IMPLEMENTING THE STRATEGIC ACTION PROGRAMME FOR THE YELLOW SEA LARGE MARINE ECOSYSTEM: RESTORING ECOSYSTEM GOODS AND SERVICES AND CONSOLIDATION OF A LONG-TERM REGIONAL ENVIRONMENTAL GOVERNANCE FRAMEWORK

(UNDP/GEF YSLME Phase II Project)

Final report on progress of drifting *Sargassum horneri* in Yellow Sea

(Seasonality and inter-annual variability of the floating *Sargassum horneri* in western Yellow Sea and the environmental drivers for the increasing blooms in recent years)

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2019. 11

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1. Background

Seaweed blooms have been increasingly observed in coastal regions and even in open water worldwide. Although coastal eutrophication is directly linked to seaweed blooms (Valiela et al., 1997; Teichberg et al., 2010), blooming dynamics vary significantly among the diversified causative species and in different regions (Ye et al., 2011; Smetacek and Zingone, 2013). The two genera, *Ulva* (including the former Enteromorpha, Hayden et al., 2003) and *Sargassum*, are the most prominent for the seaweed blooms around the world.

Sargassum blooms, so-called golden-brown tides, are most prominent in the Sargasso Sea, Gulf of México and the Caribbean Sea (Laffoley et al., 2011; Smetacek and Zingone, 2013). *Sargassum* rafts have been floating in this region for decades, and some species (notably *Sargassum natans* and *S. fluitans*) are believed to be holopelagic and are drifting in the water permanently (Parr, 1939; Amaral-Zettler et al., 2017). Recently, unusual expansions and increased beaching events of the Atlantic *Sargassum* bloom have been reported along the west coasts of the northern and tropical Atlantic and even farther to the coasts of western Africa and northern Brazil in the southern Atlantic (Gower and King, 2011; Gower et al., 2013; Smetacek and Zingone, 2013; Sissini et al., 2017; Wang and Hu, 2017). Another invasive species, *Sargassum horneri*, was recently reported blooming on the eastern boundary of the East China Sea (ECS, Komatsu et al., 2007; 2008; Mizuno et al., 2014). *S. horneri* is a cosmopolitan benthic species that was originally distributed widely along the northwestern Pacific, including the coasts of China (Tseng 1984; Hu et al., 2011). In early 2000s, this species has invaded and spread along southern California, USA, Baja California, México, and the eastern coasts of the Pacific (Marks et al., 2015). Although pelagic *Sargassum* is recognized as an important biological resource for marine conservation and evolution (Laffoley et al., 2011; Hemphill, 2013), the overgrowth of floating biomass and inundation along the coasts have caused advent impacts on coastal environments, local tourism, fisheries and aquaculture etc.

In this project, we focused on the pelagic *S. horneri* in western Yellow Sea, where both green tide and *Sargassum* blooms occurred in recent years. The remote sensing data was compiled to illustrate the overall progress and locations of the *Sargassum* blooms in East China Sea (ECS) and Yellow Sea (YS). Data from the long-term field surveys since 2009 were then analyzed to described the details on seasonality, distribution and biomass of the pelagic *S. horneri* in western YS. Along with the benthic populations of *S. horneri* along Chinese coasts, possible reasons for the recent blooms of pelagic *S. horneri* along west coasts of Yellow Sea were further investigated. In this final report, partial data from the previous two reports (Report I Distribution of benthic populations of *Sargassum horneri* along the coasts of Shandong and Jiangsu provinces, and seasonal variation of drifting *S. horneri* in western Yellow Sea, Report II Genetic diversity of benthic and floating populations of *Sargassum* in western Yellow Sea) was cited and integrated to provide a complete overview on the current situation of the pelagic *S. horneri* in Yellow Sea.

2. Structure of the report

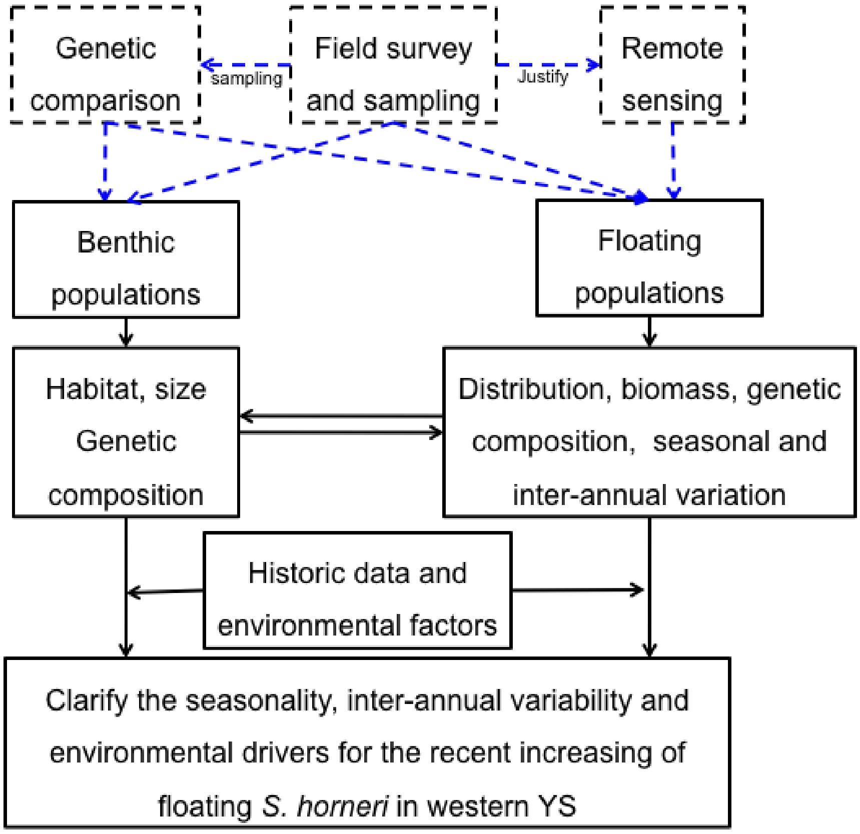

Fig. 1 Contents and structure of the final report

3. Temporal and spatial distribution of the pelagic *S. horneri*

3.1 Remote sensing analysis on the pelagic *S. horneri* in ECS and YS

The high resolution remote sensing images from series of satellites, such as MODIS (on both Terra and Aqua), GOCI, Landsat-8 OLI and GF (Gaofen)-1, GF-2, were retrieved to illustrate the distribution and development of the pelagic *Sargassum* in ECS and YS. The distribution of the floating macroalgae was outlined manually and coverage was computed by the method commonly used (Qi et al., 2016; Wang and Hu, 2016). The data from Qi et al. (2017) and Xing et al. (2017) was cited to present the typical northward and southward drifting of the floating *Sargassum* in ECS and YS. And it was compared with the data from the other years and those from field surveys to provide a complete distribution range.

3.1.1 Southward drifting of *S. horneri* in fall and winter

Series of high resolution satellite images clearly showed a southward drifting path of floating *Sargassum* in the western Yellow Sea. The floating biomass initially occurred on October 18, 2016 in the western Yellow Sea, about 50 km away from the south coast of the eastern Shandong Peninsula (Fig. 2; Xing et al., 2017). One month later, it drifted southward and extended mainly in the middle of the western Yellow Sea on November 15, 2016. On December 2, 2016, the biomass widespread over a large area off the coast of Jiangsu, reaching the north edge of the Subei Shoal. On December 31, 2016, most floating biomass was aggregated in the Subei Shoal, and caused severe damages to the local aquaculture.

During October 2017 – January 2018, another development process of the floating *Sargassum* was detected in similar region and at the same drifting trajectory (data was not shown). Whereas, the biomass and scale of the *Sargassum* patches in winter of 2017 were much smaller than that in 2016, and did not cause significant damages of the aquaculture rafts as the case in 2016. The consistent southward drifting biomass suggested a probable origin of the floating *Sargassum* in the north. Some *S. horneri* natural beds were observed along the coasts of Shandong and Liaoning provinces (described in Report 1 Distribution of benthic populations of *Sargassum horneri* along the coasts of Shandong and Jiangsu provinces, and seasonal variation of drifting *S. horneri* in western Yellow Sea), while the association between the benthic and pelagic populations needs further investigation.

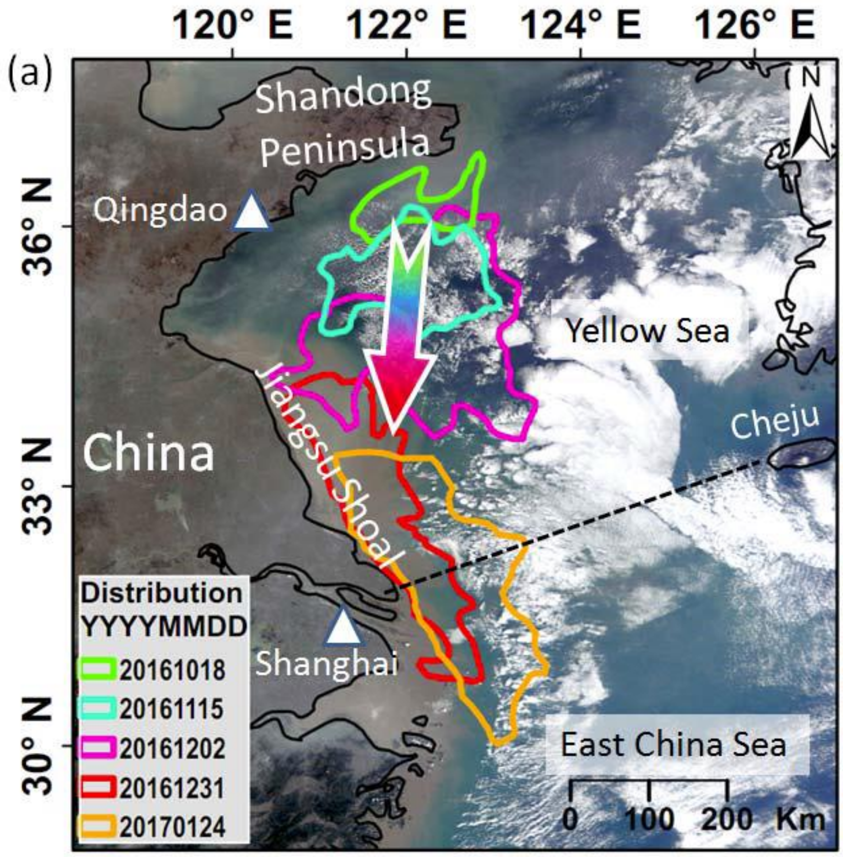

Fig. 2 Southward drifting *of Sargassum* from October 2016 to January 2017 (Xing et al., 2017).

3.1.2 Northward drifting of *S. horneri* in spring

A larger bloom of floating *Sargassum* was detected by the remote sensing analyses. Contrary to the blooms in the north, this *Sargassum* bloom was initiated off the coasts of Zhejiang province, and spread offshore and northward to western border of Kuroshio Current and Yellow Sea (Qi et al., 2017). As indicated in Fig. 3, the bloom origin is offshore Zhejiang coast where algae slicks have appeared in satellite imagery almost every February–March since 2012. Following the Kuroshio Current and Taiwan

Warm Current, these “initial” algae slicks are first transported to the northeast to reach South Korea (Jeju Island) and Japan coastal waters (up to 135°E) by early April 2017, and then transported to the northwest to enter the Yellow Sea by the end of April (Fig. 3; Qi et al., 2017). The spectral analysis suggests that most of the algae slicks may contain large amount of *Sargassum* biomass. The bloom covers a water area of ~160,000 km^2 with pure algae coverage of ~530 km^2, which exceeds the size of most *Ulva* blooms that occur every May–July in the Yellow Sea. Blooms of smaller size also occurred in previous years and especially in 2015.

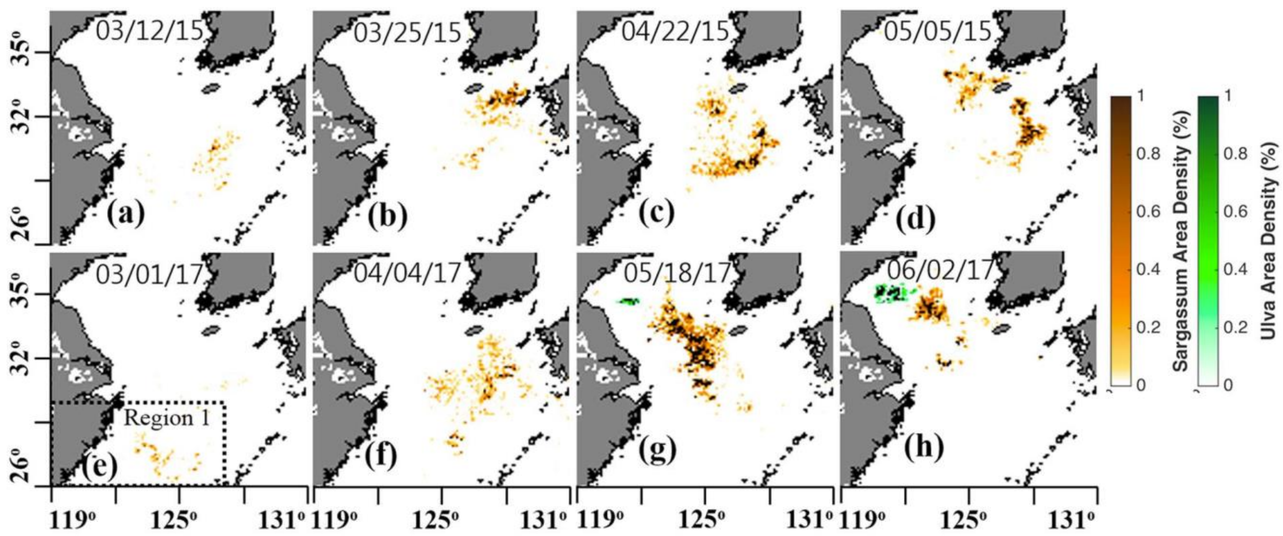

Fig. 3 Northward drifting *of Sargassum* in 2015 and 2017 (Qi et al., 2017). Yellow to brown colors represent the floating *Sargassum*, while green color indicates the floating *Ulva*.

The *Sargassum* blooms in ECS and southern YS suggested another origin of pelagic *Sargassum* biomass, which was speculated to locate along the coasts of Zhejiang Province, south to the Yangtze River Estuary. Our field data, as described below (3.2 Field survey on the pelagic *S. horneri* in western YS), supported this hypothesis that the pelagic *Sargassum* could drift northwardly from ECS to southern YS. Whereas, the exact location of the origin for the pelagic *Saragssum* in ECS needs further investigation.

3.2 Field survey on the pelagic *S. horneri* in western YS

As described above, the satellite remote sensing detected distinct *Sargassum* blooms in western YS and ECS, respectively. The two blooms went through distinct drifting pathways, indicating different origins of the floating biomass. At the same time, the remote sensing data suggested that the *Sargassum* blooms were independent to the annual *Ulva* green tides in western YS. However, our field surveys found that blooms of these two distinct seaweed species could co-occur and interplay to influence the blooming dynamics of each other. Here, we described in details about the distribution, biomass, progress and inter-annual variations of both floating *Ulva* and *Sargassum* in the overlapping region, Subei Shoal, the southwestern YS.

A year-round field survey was conducted in Subei Shoal during March 2017 – June 2018. The floating *Ulva* biomass was consistently originated from the central Shoal, around the edge of the raft region, in April. The *Ulva* biomass increased rapidly and filled the entire Shoal in May, and then declined in June or later. No floating *Ulva* biomass could be detected other than the blooming season (April – June) in this region.

The origination and progress of the floating *Sargassum* varied among years, indicating probably distinct origins of the pelagic biomass in different years. In 2017, pelagic *Sargassum* patches were initiated from two locations in late April (Fig. 4; Xiao et al., in press). One was close to the raft region at Jianggang, the other was in the offshore waters of Rudong, where only pelagic *S. horneri* was detected (Fig. 4). In May, The *Sargassum* biomass increased rapidly and widespread in the region of 33.00 – 35.00°N. In early 2018, low biomass of floating *Sargassum* persisted at outer edge of the Shoal and intruded into the shallow water in Subei Shoal in April and May. No *Sargassum* biomass was observed initiating from the central raft region in 2018.

According to the development process of floating *Sargassum* in these two years along with the remote sensing data, the pelagic *Sargassum* bloom in Subei Shoal during spring was likely derived from the coasts of ECS (including the YRE) in normal years (e.g. 2018), while multiple sources could be existing due to the unprecedented winter bloom in YS (e.g. 2017). Our field data corroborated the hypothesis from the remote sensing, which detected a recent expansion of the pelagic *Sargassum* from the ECS and speculated this expansion contributed mostly for the spring bi-macroalgal bloom in western Yellow Sea (Qi et al., 2017). Unlike the case of 2018, the pelagic *Sargassum* biomass was also detected on the raft and central shallow water close to the raft region in March and April of 2017 (Fig. 4). This was originated from the residual biomass from previous winter bloom as described by Xing et al. (2017).

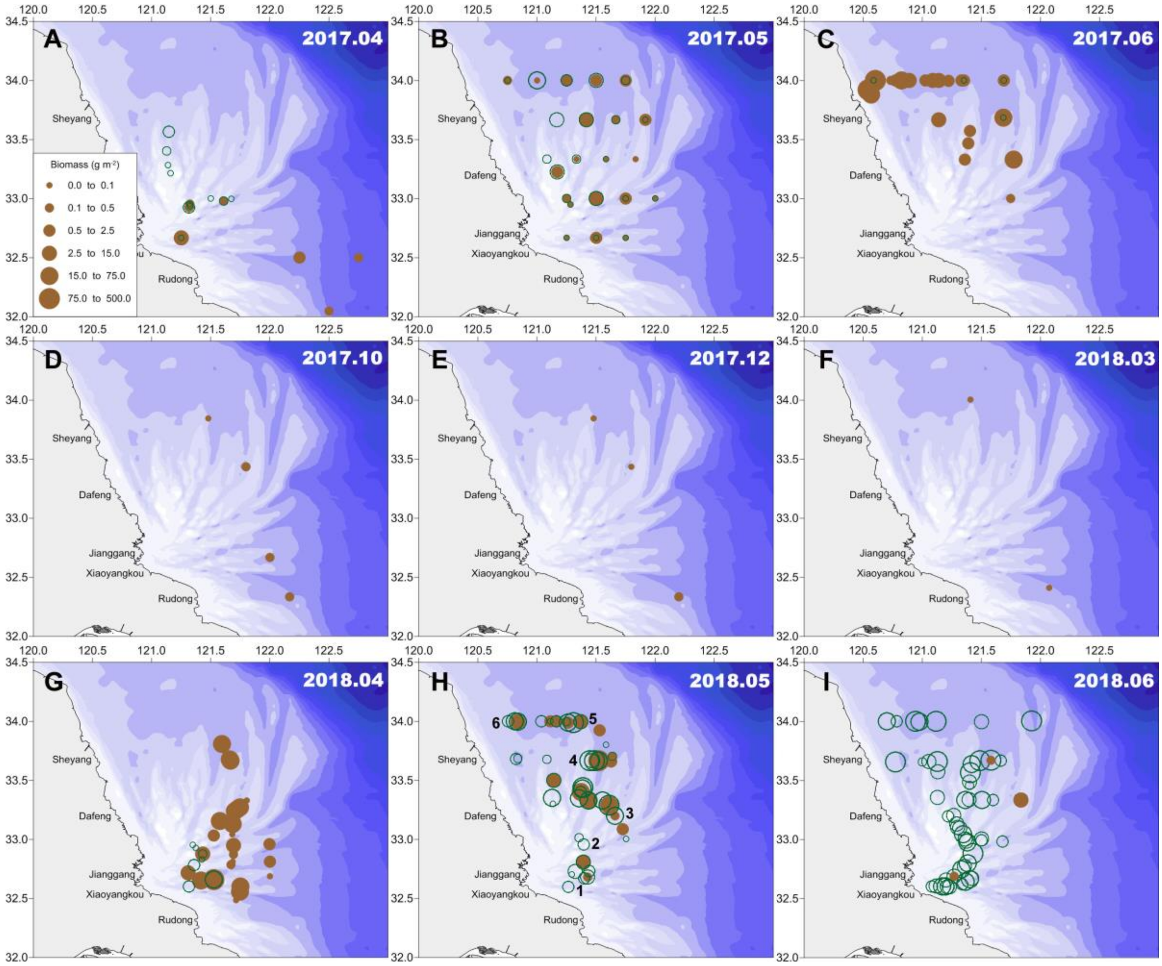

Fig. 4 Spatial progression of the floating *Ulva* (green open circles) and *Sargassum* (brown filled circles) in Subei Shoal during April 2017 – June 2018 (Xiao et al., in press).

Unlike the consistent annual occurrence of floating *Ulva* in spring (April – June) in Subei Shoal, the bloom of floating *Sargassum* was only detected in 2013, 2017 and 2018 during this period (Fig. 3). The *Sargassum* biomass was much higher than the occurring *Ulva* in 2013 and 2017 (6.49 ± 2.82 g m^{-2}, 14.15 ± 5.87 g m^{-2} by wet weight, respectively). And it was highest in April and declined quickly with a rapid increase of *Ulva* biomass. Although the average biomass of *Sargassum* in 2018 (20.10 ± 9.33 g m^{-2} in wet weight) was higher than that in 2017 (14.15 ± 5.87 g m^{-2} in wet weight), the floating *Sargassum* was restricted in a relatively small area at the peak (April) of 2018 (Fig. 5). So the maximum total biomass of the floating *Sargassum* in 2018 was still lower than that of 2017. The maximum total floating biomass was observed in 2017 when substantial pelagic *Sargassum* biomass widespread in the entire Subei Shoal and even throughout the western YS (Xiao et al., in press).

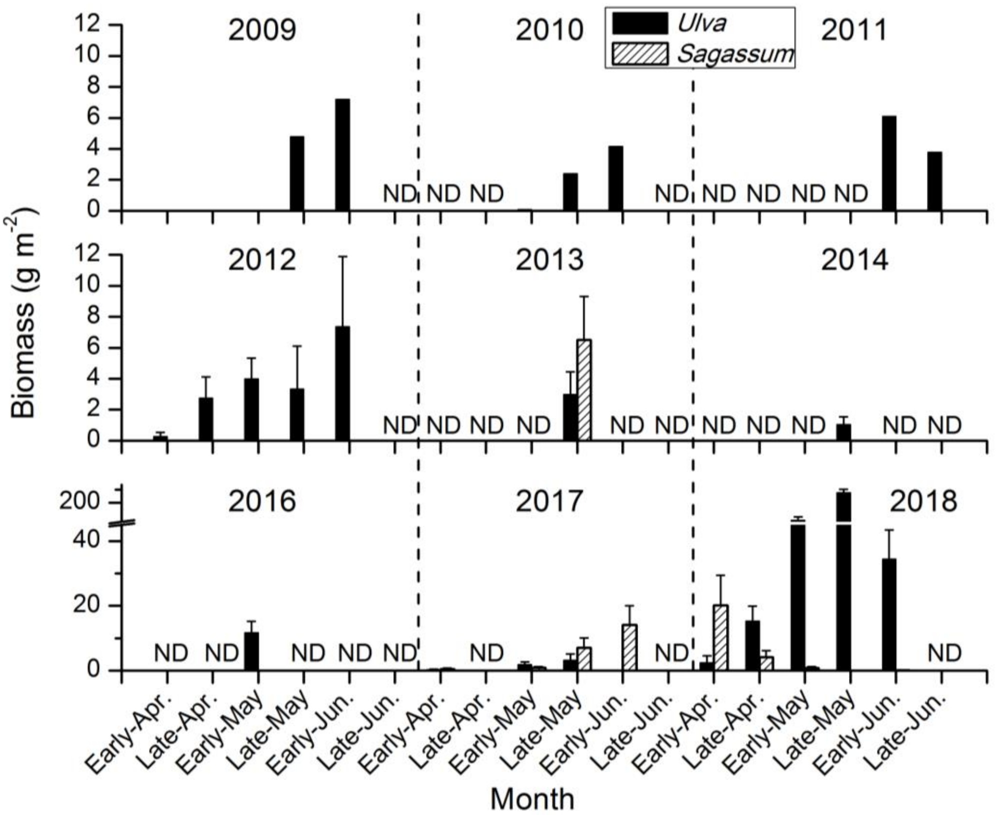

Fig. 5 Inter-annual variation of the average floating biomass, *Ulva* and *Sargassum*, in Subei Shoal during 2009 – 2018 except 2015. ND indicates no data. The Y-axis was

rescaled for 2016 – 2018 due to the high biomass in 2018.

4. Benthic populations of *S. horneri* in China

As described in the Report 1 (Distribution of benthic populations of *Sargassum horneri* along the coasts of Shandong and Jiangsu provinces, and seasonal variation of drifting *S. horneri* in western Yellow Sea), the natural *S. horneri* beds are discretely distributed along the coasts of Liaoning, Shandong and Zhejiang provinces. Only four benthic populations with substantial sustainable biomass and scale were confirmed existing recently (Fig. 6). One was at the coast of Zhangzi Island (northern Yellow Sea), in Dalian of Liaoning Province. One was located at the east mounth of Bohai Sea, Nanhuangcheng Island of Yantai in Shandong Province. The other two were located along the coast of Zhenjiang Province, East China Sea (Gouqi Island of Zhoushan, ZS; Nanji Island of Wenzhou, WZ). Overall, the natural *S. horneri* beds are decreasing in recent years and are limited in the nearshore water of the remote islands, away from the coastline of the mainland (Fig. 6).

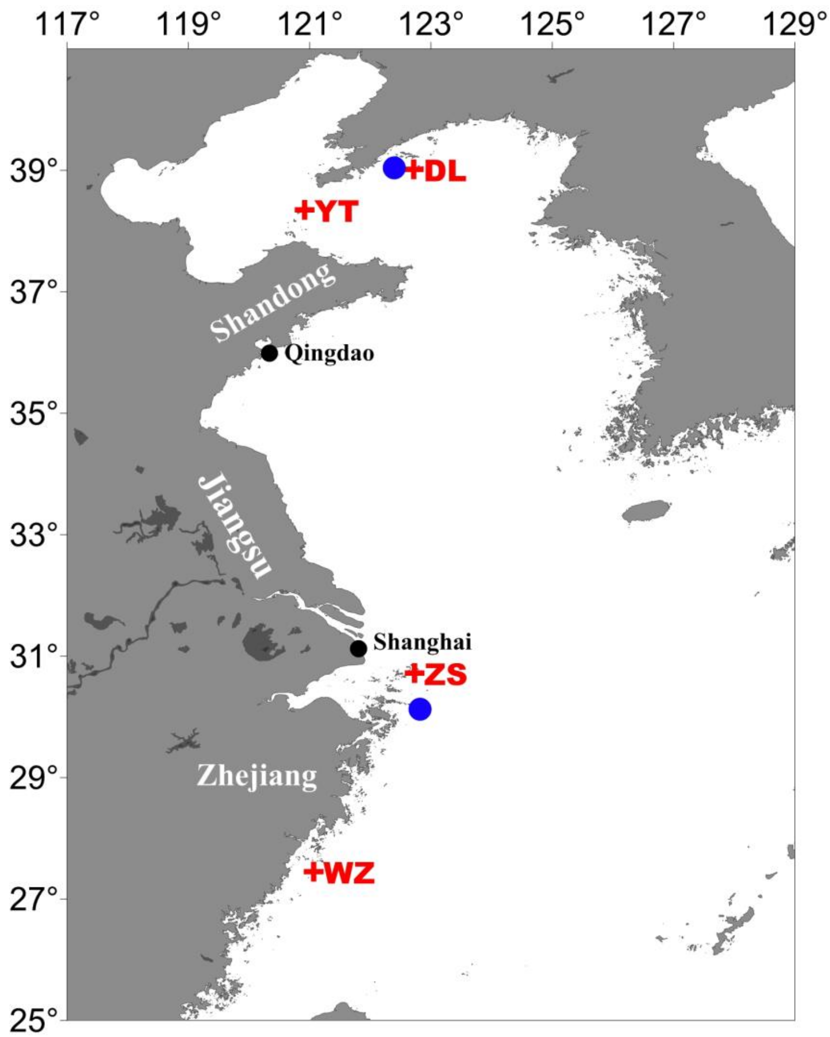

Fig. 6 Distribution of the benthic *S. horneri*. Blue dots are benthic populations from the historical reference (Tseng et al. 1959). Red markers '+' denote the locations of benthic *S. horneri* confirmed in recent research (Pang et al. 2009, Chen et al. 2015, Ren et al. 2015, Lv et al. 2018)

5. Possible reasons for the increasing *S. horneri* blooms in western Yellow Sea

To investigate the possible reasons for the increasing *Sargassum* blooms, we firstly analyzed the origin of the pelagic *Sargassum* biomass. Using the genetic markers, the pelagic *Sargassum* biomass in ECS and YS was confirmed to comprise a single species *S. horneri*. And they were genetically homogeneous with only one polymorphic locus in ITS gene (Report 2 Genetic diversity of benthic and floating populations of *Sargassum* in western Yellow Sea). Using this single polymorphic locus, the genetic composition of the floating *S. horneri* was likely closely related to the benthic population nearby, and existence of alternative haplotypes indicated multiple sources for the floating populations of *S. horneri* in these regions (esp. for the 2017 spring bloom in Subei Shoal). Additional research is ongoing to distinguish the benthic populations of *S. horneri* along the Chinese coasts and to further investigate the detailed structure of the floating populations and their affiliations with any benthic populations.

Field research was further conducted in early 2018 to identify the possible origin and reasons for the initial pelagic *S. horneri*. The survey focused on the coastal water around Gouqi island in Zhejiang Province. In Jan. – Feb., there was no floating biomass was observed. And then sporadic biomass was detected distributing in an area of 112 km^2 in March, around the Gouqi island (Fig. 7). In April, the distribution reached to approximately 28000 km^2, and the floating biomass widespread along the coasts of

Zhejiang Province, crossed the YRE and extended to the southern border of Subei Shoal (Fig. 7B). Field survey further observed substantial *S. horneri* attached on the comm aquaculture rafts around the Gouqi island (Fig. 8). The attached *S. horneri* grew rapidly during Jan. to April and could reach the maximum length of about 3 m (in average) in April. Then the holdfast of the plants withered and *S. horneri* detached from the rafts and floated in the water with substantial vesicles. The detached *S. horneri* from the mussel aquaculture rafts contributed to the floating biomass in ECS, which partially explained the source biomass of *Sargassum* blooms in ECS. Whereas, there are still quite a few unresolved questions regarding this origin, such as the initiation time of the floating *Sargassum* detected by the remote sensing was slightly earlier than that of occurrence of the detached *S. horneri* in field, where the pelagic *S. horneri* biomass comes from and how it maintained the low biomass through winter in western YS (at eastern border of Subei Shoal) etc. Qi et al. (2017) speculated the continuous expansion of *Pyropia* aquaculture along the coast of ECS might be responsible for the recent *Sargassum* blooms in ECS. This hypothesis was not supported by our field data. Based on the field observations, mussel aquaculture, instead of *Pyropia*, was associated with the *Sargassum* blooms. Besides, further research is needed to identify and study the source and mechanism of the winter bloom in western YS.

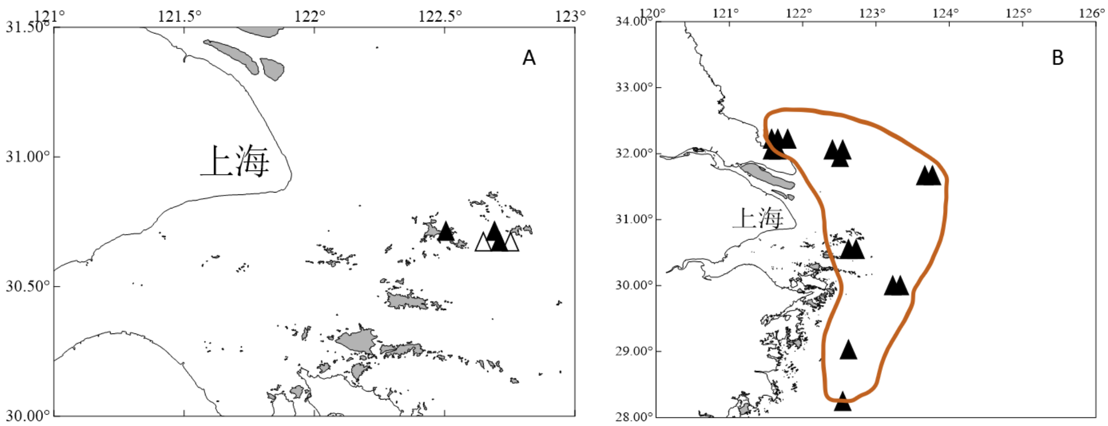

Fig. 7 Distribution of the floating *S. horneri* in March (A) and April (B) in 2018

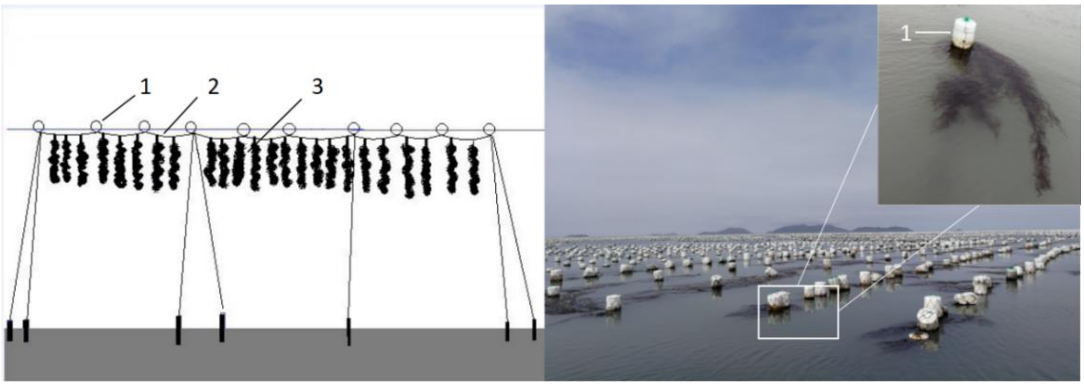

Fig. 8 Diagram of the mussel culture rafts (left) and the *S. horneri* attached on the rafts (right).

Besides the origin and source biomass, environmental factors, such as water circulation, nutrients, surface water temperature etc., could influence the drifting and growth of floating *S. horneri*, and hence regulate the blooms. Analysis on the satellite remote sensing data suggested that record-high water temperature and increased light availability might be ascribed for the bloom in 2017 (Qi et al., 2017). And continuously increased nutrients in the YS, esp. N concentration (Fig. 9), could also support the rapid growth and expansion of the pelagic *Sargassum* biomass and hence result in large-scale blooms. These conclusions, however, need to be corroborated or tested through field observations and experiments on the environmental changes, associated physiological and ecological response of benthic *S. horneri* populations. Furthermore, the water circulation and drifting trajectory of the winter and spring blooms should be investigated to clarify the hydraulic force for the diversified drifting pathways and the possible influencing factors.

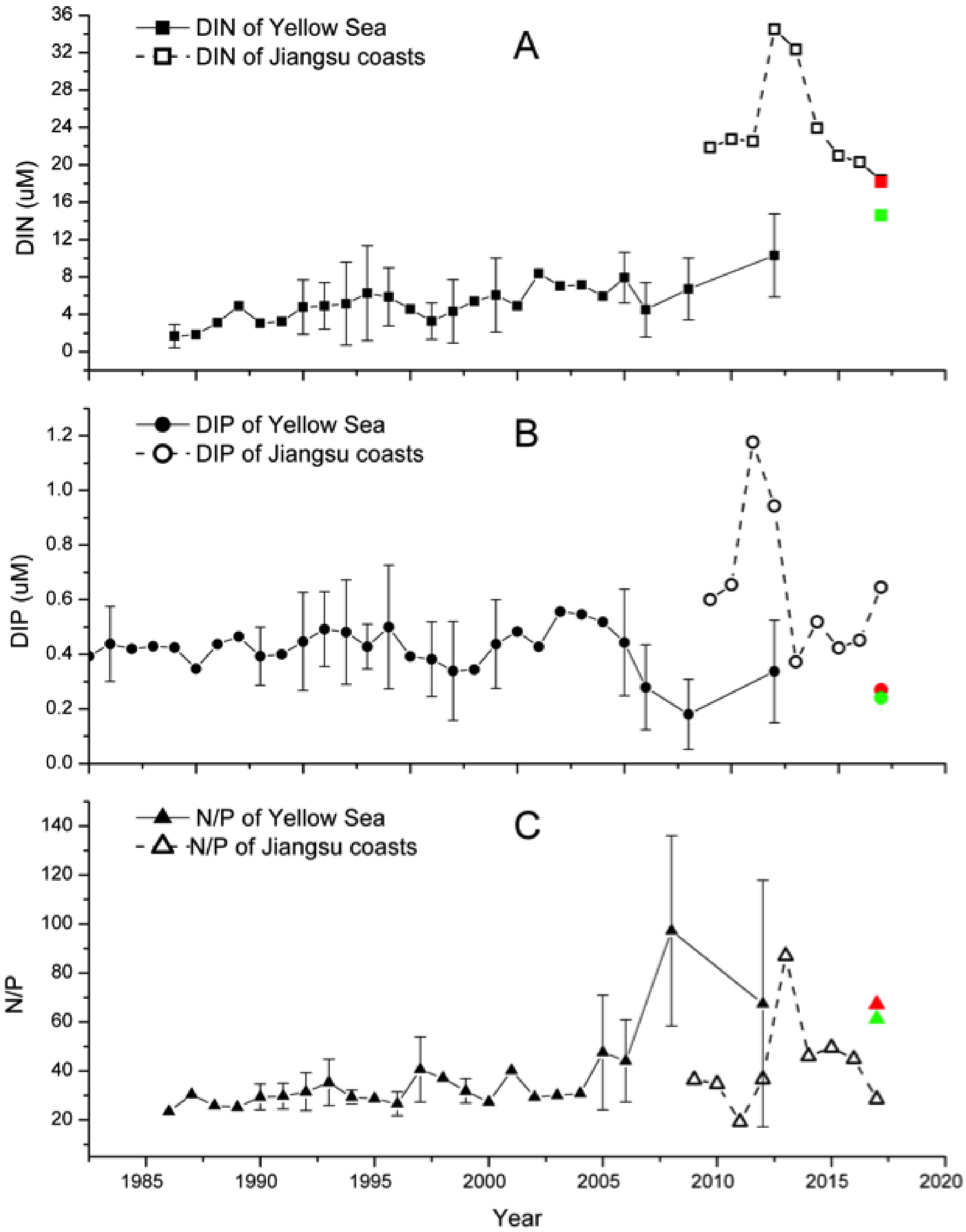

Fig. 9 The average DIN (A), DIP (B) and N/P (C) values in Yellow Sea (solid line and filled symbols) and along the coasts of Jiangsu (dashed line and open symbols) from 1980s to 2017. The colored symbols were average values of Yellow Sea (green) and Subei Shoal (red). The data was cited and redrawn from Li et al. (2015) and Xiao et al. (in press).

6. Summary

Field surveys and remote sensing analyses indicated that the pelagic *Sargassum* biomass was increasingly occurred in ECS and western YS in recent years. Two distinct blooms were detected. The winter bloom was initiated from the southeastern coast of Shandong Province, drifted southward and reached the southeastern coast of Jiangsu Province (including Subei Shoal). The spring bloom was initiated along the coasts of Zhejiang Province, drifted offshore and northward, and intruded into the YS. The biomass from both blooms contributed for the bi-macroalgal bloom in western YS during the spring to summer of 2017. Genetic screening confirmed the pelagic *Sargassum* biomass in ECS and YS comprised a single species *S. horneri*, and could be derived from multiple benthic populations. Four discrete benthic populations of *S. horneri* have been identified along the coasts of Liaoning, Shandong and Zhejiang provinces. The *S. horneri* seaweeds attached on the mussel aquaculture rafts along the coast of Gouqi island (south to the YRE) contributed for the initial floating biomass in ECS. And various environmental factors, such as seawater temperature, light availability, water circulation and nutrients, could regulate or influence the blooming dynamics. Whereas, further research is needed to identify the exact biomass source for the winter *Sargassum* bloom and clarify the bloom mechanism of both winter and spring blooms.

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