Impact of Enteromorpha Blooms on Aquaculture Research Off Qianliyan Island, Yellow Sea, China

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Abstract

Between 2008 and 2016, there were mass summer blooms of Enteromorpha in the Yellow Sea, China. They covered an area of thousands of square kilometers annually, lasting an average of 90 days. Remote sensing data, model predictions, and marine environment ecological data measured by ships before, during, and after the Enteromorpha blooms were used in this study of the Qianliyan Island area. Underwater robots survey trepang, wrinkles abalone, and submarine ecological status. We found that the time taken by Enteromorpha to cover the Qianliyan Island area was relevant, as were changes in sea surface temperature (SST). The Enteromorpha made a rise in inorganic nitrogen, reactive phosphate, and heavy metals content in upper, middle, and bottom layers of sea water, dissolved oxygen (DO) and pH were reduced; and there were changes in the dominant animal and plant population. Enteromorpha sedimentation during outbreaks was measured by benthos sampling. Considerable growth in starfish number was obtained by underwater robot observation. All of this directly influenced the regional ecological environment. Numbers of trepang and wrinkles abalone were declined over the years. Global warming and SST anomalies are the two main reasons for frequent marine disasters that take place. National aquatic germ plasm resources of Qianliyan should be protected from the blooms.

Keywords: Enteromorpha, remote sensing data, SST, trepang, wrinkles abalone, Qianliyan Island

1. Introduction

Large summer blooms of Enteromorpha occurred in the Yellow Sea, China, from 2008 to 2016. These took place in the Yancheng shoals, Jiangsu Province, and covered an area of
thousands of square kilometers, lasting for about 90 days each year. The blooms seriously affected the ecological environment of the Yellow Sea and attracted the attention of scholars [1].

Based on the differences in monitoring spectral caused by Enteromorpha covering the surface of the water, remote sensing data of MODIS data (TERRA/AQUA), image data of GF-1, HJ-1-A/1-B and Landsat-8 and so on, data source were used to study Enteromorpha drift, diffusion, and traceability [1-8]. Because the synthetic aperture radar (SAR) data are not affected by rain clouds, they are beginning to be used in Enteromorpha monitoring [9, 10]. Double polarization and cross-polarization retrieval factors were used to extract information about Enteromorpha on the sea surface. Although SAR has some limitations in the observation of large mass Enteromorpha, compact polarimetric synthetic aperture radar has solved this problem and will play an increasingly important role in such monitoring [11]. Researches show that the growth difference of Enteromorpha is not obvious when temperature is stable but nutrient conditions vary [11]. The growth difference in Enteromorpha is significant when nutrients are stable and temperature gradient is varying. The influence of temperature on Enteromorpha growth is considerable; the alga grows and quickly dies in water at 40°C; when the sea surface temperature (SST) is between 5 and 35°C, it can survive but it cannot maintain normal growth for a long time. In SST of 10–30°C, it grows normally. SSTs between 20 and 25°C are most suitable for growth, and maximum growth takes place at the SSTs of 25°C. Enteromorpha can release spores at SSTs 15–35°C [11]. They are released in great quantities and grow normally when sea water salinity (SAL) is at a range of 12–40 psu; the most favorable range is when SAL is at 28–40 psu. At 32 psu, spore release is at its maximum [12]. The ability of Enteromorpha to adapt to high SAL is greater than its ability to adapt to low SAL. The most suitable conditions for Enteromorpha growth are when SAL is at 24–28 psu and the maximum are when SAL is at 24 psu [12]. Seawater pH values of 5 or 6 prevent Enteromorpha spore release; spore can be released at pH 7–10. A pH value of 9 allows maximum spore release [12]. Enteromorpha absorption of nitrogen and phosphorus is remarkable, the absorptive character for nitrogen and phosphorus have their own characteristics [13]. Wang [14, 15] simulated an indoor Enteromorpha tide using rotting leachate, and indicate that such tides may harm wrinkles abalone in the field. Results confirmed that Enteromorpha exudates, decaying and have an acute lethal effect for wrinkles abalone, shrimps, and trepan. The sulfide and ammonia in the leachate from Enteromorpha decay are the main causes of death of wrinkles abalone. Hypoxia stress for the green tide is an important cause of harm to farmed animals [12]. This chapter will study the impact of Enteromorpha on the ecological environment in the marine national aquatic germ plasm resources of Qianliyan Island, Yellow Sea, China. The greatest impact has been to trepang and abalone yield.

Section 2 provides an overview of the methods and results used to retrieve SST, chlorophyll concentration (CHL), sea state, and wind parameters from remote sensing; SAL and ecological environment data measured by ship. The remote sensing data and site monitoring data are discussed in Section 3, and Section 4 contains our conclusions.
2. Method and results

2.1. Study area and method

The national aquatic germ plasm resources of Qianliyan Island sea area are located in the south Yellow Sea, China, at latitude 36°15′57″ N, longitude 121°23′09″ E. The reserve covers an area of 1766.27 hectares (Figure 1). The specific location of each monitoring station and its contents are shown in Table 1. Experimental Enteromorpha data were collected from the monitoring sites before, during, and after the blooms of 2010–2016. The main protected species in the reserve are the trepang, wrinkles abalone, other varieties of protection are the blue dot mackerel, anchovy, small yellow croaker, hairtail, Penaeus chinensis, Portunus trituberculatus, and Charybdis japonica. The reserve area is 24.8 sea miles distant from land, with no residents and away from the land-source pollution. The Enteromorpha blooms pass this protection zone every year. Remote sensing data (MODIS, Windsat, HY2, and Radarsat2), model prediction, and the marine environment ecological data before, during, and after the Enteromorpha blooms as measured by ships (2010–2016) were used in this research. An underwater robot was used to survey trepang, wrinkles abalone, and submarine ecological status.

Figure 1. Qianliyan Island sea area sketch map, Black grid is core area; slant lines area is experiment area; blace is Qianliyan Island; rectangle ABCD is extract area of remote sensing data; black flag is monitoring station.
2.2. Remote sensing and analysis of monitoring results

MODIS, Radarsat2 data, and the ocean numerical model of the North China Sea Marine Forecasting Centre of SOA, to predict the drift of the blooms, were used to analyze the period when Enteromorpha covered the sea off Qianliyan Island (see Table 2) from 2009 to 2016. The longest duration of an Enteromorpha blooms in the Yellow Sea was in 2012 (106 days); in contrast, the longest off Qianliyan Island was 54 days. Eight-day average MODIS data (resolution of 4 km) were used to retrieve the chlorophyll concentration (CHL) and the SST data; the altimeter data of HY2 were used to retrieve the significant wave height (SWH) and ASCAT data (resolution of 50 km) to retrieve wind field in research area (Figure 1). As Enteromorpha blooms off Qianliyan Island often occurred in June, July, and August, so average SST, CHL, wind field, and SWH change in these months were the main indexes used by remote sensing from 2009 to 2016.

Figure 2a shows that CHL rose significantly in July 2009–2016; this was because SST was between 20 and 25°C (Figure 2c) and so most suitable for the Enteromorpha growth [12]. As the SST in June, July, and August 2012 was between 20 and 25°C (Figure 2c), the duration of the Enteromorpha bloom covering the Yellow Sea and the Qianliyan Island area was the longest (Table 2). The SWH retrieved by HY2 data and at sea level in the research area were at levels 4–5 (Figure 2b). The SWH in July was the highest of these 3 months.

| Year | Began to affect the Qianliyan | End of the impact on the Qianliyan | The time and place of first discovered by satellite | Duration time of Yellow Sea (Day) |
|------|-------------------------------|-----------------------------------|-----------------------------------------------|---------------------------------|
| 2009 | July 7                        | August 4                          | 20th May Outside the sea of Yancheng           | 94                              |
| 2010 | June 30                       | August 12                         | 2nd June Yancheng coast                        | 76                              |
| 2011 | July 14                       | July 29                           | 27th May Yancheng coast                        | 82                              |
| 2012 | June 4                        | July 27                           | 16th May Yancheng coast                        | 106                             |
| 2013 | June 24                       | July 26                           | 10th May Yancheng coast                        | 96                              |
| 2014 | June 12                       | August 3                          | 12th May Yancheng coast                        | 95                              |
| 2015 | June 10                       | August 3                          | 16th May Yancheng coast                        | 93                              |
| 2016 | June 13                       | July 24                           | 11th May Yancheng coast                        | 90                              |

Table 2. The Enteromorpha starting and ending time in Yellow Sea and Qianliyan Island area.
The MODIS Enteromorpha data (resolution of 1 km) were extracted on 06 May, 20 June, 06 July 2012 and on 02, 20 and 29 June 2013 (Figure 3a and b). The Radarsat 2 Enteromorpha data (resolution of 100 m, VV) was extracted on 12 June and 14 July 2016 (Figure 3c). The floating algae index (FAI) was used to the Enteromorpha data [16]. There are wind scale from 3 to 4 in the study area and the advantages by south winds in June and July (Figure 4a and b). In August, the southwesterly wind becomes northwesterly (Figure 4c). These wind fields assist the Enteromorpha blooms in coming ashore. The drift direction of the Enteromorpha blooms was basically consistent with the wind direction.

2.3. Real-time site observation data

Site observation data were measured at different water depths (0.5 m, upper; 10–18 m, middle; and 31.5–34 m, bottom) from ships (Figure 1). Observation data analyzed the impact of
Enteromorpha on the Qianliyan Island area (average data from stations 1, 2, 3, and 4) from 2010 to 2016. Samples were taken in February, March, and May, before Enteromorpha blooms; in July, during the Enteromorpha blooms; and in August, October, and November after the Enteromorpha blooms. Figure 5a shows that the SAL was between 30 psu and 32 psu in February, March, May, July, August, October, and November from 2012 to 2016. This allowed Enteromorpha to grow normally. During the Enteromorpha blooms, the SAL was between 30.8 and 31.7 psu in July of 2013. Spores dispersal is most favored when SAL is 30.5–32 psu [11]. The dissolved oxygen (DO) content of sea water is influenced by biological, chemical, physical, and other factors. When the density of phytoplankton is very great, the high concentrations of chlorophyll-a and active photosynthesis increase the oxygen content of the water. In contrast, when large numbers of phytoplankton die, oxidation is greater than photosynthesis and the DO content of the water falls sharply [17]. DO was clearly lower in upper, middle, and bottom water layers after blooms than before them, from 2014 to 2016 (Figure 5b). We suggest that this was because of Enteromorpha decomposition and settlement. After the large algal blooms, seaweed decomposition release large amounts of ammonium salts into the water, leading to a hypoxic environment and the

Figure 3. Enteromorpha image extraction by MODIS data on 26 May, 20 June, and 06 July 2012(a); 02, 20, and 29 June 2013(b); and on 12 June and 14 July 2016(c) by Radarsat 2 data from an area near Qianliyan Island.
formation of hydrogen sulfide [18]. The inorganic nitrogen concentration (INC) of research area from upper, middle, and bottom layers in August was more than in May, in 2010 and 2015, only upper INC in August 2016 was more than in May 2016 (Figure 5c). In October 2016, the DIN

Figure 4. Average wind field variation in Qianliyan area in June (a), July (b), and August (c) 2009–2016.
of upper, middle, and bottom levels of the research area was more than in May and August of 2016. $H_3PO_4$ is often referred to as reactive phosphate (RP), for around 10% of $PO_4^{3-}$ ion, and the rest are almost all $HPO_4^{2-}$ ion RP in sea water, the main source is input from mineral weathering.

Figure 5. Variations in SAL, DO, INC, RP, COD, PH, oil; and Zn, Cu, Pb, Cd, Hg at surface, middle, and bottom layers of research area. Observation data from ship, 2010–2016.
process and rivers. The RP of August, October, and November was more than in May in 2010 and 2016; but the RP of August in 2015 was less than in May 2015 (Figure 5d). Chemical oxygen demand (COD) as a characterization of the effective index of organic matter content in water, indirectly reflects the degree of organic pollution in a water body. The COD of August was less than in May in 2015 and 2016; but the COD of August was more than that of May in 2010. We found that the COD of August 2010, 2014, 2015, and 2016 was less than that of July 2012 and 2013 (Figure 5e). Death of Enteromorpha lethal effect of micro algae has a strong nutrient that is almost not consumed, but DO and pH got reduced [19]. The pH from upper, middle, and bottom layers in August were less than in May in 2010, 2015, and 2016 (8.10 < pH < 8.30) and the pH of July from upper and bottom layers was between 8.15 and 8.27 in 2012 and 2013. All the pH levels shown in Figure 5f are above 8 and less than 8.5. Enteromorpha spores can be released at this pH level (Figure 5f). Figure 5g shows that the oil content of upper layers in August was higher than those of May in 2015 and 2016, but the oil content in August was less than in May in 2010. The oil content in July 2012 was very low, but in July 2013, it was above 10 μg/L. The Zn content in August was more than in May in 2010 (upper layer) and 2015 (upper, middle, and bottom layers). Concentrations of Cu, Zn, Pb, and As were more than 0.2 mg/L, and Enteromorpha experienced an inhibitory effect on growth [20]. Concentrations of Cd and Hg were less than 0.2 mg/L. Enteromorpha drift introduced oil, Zn, Cu, Pb, Cd, Hg, and As into the reserve (Figure 5g and f) and polluted the environment. The underwater robot (Figure 6a) was used to survey the marine ecological environment in March and May of 2017 from Island 3 and 4 off Qianliyan Island (Figure 1). About 10 trepangs (Figure 6b and c) were distributed at a distance of 1000 m and there were many starfish in this area, but no wrinkles abalone could be found. Monitoring and field investigation data indicated that the total yield of trepang was decreasing yearly in the Qianliyan

Figure 6. (a) The underwater robot; observations of (b, c) trepang, and (d) starfish in March and May 2017.
Island area (Table 3) and wrinkles abalone was rarely discovered. A site survey examined the average value of phytoplankton, zooplankter, and bentonic organisms from stations 1, 2, 3, and 4 found that the index of diversity ($H'$) and degree of dominance ($D_2$) were increasing, abundance ($d$) was declining, and uniformity ($J$) was swinging between the two. There were slight fluctuations in phytoplankton and zooplankton; but the $H$, $d$, and $J$ of bentonic organism have slight fluctuations and Table 4 shows an upward trend.

3. Discussion

The analyses in Section 2.2 and 2.3 found that June, July, and August were the main periods of Enteromorpha cover of the Qianliyan Island area, when the July SST was between

| Time (year) | The sea cucumber yield | Explain |
|------------|------------------------|---------|
| 2000       | 5000 kg                | Two seasons |
| 2011       | 2500–3000 kg           | A year |
| 2010       | 6.33 g/m²              | Local biomass |
| 2012       | 4.53 g/m²              | Local biomass |
| 2013       | 4.22 g/m²              | Local biomass |
| 2014       | 4.41 g/m²              | Local biomass |

Table 3. Annual survey table of the sea cucumber of Qianliyan Island area.

| Time       | Aug 2010 | July 2012 | July 2013 | Aug 2014 |
|------------|----------|-----------|-----------|----------|
| Phytoplankton | $D_2$   | $D_2$    | $D_2$    | $D_2$    |
| $H'$       | 1.98     | 2.32      | 2.45      | 2.05     |
| $d$        | 2.39     | 0.47      | 0.53      | 0.51     |
| $J$        | 0.54     | 0.83      | 0.75      | 0.67     |
| Zooplankter | $D_2$   | $D_2$    | $D_2$    | $D_2$    |
| $H'$       | 1.28     | 1.23      | 1.90      | 2.19     |
| $d$        | 1.39     | 0.84      | 1.15      | 1.34     |
| $J$        | 0.62     | 0.51      | 0.55      | 0.72     |
| Bentonic organism | $H'$  | $H'$    | $H'$    | 10    |
| $d$        | 0.62     | 1.05      | –        | –       |
| $J$        | 0.41     | 0.85      | –        | –       |

Table 4. Biological community characteristics index comparison table. ($D_2$ of bentonic organism has no observational data).
20 and 25°C from 2009 to 2016. The longest Enteromorpha bloom in the Yellow Sea was the 106 days and the longest time off Qianliyan Island was 54 days in 2012. SSTs in June, July, and August were between 20 and 25°C, and suitable for the growth of Enteromorpha. Figure 3 shows that Enteromorpha did not cover the research area, uniformly; nevertheless, it was still found that the July SST and its corresponding CHL were the highest observed for 3 months from 2009 to 2016 (Figure 2a and c). Enteromorpha blooms moved closer to the shore under the action of wind and waves in August (Figure 2b and 4). Site observation data were from Enteromorpha covering Qianliyan Island before the blooms (February, March, or May), during the blooms (July) and after the blooms (August or October) in 2010–2016. The SAL of the research area was between 30 and 32 psu, levels most favorable for Enteromorpha spore dispersal. After Enteromorpha blooms, DO measurements were significantly lower than beforehand. The DIN in August 2015 was higher than that of May. In the INC measurements in August 2016, only the upper layer was higher than that of May. The pH of sea water from the research area from 2010 to 2016 (8 < pH < 8.5) was suitable for release of Enteromorpha spores; and after the Enteromorpha blooms, the pH and COD declined. Enteromorpha outbreaks have introduced heavy metals and petroleum pollution into the Qianliyan Island area and their concentrations have inhibited the growth of Enteromorpha. Benthos sampling in July 2013 found high levels of Enteromorpha on the seabed near the Qianliyan Island area. Table 4 shows that the diversity index has generally increased, while the abundance value has decreased significantly. Uniformity has fluctuated from 2010 to 2016 (except in 2011), and this indicates that the environmental quality of the survey area has declined.

4. Conclusion

Sections 2 and 3, examining the remote sensing data and the site observation data analysis, show that the SST, SAL, pH of the Qianliyan Island area are suitable for Enteromorpha growth and spore release. There is a direct relationship between the SST and the strength or weakness of an Enteromorpha bloom. After a bloom, pH and COD decline. Results of benthos sampling in July 2013 confirm that Enteromorpha settled in the region during June–August. Enteromorpha decomposition is a threat to the survival and reproduction of shellfish and zooplankton, and it has an especially acute, lethal effect on abalone and trepang. In consecutive years, Enteromorpha has covered the Qianliyan Island area, bringing significant effects including DO depression, COD rise, RP, and heavy metals into the research area and polluting the environment. Comparison with the biogenesis characteristics index found that the environmental quality of the survey has declined. Number of starfish increased and shellfish, especially abalone, were damaged. This explains why wrinkles abalone is hardly to be found at present and trepang are decreasing yearly. The subsidence of the Enteromorpha and the rise in SSTs are two main reasons for the decline in the ecological environment off the Qianliyan Island area. To protect the national aquatic germ plasm resources of Qianliyan Island, we need to: (1) halt the growth in starfish numbers; (2) salvage the Enteromorpha blooms when they cover the Qianliyan Island area; (3) reduce human interference; and (4) improve fishery resources and revegetation of the eco-environment.
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