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Analysis of the impact and causes of Enteromorpha prolifera disaster in the Yellow Sea

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Abstract: *The Southwest Yellow Sea is close to Chinese mainland and belongs to the coastal temperate shelf area. In the summer of 2008, the world's largest green tide (mainly Enteromorpha prolifera) event occurred in Qingdao, and every year thereafter, Enteromorpha prolifera disaster events have occurred along the southwest coast of the Yellow Sea. Based on the observation data of Enteromorpha prolifera and the results of previous studies, the influence and causes of Enteromorpha prolifera disaster in the Yellow Sea are analyzed in this paper. It is found that the duration of Enteromorpha prolifera disaster is about 3 months, with significant inter-annual variation characteristics. This helps to provide direct and effective new cognition for the prevention and control of Enteromorpha prolifera from multiple perspectives, and better serve the environmental protection and sustainable development planning of the Yellow Sea.*

Keywords: *Yellow Sea; Enteromorpha prolifera disaster; Inter-annual variation; Analysis of causes*

1. Introduction

The Yellow Sea is located between the Chinese mainland and the Korean Peninsula, connecting the Bohai Sea to the north and the East China Sea to the south, with a relatively wide shoal to the west of the north-south Yellow Sea Trough. The Lunan Trough extends westward from the center of the Yellow Sea Trough into Haizhou Bay between the Shandong Peninsula and the northern coastline of Jiangsu Province, forming an important channel for deep water intrusion into the shallow shoals along the coast of Jiangsu Province, and realizing the water exchange between the middle of the Yellow Sea and the eastern offshore area of Qingdao (Figure 1). Since 2008, the green tide disaster, as a new marine environmental event, has affected the biochemical conditions of China's Southwest Yellow Sea waters every summer. So far, in all the green tide events in the Yellow Sea, six kinds of green algae species such as Enteromorpha prolifera, Blidingia, Intestinalis have been detected, but all of them are dominated by Enteromorpha prolifera. Therefore, the Yellow Sea green tide disaster can be characterized as the Yellow Sea Enteromorpha prolifera disaster basically. In the summer of 2008, the world's largest green tide event occurred in Qingdao, triggering a widespread concern about the environmental conditions in China's offshore waters. The negative concern has been affecting Qingdao and other coastal cities uninterruptedly for more than a decade since 2008[1].

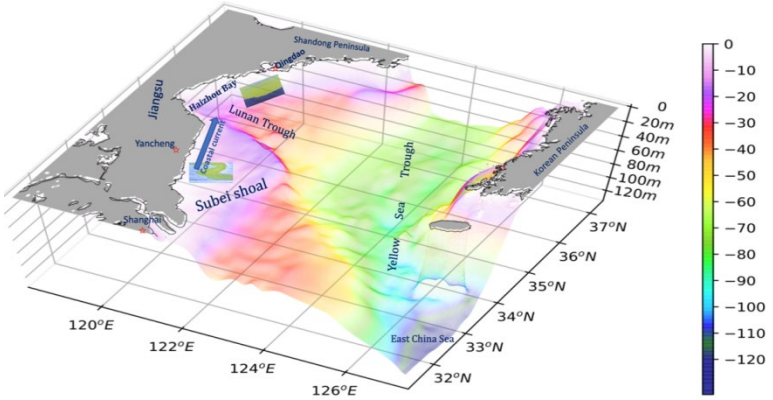

Figure 1: Topographic distribution of the Yellow Sea (color indicates water depth, unit: m)

It is a benthic green algae of the genus Ulva in the family Ulvaceae, with a complex life history. It

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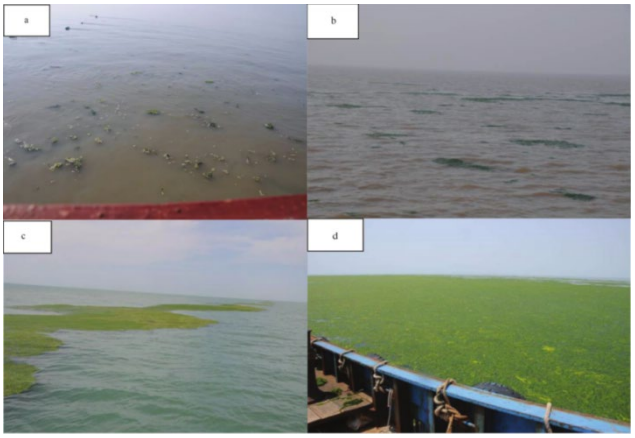
exists on the surface of seawater in a floating state in the early stage, and turns to be suspended in the extinction stage, and generally grows in a diffuse manner according to the morphological order of sporadic algal bodies, small group blocks, stripes and large patches according to the different stages of growth aggregation (Figure 2). Valiela et al. (1997) concluded that large green algal blooms mainly occur in estuaries[2], shallow seas and other waters. Although Enteromorpha prolifera itself is non-toxic, but along with its growth process, it will absorb a lot of oxygen and seize the basic resources needed for the survival of other marine plants and animals. When a large number of Enteromorpha prolifera continues to reproduce, floating with seawater or gathered on the shore, it will also cause the obstruction of navigation channels. The gathered Enteromorpha prolifera rots on the shore, often accompanied by a pungent and fishy odor, which not only pollutes the coastal zone, but also affects coastal fisheries and tourism, and seriously hinders the development of coastal economic activities. This paper collects and organizes publicly available data and relevant studies on the Yellow Sea green tide disasters, focuses on summarizing the time period and impacts of the disaster, and analyzes the causes of the green tide outbreak into a disaster from multiple perspectives[3].



a) sporadic algal bodies; b) small group blocks; c) striped; d) large patches

Figure 2: Schematic diagram of the distribution pattern of different forms of green tide algae in the Yellow Sea (Reproduced from Wang et al., 2018)

2. Time period and affected area of the Yellow Sea Enteromorpha prolifera disaster

2.1. Occurrence time of the Enteromorpha prolifera disaster in the Yellow Sea

Due to its floating properties, the extent of Enteromorpha prolifera is associated with the effects of many dispersal mechanisms, including environmental turbulence, and shear dispersion caused by winds, ocean currents, and tides. It is now widely accepted that the Enteromorpha prolifera that has become a problem in the Yellow Sea originated from rafting areas in the shallow shoals of northern Jiangsu in the southwestern Yellow Sea (Liu et al, 2013; Keesing et al, 2011) and drifted from the outer waters of northern Jiangsu[4]. The shallow depth and strong tidal mixing along the shallow shore of northern Jiangsu, and its proximity to rivers such as the Yangtze River, Sheyang River, and Guanhe River, which enter the sea, reduce salinity and increase nutrient concentrations, all of which provide a good environment for Enteromorpha prolifera to grow (Fan et al, 2015).

According to the North Sea Region Marine Hazards Bulletin (hereinafter referred to as the Bulletin) issued annually by the North Sea Bureau of the Chinese Ministry of Natural Resources from 2008 to 2021 (Table 1), Enteromorpha prolifera was detected in the area off Yancheng, Jiangsu Province (34.2°N, 121.5 °E) using satellite remote sensing as early as 10 May (2013 and 2016) and as latest as 2 June (2010). Data provided by the National Aeronautics and Space Administration (NASA) of the United States indicated that the Qingdao Enteromorpha prolifera could be traced to the Sheyang River and nearby waters in Jiangsu Province in 2008, and in 2009 to the distribution area with the center of 33.02°N, 121.45°E (Lu et al., 2014). The distribution of Enteromorpha prolifera basically reached its extreme value in mid-to-late June of that year, and then gradually disappeared in mid-to-late August, with an average duration of about 3 months[5].

ISSN 2616-5872 Vol.5, Issue 2: 9-14, DOI: 10.25236/AJEE.2023.050202

Table 1: Yellow Sea Enteromorpha prolifera monitoring information table (compiled from the North Sea Region Marine Hazards Bulletin), "/" indicates the lack of monitoring records

Year	Date of discovery of green tide	Duration/day	Maximum area date	Date of disappearance
2008	14 May	110	/	1 September
2009	20 May	94	/	22 August
2010	2 June	76	/	17 August
2011	27 May	82	/	22 August
2012	16 May	107	13 June	30 August
2013	10 May	97	30 June	14 August
2014	12 May	95	14 July	15 August
2015	16 May	93	19 June	14 August
2016	10 May	85	25 June	2 August
2017	14 May	68	19 June	20 July
2018	16 May	/	29 June	Mid-August
2019	22 May	/	17 June	Early-September
2020	21 May	/	23 June	Late July
2021	17 May	/	21 June	Late August

2.2. Affected area by Enteromorpha disaster in the Yellow Sea

Figure 3 shows the maximum coverage area and the maximum distribution area of Enteromorpha prolifera in the Yellow Sea from 2008 to 2021 based on the annual-issued Bulletin, with the bars representing the distribution area and the line representing the coverage area[6]. The maximum distribution area represents the daily area of the area enclosed by the boundary of Enteromorpha prolifera reaches its extreme value, and the maximum coverage area represents the actual existence and coverage of seawater area of Enteromorpha prolifera, because Enteromorpha prolifera is generally banded distribution, the spacing between the bands can reach more than 1 km. In the past 14 years, since the outbreak of Enteromorpha prolifera in Qingdao coastal area in 2008, the maximum distribution area of enteromorpha prolifera reached the maximum in 2009 and 2021, respectively, and the minimum in 2020. The maximum distribution area of Enteromorpha prolifera increased year by year from 2008 to 2009, 2012 to 2016, 2017 to 2019, 2020 to 2021; while from 2009 to 2012, 2016 to 2017, 2019 to 2020, the maximum distribution area of Enteromorpha prolifera decreased compared with the previous year[7].

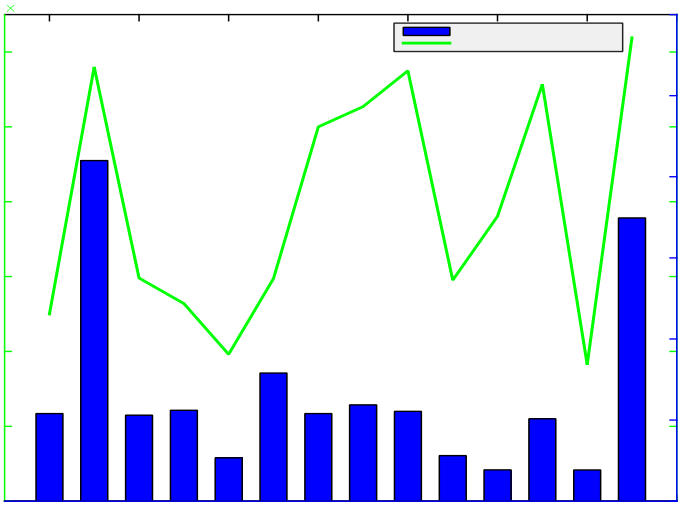


Figure 3: Maximum distribution area and coverage area of Enteromorpha prolifera in the Yellow Sea from 2008 to 2021

In addition, the interannual variation of Enteromorpha prolifera is reflected in both the characteristics and regularity of drifting paths. By compiling and analyzing the drift path of Enteromorpha prolifera from 2008 to 2015 after it exceeded 34.5°N to the north, Guo et al. (2016) divided them into three cases accordingly: 1) northwestward perpendicular to the shoreline (2008, 2011), landing in Lianyungang, Qingdao and Rizhao, causing negative impacts; 2) northeastward

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parallel to the shoreline (2009, 2012), with only a little green tide arrived at the coast, and the harm was relatively weak; 3) northwestward drift to near shore and then turned to northeastward drift along the coast (2010, 2013, 2014, 2015), at this time the Enteromorpha prolifera caused a large impact on the coast of Jiangsu and Shandong[8].

3. Causes of the Yellow Sea Enteromorpha prolifera disaster

3.1. Growth factors of the Enteromorpha prolifera itself

Enteromorpha prolifera is a benthic green algae of Ulva Prolifera genus of Ulva Family, which is highly adaptable to the environment and can survive and reproduce under a wide range of temperature and salinity conditions, with no special requirements for sunlight and water quality. In summer, the Enteromorpha prolifera mainly exists in floating form in the southwest Yellow Sea coast in the early stage of development. Xia et al. (2009) carried out a multidisciplinary comprehensive investigation on the causes of Enteromorpha prolifera outbreak in the sea area of 120°E-122°E, 33.3°N-36°N from July 9 to July 14, 2008, which coincided with the period of Enteromorpha prolifera outbreak in that year, and the investigation obtained the surface and 10 m layer temperature in the southwest Yellow Sea[9]. The average temperature of the surface and 10-meter layer of the Southwest Yellow Sea was 23.22°C and the average salinity was 30.75, which both were in the optimal range (20°C-35°C temperature, 29-31 salinity) for the growth and reproduction of Enteromorpha prolifera (Wang et al., 2007).

At the same time, the upwelling between the shoal of northern Jiangsu and the center of the Yellow Sea provided nutrients for the outbreak of Enteromorpha prolifera. The average value of dissolved oxygen, as an important index reflecting the biological growth and pollution status in the southwest Yellow Sea area, was 9.22mg/L, indicating that Enteromorpha prolifera in the southwest Yellow Sea maintained strong photosynthesis and good physiological state. The temperature, salinity and dissolved oxygen provided the material basis for the outbreak of Enteromorpha prolifera along the coast of the Southwest Yellow Sea. Secondly, compared with other green algae, Enteromorpha prolifera has the characteristic of short-term rapid absorption of reserve nutrients, which is conducive to its seizure of ecological niches and becoming a dominant species in the process of proliferation (Kim et al., 2013). As a result, the strong reproductive capacity of Enteromorpha prolifera might be one of the main reasons of green tide outbreak [10].

3.2. The importance of material conditions for the growth of Enteromorpha prolifera

Conditions such as temperature, salinity and nutrients are the material basis for the growth of Enteromorpha prolifera, but these conditions may not be the most significant factors affecting the inter-annual variability of Enteromorpha prolifera during the annual occurrence of Enteromorpha prolifera events in the Yellow Sea. It was found that the most suitable temperature for the growth of Enteromorpha prolifera in the early stage is 15°C-20°C and 2008, 2009 and 2013 were the three years with serious outbreak of the Enteromorpha prolifera. Usually in May, the seawater temperature near the Enteromorpha prolifera outbreak is higher 1°C-2°C than in most years, however, the temperature in 2008, 2009 and 2013 showed a decreasing trend, especially in the southwest of Lianyungang, the sea water temperature was only 13°C, which was not the best temperature for Enteromorpha prolifera growth, indicating that the sea water temperature was not the decisive factor for the inter-annual difference of Enteromorpha prolifera growth. In addition, the distribution of sea surface temperature in May was similar in 2008 and 2010, but the outbreak time of Enteromorpha prolifera in 2008 was about 15 days earlier than that in 2010, which can also confirm this point [11].

3.3. Effects of wind and ocean circulation

In addition to the strong adaptive capacity of Enteromorpha prolifera itself, external transport factors also play a very important role in the outbreak of Enteromorpha prolifera. Although Enteromorpha prolifera breaks out every year along the coast of Qingdao, but its origin is located in the shallows of northern Jiangsu. The aquaculture industry in the shallows of northern Jiangsu is usually sown in September-October, and harvested in March-April of the following year. At this time, the seaweed breeding raft used in the production cycle will be removed to prepare for the next breeding cycle, the green algae attached to the raft were cleaned up and became the origin of the outbreak.

Therefore, wind and ocean circulation may affect the spread and outbreak of Enteromorpha

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prolifera in the Yellow Sea. Qiao et al. (2011) used a state-of-the-art coupled wave-tide-circulation numerical model to investigate the drift path of Yellow Sea Enteromorpha prolifera in summer 2008 and concluded that the Enteromorpha prolifera affecting Qingdao offshore came from the outer waters of northern Jiangsu Province, which to some extent reflects the transport role of the northward coastal current in northern Jiangsu, suggesting a link between the ocean circulation and Enteromorpha prolifera outbreak to a certain extent. Wei et al. (2020) similarly identified the northeast expansion of the shallow waters of northern Jiangsu as an important physical driver of Enteromorpha prolifera dispersal in summer. It can be said that the northward transport of coastal currents in northern Jiangsu in spring and summer provides an important driving force and pathway for the movement and dispersal of Enteromorpha prolifera from the shoals of northern Jiangsu to the waters of Lunan Trough[12].

4. Conclusion

Since 2008, green tide disasters have occurred every summer along the Yellow Sea coast, and the species source is mainly Enteromorpha prolifera. By analyzing the occurrence time and affecting area of the Yellow Sea Enteromorpha prolifera disaster, it is found that there are obvious inter-annual variation characteristics, which is related to the strong environmental adaptability of the Enteromorpha prolifera itself, and the external transport factors also play a very important role in the outbreak and disaster of Enteromorpha prolifera. Although Enteromorpha prolifera breaks out in Qingdao coast every year, but its birthplace is located in Subei shoal. Moreover, Enteromorpha prolifera outbreaks mainly depend on the availability of enough seeds, sufficient sunlight, and adequate nutrient sources. Over the years, global changes have provided important environmental factors for the outbreak of Enteromorpha prolifera, and the eutrophication of seawater caused by excessive human economic activities is also an important reason for the outbreak of Enteromorpha prolifera. Therefore, in the face of such a large amount of Enteromorpha prolifera, how to turn waste into treasure and use it for our own benefit is also one of the issues that need to be considered first and foremost.After years of exploration, a standardized scientific process has been formed for Enteromorpha prolifera disposal. After dewatering and compressing the salvaged Enteromorpha prolifera, factory disposal is carried out to make a variety of seaweed organic fertilizers from Enteromorpha prolifera as raw material. In addition, methane, or biogas, can be produced after the death of the Enteromorpha prolifera. Biogas is clean energy and biogas stations can be built, then using ready-made gas pipelines, biogas could be transported to thousands of households and used for cooking, boiling water and heating, etc. In the face of the invasion of Enteromorpha prolifera, one can also use satellite remote sensing, helicopters, sea cruises, near-shore monitoring, Enteromorpha prolifera tracker and other means to increase monitoring/forecasting and information comprehensive judgment, timely adjustment of marine interception forces, optimize near-shore interception network deployment, the full implementation of marine interception of Enteromorpha prolifera.Secondly, it is worthy to mention that "nori seaweed culture" has not been recognized by all people. Someone think that the ocean current monitoring and surveillance of Enteromorpha prolifera is mainly concentrated in Jiangsu waters, no matter what time and place it is found, it will be concluded that the earliest sea area found is Jiangsu waters. At the same time, the growth and development of algae is very much influenced by the seawater temperature, and the sea area of Jiangsu reaches the most suitable temperature for the growth of Enteromorpha prolifera certainly earlier than Shandong, which is easy to make people think that Enteromorpha prolifera is formed in Jiangsu and then drifted to the north. Therefore, it is suggested here that surveillance and monitoring should be carried out on a larger scale, and multiple measures should be taken to achieve certain results in the Enteromorpha prolifera interdiction war for sure. At present, Shandong and Jiangsu Provinces are carrying out the front salvage work. According to the deployment, Shandong Province set three lines of defense to prevent and control the green tide of Enteromorpha prolifera. Jiangsu Province promotes algae removal operation and raft recovery, and supervises and rectifies the problems found in the farming enterprises such as Enteromorpha prolifera into the beach and bamboo poles into the sea. This Enteromorpha prolifera interdiction war will continue in the coming period.Finally, it is interesting to note that among the three types of Enteromorpha prolifera drift paths mentioned earlier, the three years with more serious disasters (2008, 2009 and 2013，Guo et al. (2016)) were respectively distributed in different paths. This may indicate that the differences in sea surface circulation caused by factors such as monsoon differences in the sea area when the Enteromorpha prolifera disaster occurs may cause different green tide drift paths in different years, but is not related to the severity of the Enteromorpha prolifera outbreak. Therefore, only under the premise of fully understanding and establishing the connection between the Yellow Sea circulation and Enteromorpha prolifera, we can start from the study of the inter-annual changes of ocean circulation, and then study

ISSN 2616-5872 Vol.5, Issue 2: 9-14, DOI: 10.25236/AJEE.2023.050202

the pathway of Enteromorpha prolifera and the extent of the disaster, and propose more direct and effective new measures for the prevention and control of Enteromorpha prolifera, so as to better serve the environmental protection and sustainable development planning of the Yellow Sea.

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