraction index [50], normalized differenced vegetation index [51], and enhanced vegetation index [52]. Different saltmarsh species varied in these indices especially in remote sensing images acquired in autumn (see Fig. 2). After classification, we postprocessed the results of SVM classification by elimination and majority filter in ArcGIS 10.7 (ESRI 2019) and corrected obvious misclassification by visual interpretation. Field survey and aerial photographs taken by the drone also helped validate and correct the final classification results. A standard remote-sensing error ("confusion") matrix, accuracy index, and Kappa index were used to evaluate the quality of the SVM classifier and validation results. Maps of saltmarsh distribution with 10 × 10 m minimum mapping unit were drawn in ArcGIS 10.7 (ESRI 2019). The flow chart of saltmarsh classification was shown in Fig. 3.

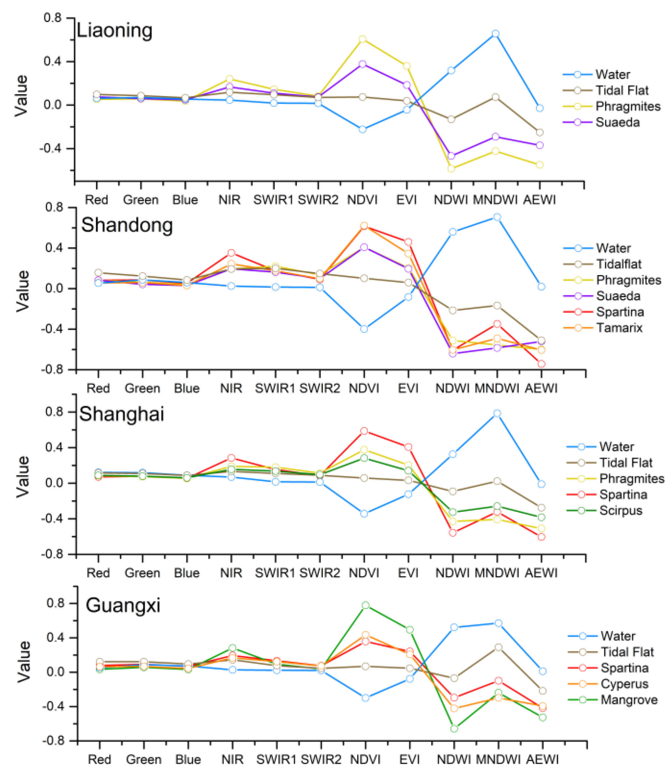

Fig. 2. Band reflectance and indices for land use and saltmarsh species classification. (As bands Blue, Green, Red, and SWIR2 have little differences among land use and saltmarsh species, these three bands are excluded from SVM classification model).

III. RESULTS

A. Classification Accuracy

The SVM training accuracy ranged from 89.3% to 97.8% in different regions with an average of 93.3%. The training Kappa index ranged from 0.86 to 0.97 with an average of 0.91. The validation accuracy ranged from 88.6% to 96.9% in different regions with an average of 93.9%. The validation Kappa index ranged from 0.86 to 0.96 with an average of 0.92 (see Table I). These estimation index indicated overall satisfactory classification results. For further information about classification accuracy, confusion matrix, producer's accuracy,

TABLE III
PUBLISHED SALTMARSH EXTENT COMPARED TO OUR OWN ESTIMATES AND THE RATE OF CHANGE IN AREA ACROSS FIVE MAIN COASTAL WETLANDS IN CHINA

	Phragmites australis			*Suaeda salsa*			*Spartina alterniflora*			*Scirpus mariquater*			Year[a]	Reference
	Area[a]	Area[b]	Rate	Area[a]	Area[b]	Rate	Area[a]	Area[b]	Rate	Area[a]	Area[b]	Rate		
Liao River delta				682	904	15							2004	Huang, 2011
Yellow River delta	9687	8764	-103	11239	965	-1142	3332[c]	4376	348				2010,2016[c]	Sun et al. 2016; Yang, 2017
Yancheng	4046	6841	699	4662[d]	460	-420	8961	11115	539				2009[d],2015	Zheng et al. 2018
Chongming Dongtan	1500	1551	6				1500	726	-86	1400	899	-56	2010	Ren et al., 2014
Jiuduansha	2213	2790	64				2278	5740	385	437	849	46	2010	Liu, 2013

Note: Extent unit: ha; rate unit: ha·y^{-1}, negative loss, positive gains. Data in Area[a] were from published papers; Data in Area[b] were from our results. Year[a] refers to the saltmarsh data reported in references. [c] Data were reported in 2016. [d] Data were reported in 2009. The rate was calculated from the year reported in references to 2019.

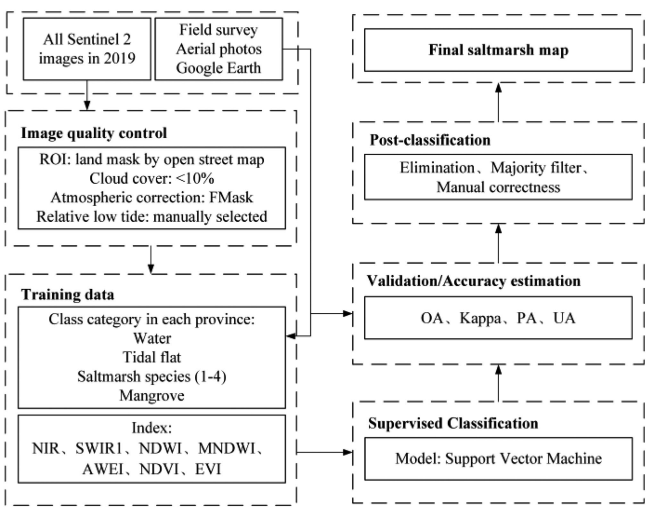

Fig. 3. Flow chart of saltmarsh classification (OA: overall accuracy; PA: producer's accuracy; UA: user's accuracy).

and user's accuracy for each classification category were showed in supplement Tables SII and SIII.

To better display the classification accuracy, we selected six regions as examples to compare classification results and aerial photos taken in the field (see Fig. 4). In Liao River estuary, sites V1, V2, and V3 represented *Suaeda* community, *Suaeda-Phragmites* mixed community, and *Phragmites* community, respectively. In the Yellow River estuary, sites V4, V5, and V6 represented *Tamarix*-dominated community, *Tamarix-Phragmites* mix community, and *Phragmites* community, respectively. In Xinyang and Dafeng, sites V7 and V8 represented *Phragmites* community and *Spartina* community. In north Choming island, sites V9, V10, and V11 represented *Phragmites* community, *Phragmites-Spartina* transition community, and *Spartina* community. In Jiulong estuary, sites V12, V13, and V14 represented mangrove-*Spartina* transition community and *Spartina* communities. The saltmarsh classification results at these sites were exactly the same as the aerial photos considering the saltmarsh species, distribution pattern, and community transition.

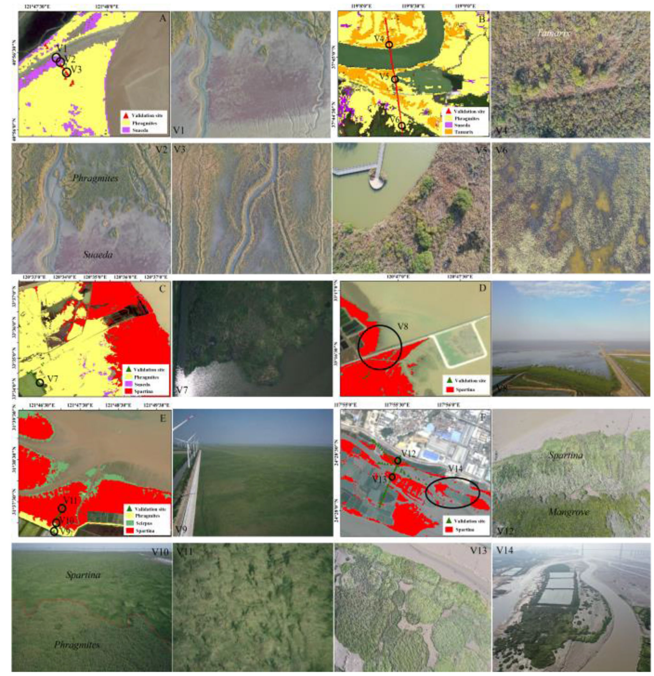

Fig. 4. Comparison for classification results and aerial photographs. (A: classification results in Liao river estuary; V1-V3: aerial photos in Liao river estuary; B: classification results in Yellow river estuary; V4–V6: aerial photos in Yellow river estuary; C: classification results in Yancheng nature reserve; V7: aerial photo in Yancheng nature reserve; D: classification results in Dafeng; V8: aerial photo in Dafeng; E: classification results in north Chongming; V9–V11: aerial photos in north Chongming; F: classification results in Jiulong estuary; V12–V14: aerial photos in Jiulong estuary).

B. Extent and Distribution of Saltmarsh Species

A total of 118 010 ha saltmarshes was delineated (see Table II). Shanghai had the largest areal extent (34 086 ha) of saltmarshes, accounting for 28.9% of the total national inventory. Jiangsu (25 025 ha), Shandong (20 067 ha), Zhejiang (19 809 ha), and Fujian (10 483 ha) followed, together contributing 63.9% of China's saltmarshes. We identified 5181 ha saltmarshes in Liaoning and 1520 ha in Guangxi. The area of saltmarshes in

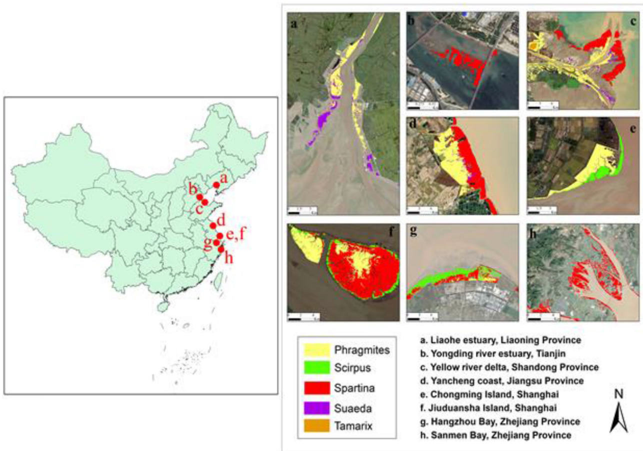

Fig. 5. Characteristic examples of saltmarsh distribution in Liaoning, Tianjin, Shandong, Jiangsu, Shanghai and Zhejiang provinces. (Base maps are Sentinel 2 images in true color).

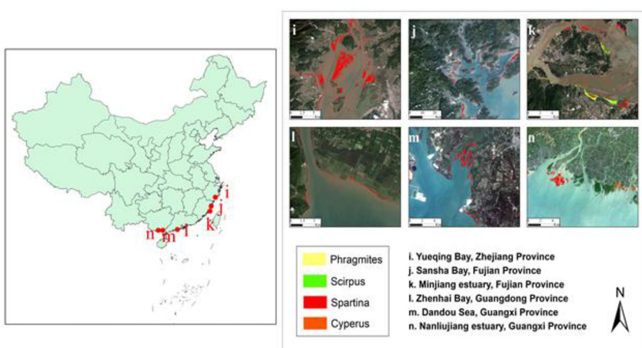

Fig. 6. Characteristic examples of saltmarsh distribution in Zhejiang, Fujian, Guangdong, and Guangxi provinces. (Base maps are Sentinel 2 images in true color).

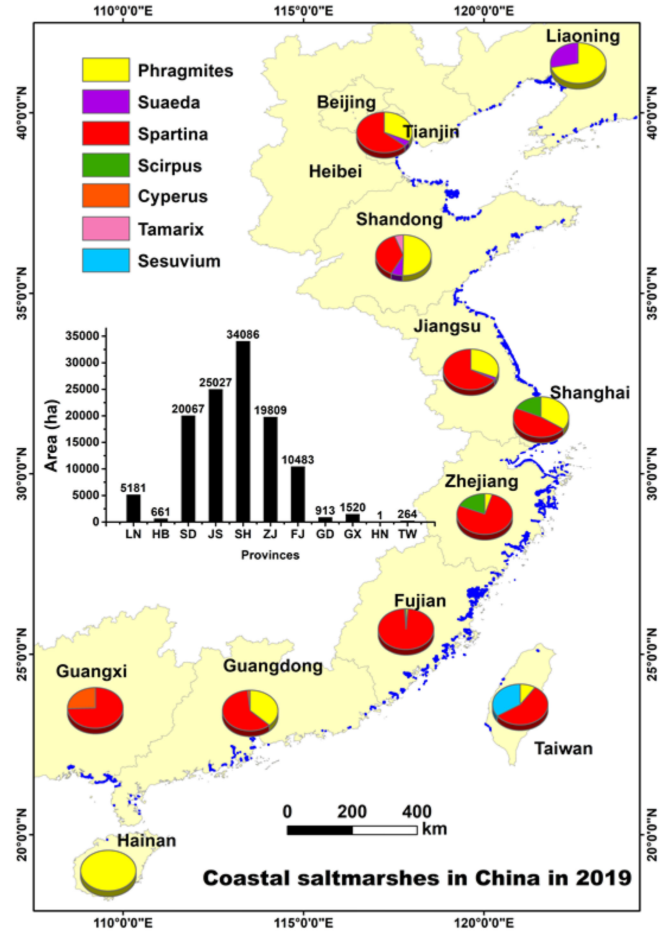

Fig. 7. Compositions of seven typical saltmarsh species along the coastal China. (Dark blue areas represent saltmarsh distribution).

Guangdong, Hebei, and Tianjin were less than 1000 ha. There were scattered saltmarshes in Hainan, Taiwan, Hong Kong and Macau, with all together comprising less than 300 ha. As mentioned previously, Hangzhou Bay is a dividing point for different types of shorelines. Saltmarsh extent north of Hangzhou Bay accounted for 72.0% of China's total saltmarsh extent while the saltmarsh south of Hangzhou Bay only 28.0% of the extent.

Mainly seven typical saltmarsh species were identified along coastal China, including Phragmites australis, Suaeda salsa, Spartina alterniflora, Scirpus mariqueter, Tamarix chinensis, Cyperus malaccensis, and Sesuvium portulacastrum (see Table II). Saltmarsh species identification was based on the satellite images, literature review, field survey, and interview with local people. Among these species, S. alterniflora, P. australis, and S. mariqueter are dominant species, covering 57.2%, 29.3%, and 8.9% of total saltmarsh extent, respectively. Other species are present with limited abundance with only 4.5% of coverage (see Table II).

In the entire coastal scale, the distribution of these saltmarshes varies with regions (see Figs. 5 –7; Table II). *Phragmites australis* grows along coastal China, except Hong Kong, and is concentrated on the north and the middle part. *Spartina alterniflora* occurs in all regions (We found *S. alterniflora* in Hainan in field survey but the area was too small to be identified in remote sensing images), except Macau, and covers large areas in the middle part of coastal China. *Suaeda salsa* mainly grows in the regions north of Jiangsu. *Tamarix chinensis*, alone or in a mixed community with *P. australis* and *S. salsa*, is found in Shandong, especially in the Yellow River Delta. *Scirpus mariquater*, a pioneer species that are native and specific to China, only retains abundant cover in the Yangtze River estuary and Hangzhou Bay. *Sesuvium portulacastrum* only occurs with abundant cover in Taiwan and small cover in Guangxi and Hainan (only found in field survey), while *Cyperus malaccensis* only occurs in Guangdong and Guangxi, usually growing along with *P. australis*.

The diversity and abundance of saltmarsh species varied across regions (see Fig. 7). Generally, saltmarshes north of Hangzhou Bay have higher plant species diversity and larger extents than those south of that bay. Specifically, the Liao River delta in Liaoning has two native saltmarsh species, with *P. australis* dominating with 71.7% of the total saltmarsh extent and *S. salsa* covering 27.6% [see Fig. 5(a)]. The exotic *S. alterniflora* only occurred in small patches. Saltmarshes in Hebei and Tianjin have three species with *S. alterniflora* being the dominant species covering 65.1% of extent. Saltmarshes in Shandong especially the Yellow River delta have four saltmarsh species, dominated by *P. australis* covering 50.6% of the extent while *S. alterniflora* covers 34.8% [see Fig. 5(c)]. Especially, *S. alterniflora* is expanding obviously in the Yellow River Delta. Saltmarshes in Jiangsu have more species than any other regions except Shandong, due to its broad and flat intertidal zones with abundant sediment inputs as well as its suitable climate with moderate temperature and precipitation [53]. *Spartina alterniflora* is expanding extensively along the coast of Jiangsu from Sheyang to Rudong county and has become the dominant species covering 67.6% of extent, larger than *S. salsa*, the native dominant species prior to this invasion. Native species *P. australis* covered 30.3% of the extent with abundant distribution in Yancheng National Nature Reserve [see Fig. 5(d)]. Saltmarshes in Shanghai, especially Chongming Dongtan and Jiuduansha, have three species, where *S. alterniflora* invades into areas formerly occupied by two native species communities [see Fig. 5(e) and (f)]. Management actions have slowed down the expansion of *S. alterniflora*, but it still occupies a quite large extent in Shanghai, covering 47.6% of extent. *Scirpus mariqueter* colonizes mudflats that are expanding with increased sediment input, thus covering 19.0% of the saltmarsh extent. Saltmarshes in Zhejiang and Fujian have three species with *S. alterniflora* as the dominant one, covering 75.1% and 97.5% of extent, respectively. Saltmarshes in Zhejiang are mainly distributed in bays and estuaries, such as Hangzhou Bay [see Fig. 5(g)], Xiangshan Bay, Sanmen Bay [see Fig. 5(h)], Yueqing Bay [see Fig. 6(i)], Ou River estuary, Feiyun River estuary, and Ao River estuary. In Fujian, *Spartina alterniflora* is mainly distributed in Zhangjiang estuary, Jiulongjiang estuary, Luoyuan Bay, Sansha Bay [see Fig. 6(j)], and the coastal areas of Ningde city. Guangdong and Guangxi have the same three species with *S. alterniflora* dominated covering 61.0% and 74.5%, respectively [see Fig. 6(l)]. *Spartina alterniflora* expanded extensively in Dandou Sea, Guangxi [54] [see Fig. 6(m)]. *Cyperus malaccensis* has a relatively large extent in the Nanliujiang and Qinzhou Bay, Guangxi [55] [see Fig. 6(n)]. Hainan has *P. australis*, *S. alterniflora*, and *Sesuvium portulacastrum*, but the latter two species have too small extents to be identified in Sentinel 2 images. Taiwan has three saltmarsh species including *P. australis*, *S. alterniflora*, and *S. portulacastrum* with *S. alterniflora* in abundant distribution. Only *S. alterniflora* is found in Hong Kong. *Phragmites australis* and *Cyperus malaccensis* grow together in Macau with quite limited abundance.

C. Distribution Pattern of Typical Saltmarsh Species

Different saltmarsh species have their specific distribution pattern along the coast. *Phragmites australis*, with the largest areal extent of native saltmarsh species, usually occurs in estuaries and along the river bank. In the north of coastal China, *Phragmites australis* grows as monpspecific stands, while in the central part of coastal China, exotic *S. alterniflora* invades into *P. australis* dominated community as patches to gradually occupy the whole intertidal zone with decreasing elevation. In the south of coastal China, *Phragmites australis* usually grows with *Cyperus malaccensis*, which renders their identification in satellite images cumbersome. *Scirpus mariqueter*, the native species with the second largest extent, only occurs in Chongming Dongtan, Jiuduansha, Hangzhou Bay, and Minjiang estuary (*Scirpus triqueter*). In these regions, *Scirpus mariqueter* usually occupies low intertidal zones and is invaded by *S. alterniflora* in upper boundary. *Suaeda salsa*, another native species, is abundant in Liaoning, Shandong, and Jiangsu, and occurs with a limited extent in Hebei and Tianjin. *Suaeda salsa* usually grows in lower intertidal zones than *P. australis* communities or outside the artificial coast like dyke. However, the landward expansion of the invasive *S. alterniflora* squeezes the extent of *S. salsa* in some regions such as the Yellow River Delta and Yancheng nature reserve in Jiangsu.

The exotic species *S. alterniflora* grows in three different ways along the Chinese coast. In the northern and middle part of coastal China, where native saltmarsh species occupy the intertidal zones, *S. alterniflora* invades landward into the *P. australis* and *S. salsa* communities and invades seaward into the *S. mariqueter* community. In the south coast of China, *S. alterniflora* is distributed as a belt along the seaward boundary of mangroves. *Spartina alterniflora* also usually occupies large extents in estuaries and bays where there are no native saltmarsh species along the whole coast. Since *S. alterniflora* stands promote sediment accumulation, it also occurs outside the artificial coast, such as outside dykes or ponds [see Figs. 5(b) and 6(l)]. In some regions, *S. alterniflora* still grows in formerly reclaimed, but now abandoned coastal areas.

IV. Discussion

A. Total Extent Estimate

Due to the spatial resolution of Sentinel 2 images, small patches ($<$10 m $\times$ 10 m) of saltmarshes were not identified, thus the total extent of saltmarshes reported here should be considered a conservative one. Our assessment estimates saltmarshes in coastal China to cover 118 010 ha in 2019 and provides a baseline with different saltmarsh species to assess subsequent changes. Accordingly, Chinese saltmarshes represented 2.1% of the global saltmarsh area, estimated at 5 495 100 ha by Mcowen *et al*. [56], which, however, estimated that saltmarshes in China accounted for 10% of the global area. This apparent discrepancy arises because the global estimate of Mcowen *et al*. [56] corresponds to estimates acquired across a broad time window (1973–2015, depending on region) around the world from different available information, which was more likely a spatial database not a baseline of saltmarsh. Hence, the value of the estimates of Mcowen *et al*. [56] as a baseline for comparison is limited, as it compounds area estimates across four decades. Our saltmarsh extent result provides a far more reliable baseline for saltmarsh comparison in the global scale and into the future.

Hu *et al.* [57] mapped coastal saltmarshes in China using time series of Sentinel-1 SAR data and interpreted 127 477 ha with 4 species of saltmarshes. Our results were 7.4% lower than Hu *et al.* [57] mainly due to the discrepancy of *Suaeda*. The plants of *Suaeda* are quite short and small and sparsely distributed if newly transplanted, thus leading to low reflectance in multispectral Sentinel-2 data and difficulty in differentiating from tidal flats. In southern China, *P. australis* usually grows with *C. malaccens* and the latter is dominant in Guangxi as we found in the field survey. Hu *et al*. [57] found no *C. malaccens* but only *P. australis* in southern China, which was due to the difficulty in distinguishing these two species by SAR. Also, the similarity of dense *P. australis* and *S. alterniflora* stands represented in SAR data may lead to misclassification of these two species in some regions. For example, Hu *et al*. [57] misclassified *S. alterniflora* as *P. australis* in Yueqing Bay where our results showed only *S. alterniflora* covered large extents as founded in our field survey. SAR data have the advantages of differentiating plant species with various heights, while multispectral data contain abundant spectral information. Therefore, the combination of SAR and multispectral data could further improve the interpretation of saltmarshes.

B. Saltmarsh Variation in Typical Regions

Globally, saltmarshes have suffered large losses due to anthropogenic and natural reasons [11], [58]. Indeed, coastal saltmarshes in China suffered a great loss (59%) from the 1980s to the 2010s [59], with rates of loss differing across species and regions. Based upon the saltmarsh data reported in previous research papers, we calculated the rates of change of different saltmarsh species in five main coastal wetlands (see Table III). In the Liao River delta (Liaoning), *S. salsa* slowly increased at a rate of 15 ha·y^{-1} from 2004 to 2019 due to natural succession and protection and restoration efforts to create "Red beach," which describes the *S. salsa* saltmarsh landscape when it is changing the color during cold winter days [60]. The change in *Phragmites australis* was not calculated, as the published data covered lots of *P. australis* inland of artificial seawalls, which represents freshwater wetlands that were not included in our saltmarsh mapping. In the Yellow River delta, *Phragmites australis* decreased with 103 ha·y^{-1} while *S. salsa* decreased dramatically with 1142 ha·y^{-1} from 2010 to 2019. These large losses were due to saltmarsh conversion to agricultural lands, aquaculture ponds, salt pans, and urban development [61], [62]. Coastal erosion also led to rapid decline of *S. salsa* saltmarsh [62]. Another reason for this large loss of *S. salsa* was the overestimated extent in 2010. We verified the remote sensing images in Google Earth and found that the large area identified as *S. salsa* in south part of the Yellow River delta could be instead mudflats. The exotic *S. alterniflora* increased significantly by 348 ha·y^{-1} from 2016 to 2019. The large expansion concentrated in new expanding mudflats of the Yellow River delta due to the abundant sediment inputs. In Yancheng, Jiangsu, *P. australis* and *S. alterniflora* expanded extensively at 699 ha·y^{-1} and 539 ha·y^{-1} respectively from 2015 to 2019. The expansion of *P. australis* mainly occurred in Yancheng nature reserve as a result of effective protection and restoration management. The expansion of *S. alterniflora*, however, was due to invasion into native saltmarsh species and continuous colonization on mudflats. The native species *S. salsa* decreased rapidly due to reclamation [27] and invasion by *S. alterniflora* [40]. In Chongming Dongtan, *P. australis* slowly increased by 6 ha·y^{-1} from 2010 to 2019 due to conservation while *S. mariqueter* decreased by 56 ha·y^{-1} as it was invaded by *S. alterniflora*. In our estimates, the area of *S. alterniflora* decreased, which was quite surprising. From 2010 to 2019, there were reclamation projects in the northeast of Chongming Dongtan. Our saltmarsh mapping focused on saltmarshes outside of seawalls, thus leading to lower estimates of the area of *S. alterniflora*. Another reason was due to saltmarsh management efforts to remove *S. alterniflora* in Chongming Dongtan. Saltmarshes in Jiuduansha increased due to high sedimentation rates, colonization, and wetland evolution from 2010 to 2019, however, the increasing rate was largest for *S. alterniflora* (385 ha·y^{-1}), as this species could invade into areas occupied by other two native species.

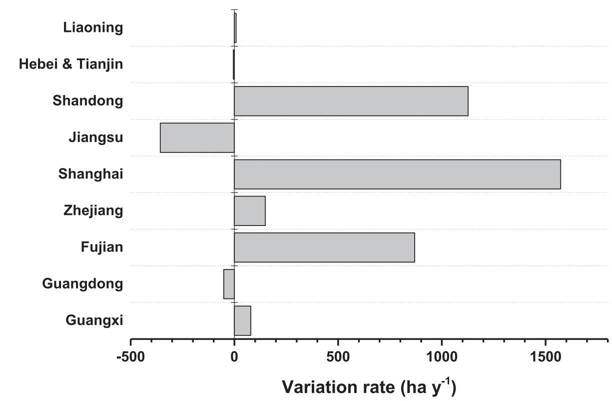

Fig. 8. *Spartina alterniflora* variation from 2015 to 2019 along the coastal China. (Data in 2015 were from Liu *et al.* [37]).

C. Exotic Spartina Alterniflora Variation Along the Coast

Several studies have reported the national distribution of *S. alterniflora* in 2007 and 2015 [34]–[37], allowing us to calculate the rate of change in the area along the coast. *Spartina alterniflora* is expanding along the coast and increasing by 2768 ha·y^{-1} (average rate from 2007 to 2019) across China, when our estimates were compared to those of Zuo *et al*. [35] and Zhang [34]. The rate of expansion has accelerated recently, as *S. alterniflora* has increased at 3163 ha·y^{-1} between 2015 and 2019, based on the national *S. alterniflora* extent reported by Zhang *et al*. [36] and Liu *et al*. [37]. The expansion of *S. alterniflora* from 2015 to 2019 differed among provinces. Compared to the areal extent in 2015 reported by Liu *et al*. [37], we found that *S. alterniflora* increased in Shandong, Shanghai, Zhejiang, Fujian, and Guangxi, but decreased in Hebei, Tianjin, Jiangsu, and Guangdong (see Fig. 8). The decrease of *S. alterniflora* in Hebei and Tianjin was due to reclamation. In Jiangsu, the decrease was due to the efforts to restore *P. australis* in Yancheng nature reverse. The Guangdong government planted mangrove *Sonneratia apetala* to replace *S. alterniflora* or simply removed it as management to control the *S. alterniflora* expansion.

Our results showed that *S. alterniflora* was found in Taiwan where previous studies had no record of this invasive species. The occurrence of *S. alterniflora* in Liaoning was disputed. Liu *et al*. [37] reported no occurrence, however, in our study, we found small patches of *S. alterniflora* in Zhuanghe and Yingnahe estuary, Liaoning. Indeed, northward expansion of *S. alterniflora* is expected with warming temperatures [63]. Overall, though *S. alterniflora* covered a small extent in these regions, we still need to pay attention to monitor its expansion.

V. Conclusion

This study mapped the spatial distribution, identified the species composition, and delineated the areal extent of coastal saltmarshes in 2019, providing a baseline for coastal saltmarshes across the country. The total area of saltmarshes was 118 010 ha, with *Spartina alterniflora* covering for 57.2%, *Phragmites australis* for 29.3%, *Scirpus mariqueter* for 8.9%, *Suaeda salsa* for 3.0%, and other species (*Tamarix chinensis*, *Cyperus malaccens*, and *Sesuvium portulacastrum*) for 1.5%. In main coastal wetlands, different saltmarsh species showed various changes compared to previous years, which were the results of natural succession and human effects, including restoration of native saltmarsh species and removal of exotic species. Invasive species *S. alterniflora* is expanding extensively along the coast with an average of 2768 $ha\cdot y^{-1}$ from 2007 to 2019, and 3163 $ha\cdot y^{-1}$ during 2015–2019, showing an acceleration in recent years. Though the total national areal extent of *S. alterniflora* is still increasing, its area in some provinces showed a decline due to the control and removal efforts.

China is implementing ambitious saltmarsh protection and restoration projects. Progress toward restoring the historical extent of saltmarshes requires a reliable baseline, which our results provide. This baseline also represents a reference to calculate the contribution of saltmarsh conservation and restoration efforts to avoidance of greenhouse gas emissions, enhancement of carbon sequestration, and climate change mitigation, which helps to achieve carbon neutrality.

References

[1] W. J. Mitsch and J. C. Gosselink, *Wetlands*. Canada, Toronto: Wiley, 2000.

[2] I. Möller *et al.*, "Wave attenuation over coastal saltmarshes under storm surge conditions," *Nat. Geosci.*, vol. 7, no. 10, pp. 727–732, Sep. 2014.

[3] F. Ge, B. Tian, Y. Zhou, Q. He, and W. Qian, "Analyzing the role of saltmarshes on attenuating waves in Changjiang Estuary," *Resources Environ. Yangtze Basin*, vol. 27, no. 8, pp. 1784–1792, Aug. 2018.

[4] K. Alizad, S. C. Hagen, J. T. Morris, S. C. Medeiros, M. V. Bilskie, and J. F. Weishampel, "Coastal wetland response to sea-level rise in a fluvial estuarine system," *Earth's Future*, vol. 4, no. 11, pp. 483–497, Nov. 2016.

[5] S. C. Pennings and M. D. Bertness, "Saltmarsh communities," *Marine Community Ecology*. Sunderland, MA, USA: Sinauer Associates, 2001, pp. 289–316.

[6] M. K. McCurdy, "Public trust protection for wetlands," *Environ. Law*, vol. 19, 1988, Art. no. 696.

[7] J. D. Goss-Custard and M. G. Yates, "Towards predicting the effect of saltmarsh reclamation on feeding bird numbers on the Wash," *J. Appl. Ecol.,* vol. 29, no. 2, pp. 330–340, 1992.

[8] N. Phelan, A. Shaw, and A. Baylis, "The extent of saltmarsh in England and Wales: 2006–2009," Rep. SCHO0811BUBC-E-E, Environ. Agency, Bristol, U.K., 2011.

[9] P. W. Stevens, C. L. Montague, and K. J. Sulak, "Fate of fish production in a seasonally flooded saltmarsh," *Mar. Ecol. Prog. Ser.*, vol. 327, pp. 267–277, Dec. 2006.

[10] G. L. Chmura, S. C. Anisfeld, D. R. Cahoon, and J. C. Lynch, "Global carbon sequestration in tidal, saline wetland soils," *Glob. Biogeochem. Cycles*, vol. 17, no. 4, pp. 22-1–22-12, Dec. 2003.

[11] E. McLeod *et al.*, "A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2," *Front. Ecol Environ.*, vol. 9, no. 10, pp. 552–560, Jan. 2011.

[12] C. M. Duarte, I. J. Losada, I. E. Hendriks, I. Mazarrasa, and N. Marbà, "The role of coastal plant communities for climate change mitigation and adaptation," *Nat. Clim. Change*, vol. 3, pp. 961–968, Oct. 2013.

[13] B. J. Johnson, C. E. Lovelock, and D. Herr, "Climate regulation: Saltmarshes and blue carbon," in *The Wetland Book: I: Structure and Function, Management, and Methods*. Berlin, Germany: Springer, 2018, pp. 1185–1196, doi: 10.1007/978-90-481-9659-3_213.

[14] S. Sifleet, L. Pendleton, and B. C. Murray, "State of the science on coastal blue carbon: A summary for policy makers," Nicholas Inst. Environ. Policy Solutions, Duke Univ., Durham, NC, USA, 2011.

[15] G. Vaidyanathan, "'Blue carbon' plan takes shape," *Nature*, Feb. 2011. https://doi.org/10.1038/news.2011.112

[16] J. Gattuso *et al.*, "Ocean solutions to address climate change and its effects on marine ecosystems," *Front. Mar. Sci.*, vol. 5, Oct. 2018, Art. no. 337.

[17] E. McKinley, J. F. Pages, M. Alexander, D. Burdon, and S. Martino, "Uses and management of saltmarshes: A global survey," *Estuar. Coast. Shelf Sci.*, vol. 243, Sep. 2020, Art. no. 106840.

[18] J. Wu *et al.*, "Opportunities for blue carbon strategies in China," *Ocean Coast. Manage.*, vol. 194, Aug. 2020, Art. no. 105241.

[19] Department of Climate Change, National Development & Reform Commission of China, "Enhanced actions on climate change: China's intended nationally determined contributions," 2015. Accessed: Sep. 21, 2020. [Online]. Available: http://www.scio.gov.cn/xwfbh/xwbfbh/wqfbh/2015/20151119/xgbd33811/Document/1455864/1455864.htm

[20] R. Van Dyke and K. Wasson, "Historical ecology of a central California estuary: 150 years of habitat change," *Estuaries*, vol. 28, no. 2, pp. 173–189, Apr. 2005.

[21] P. Esselink *et al.*, "Saltmarshes," in *Wadden Sea Quality Status Report*. Kloepper, S., Ed., Common Wadden Sea Secretariat, Wilhelmshaven, Germany Last updated 21.12.2017. Downloaded 27.06.2018, 2017. [Online]. Available: qsr.waddensea-worldheritage.org/reports/salt-marshes

[22] G. Huang, "Study on wetland landscape change driving-mechanism in Liaohe estuary," Ph.D. dissertation, Beijing Forestry Univ., Beijing, China, 2011.

[23] T. Liu, X. Liu, J. Du, and K. Song, "Pattern and change of coastal wetlands in the Liaohe River delta for 5 periods," *Wetland Sci.*, vol. 15, no. 4, pp. 622–628, Aug. 2017.

[24] W. Sun, Z. Sun, X. Lu, M. Wang, and W. Wang, "Relationship between coastline changes and the landscape pattern heterogeneity of the saltmarsh in the Yellow River Delta, China," *Acta Ecologica Sinica*, vol. 36, no. 2, pp. 480–488, Jun. 2016.

[25] J. Yang, "Remote sensing monitoring and analysis of invasive plant Spartina alterniflora in modern Yellow River Delta," M.S. thesis, China Univ. Petroleum, Beijing, China, 2017.

[26] Y. Liu, R. Zhang, and M. Li, "Approach on the dynamic change and influence factors of Spartina alterniflora Loisel saltmarsh along the coast of the Jiangsu Province," *Mar. Geol. Lett.*, vol. 20, no. 2, pp. 18–21, Feb. 2004.

[27] C. Sun, Y. Liu, M. Li, S. Zhao, and M. Zhou, "Spatiotemporal evolution of saltmarsh and influential analysis of reclamation of Jiangsu middle coast in recent 25 Years," *J. Natural Resour.*, vol. 30, no. 9, pp. 1486–1498, Sep. 2015.

[28] Y. Zheng, L. Shi, D. Xu, Z. Jiang, and J. Guo, "Analysis on the rules of spatial and temporal distribution of saltmarsh in Yancheng coastal area over the past 30 years and its influencing factor," *J. Mar. Sci.*, vol. 36, no. 3, pp. 57–66, Sep. 2018.

[29] Y. Liu, "The assessment of carbon storage of vegetation zones in the Jiuduan Shoal wetland," M.S. thesis, East China Normal Univ., Shanghai, China, 2013.

[30] L. Ren, X. Li, S. Yang, Z. Yan, and X. Huang, "The impact of salt marsh change on sediment accumulation and wave attenuation at the East Chongming Island," *Acta Ecologica Sinica*, vol. 34, no. 12, pp. 3350–3358, Jun. 2014.

[31] W. Wu, Y. Zhou, and B. Tian, "Coastal wetlands facing climate change and anthropogenic activities: A remote sensing analysis and modeling application," *Ocean Coast Manage.*, vol. 138, pp. 1–10, Mar. 2017.

[32] C. Tong, "Effects of vegetation type on arthropod functional groups in the aerial habitat of saltmarsh," *Acta Ecologica Sinica*, vol. 32, no. 3, pp. 786–795, Feb. 2012.

[33] N. Li, L. Li, Y. Zhang, and M. Wu, "Monitoring of the invasion of Spartina alterniflora from 1985 to 2015 in Zhejiang Province, China," *BMC Ecol.*, vol. 20, Feb. 2020, Art. no. 7.
[34] Y. Zhang, "The spatial distribution and bioenergy estimation of an invasive plant Spartina alterniflora in China," M.S. thesis, Zhejiang Univ., Hangzhou, China, 2010.
[35] P. Zuo, S. Zhao, C. Liu, C. Wang, and Y. Liang, "Distribution of Spartina spp. along China's coast," *Ecol. Eng.*, vol. 40, pp. 160–166, Mar. 2012.
[36] D. Zhang *et al.*, "Introduction and spread of an exotic plant, Spartina alterniflora, along coastal marshes of China," *Wetlands*, vol. 37, pp. 1181–1193, Sep. 2017.
[37] M. Liu *et al.*, "Rapid invasion of Spartina alterniflora in the coastal zone of mainland China: New observations from Landsat OLI images," *Remote Sens.*, vol. 10, no. 12, Dec. 2018, Art. no. 1933.
[38] D. Mao *et al.*, "Rapid invasion of Spartina alterniflora in the coastal zone of mainland China: Spatiotemporal patterns and human prevention," *Sensors*, vol. 19, no. 10, May 2019, Art. no. 2308.
[39] H. Zhao and L. Wang, "Classification of the coastal wetland in China," *Mar. Sci. Bull.*, vol. 19, no. 6, pp. 72–82, Dec. 2000.
[40] X. Qi, H. Liu, Z. Lin, X. Liu, and H. Gong, "Impacts of age and expansion direction of invasive Spartina alterniflora on soil organic carbon dynamics in coastal saltmarshes along eastern China," *Estuaries Coast*, vol. 42, pp. 1858–1867, Jul. 2019.
[41] J. Gu, "The distribution and change of coastal saltmarshes in China and the Carbon stock effects of exotic species," Ph.D. dissertation, Zhejiang Univ., Hangzhou, China, 2020.
[42] D. Lagomasino, T. Fatoyinbo, S K. Lee, and M. Simard, "High-resolution forest canopy height estimation in an African blue carbon ecosystem," *Remote Sens. Ecol. Conserv.*, vol. 1, no. 1, pp. 51–60, Jun. 2015.
[43] N. Gorelick, M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau, and R. Moore, "Google earth engine: Planetary-scale geospatial analysis for everyone," *Remote Sens. Environ.*, vol. 202, pp. 18–27, Dec. 2017.
[44] N. J. Murray *et al.*, "The global distribution and trajectory of tidal flats," *Nature*, vol. 565, pp. 222–225, Dec. 2019.
[45] D. Poursanidis, D. Traganos, L. Teixeira, A. Shapiro, and L. Muaves, "Cloud-native seascape mapping of Mozambique's Quirimbas National Park with Sentinel-2," *Remote Sens. Ecol. Conserv.*, vol. 7, no, 2, pp. 275–291, Nov. 2020.
[46] S. Foga *et al.*, "Cloud detection algorithm comparison and validation for operational Landsat data products," *Remote Sens. Environ.*, vol. 194, pp. 379–390, Jun. 2017.
[47] A. Campbell and Y. Wang, "Examining the influence of tidal stage on salt marsh mapping using high-spatial-resolution satellite remote sensing and topobathymetric LiDAR," *IEEE Trans. Geosci. Electron.*, vol. 56, no. 9, pp. 5169–5176, Sep. 2018.
[48] S. K. McFeeters, "The use of the normalized differenced water index (NDWI) in the delineation of open water features," *Int. J. Remote Sens.*, vol. 17, no. 7, pp. 1425–1432, Apr. 1996.
[49] H. Xu, "Modification of normalized differenced water index (NDWI) to enhance open water features in remotely sensed imagery," *Int. J. Remote Sens.*, vol. 27, no. 14, pp. 3025–3033, Jan. 2006.
[50] G. L. Feyisa, H. Meilby, R. Fensholt, and S. R. Proud, "Automated water extraction index: A new technique for surface water mapping using Landsat imagery," *Remote Sens. Environ.*, vol. 140, pp. 23–35, Jan. 2014.
[51] N. Pettorelli, J. O. Vik, A. Mysterud, J. Gaillard, C. J. Tucker, and N. C. Stenseth, "Using the satellite-derived NDVI to assess ecological responses to environmental change," *Trends. Ecol. Evol.*, vol. 20, no. 9, pp. 503–510, Sep. 2005.
[52] A. R. Huete, H. Liu, K. Batchily, and W. J. D. van Leeuwen, "A comparison of vegetation indices over a global set of TM images for EOS-MODIS," *Remote Sens. Environ.*, vol. 59, no. 3, pp. 440–451, Mar. 1997.
[53] Y. Shen, Y. Liu, and Q. Chen, "Analysis of the expanding process of the Spartina alterniflora Loisel saltmarsh on Jiangsu province coast by remote sensing," *J. Plant Resour. Environ.*, vol. 11, no. 2, pp. 33–38, May 2002.
[54] Y. Tao, L. Pan, H. Fan, W. Ge, W. Liu, and X. Shi, "Remote sensing monitoring of Spartina alterniflora in coastal intertidal zone of Guangxi," *Guangxi Sci.*, vol. 24, no. 5, pp. 483–489, Sep. 2017.
[55] L. Pan, X. Shi, C. Zeng, Y. Tao, and H. Fan, "Status and characteristics of the research on salt marshes along Guangxi coast," *Guangxi Sci.*, vol. 24, no. 5, pp. 453–461, Aug. 2017.
[56] C. Mcowen *et al.*, "A global map of saltmarshes," *Biodiversity Data J.*, vol. 5 Mar. 2017, Art. no. e11764.
[57] Y. Hu *et al.*, "Mapping coastal salt marshes in China using time series of Sentinel-1 SAR," *ISPRS J. Photogramm. Remote Sens.*, vol. 173, pp. 122–134, Mar. 2021.
[58] K. B. Gedan, B. R. Silliman, and M. D. Bertness, "Centuries of human-driven change in salt marsh ecosystems," *Ann. Rev. Mar. Sci.*, vol. 1, pp. 117–141, Jan. 2009.
[59] J. Gu *et al.*, "Losses of saltmarsh in China: Trends, threats and management," *Estuar. Coast Shelf Sci.*, vol. 214, pp. 98–109, Dec. 2018.
[60] M. Jia, Z. Wang, D. Liu, C. Ren, X. Tang, and Z. Dong, "Monitoring loss and recovery of saltmarshes in the Liao River delta, China," *J. Coast Res.*, vol. 31, no. 2, pp. 371–377, Mar. 2015.
[61] L. Huang, J. Bai, B. Chen, K. Zhang, C. Huang, and P. Liu, "Two-decade wetland cultivation and its effects on soil properties in saltmarshes in the Yellow River Delta, China," *Ecol. Informat.*, vol. 10, pp. 49–55, Jul. 2012.
[62] X. Zhang and P. Li, "Coastal erosion and its environmental effect in the modern Yellow River delta," *Mar. Environ. Sci.*, vol. 27, no. 5, pp. 475–479, Oct. 2008.
[63] X. Xiao *et al.*, "Warming amplifies the frequency of harmful algal blooms with eutrophication in Chinese coastal waters," *Environ. Sci. Technol.*, vol. 53, no. 22, pp. 13031–13041, Oct. 2019.

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