Marine Pollution Bulletin 58 (2009) 888–895

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

World's largest macroalgal bloom caused by expansion of seaweed aquaculture in China

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ARTICLE INFO

Keywords:
Macroalgal bloom
Green-tide
Seaweed aquaculture
Enteromorpha prolifera
Porphyra yezoensis
Qingdao

ABSTRACT

In late June 2008, just weeks before the opening of the Beijing Olympics, a massive green-tide occurred covering about 600 km^2 along the coast of Qingdao, host city for Olympic sailing regatta. Coastal eutrophication was quickly attributed with the blame by the international media and some scientists. However, we explored an alternative hypothesis that the cause of the green-tide was due to the rapid expansion of *Porphyra yezoensis* aquaculture along the coastline over 180 km away from Qingdao, and oceanographic conditions which favoured rapid growth of the bloom and contributed to transport of the bloom north into the Yellow Sea and then onshore northwest to Qingdao. At its peak offshore, the bloom covered 1200 km^2 and affected 40,000 km^2. This is the largest green-tide ever reported, the most extensive translocation of a green-tide and the first case of expansive seaweed aquaculture leading to a green-tide. Given similar oceanographic conditions to those that occurred in 2008, these green-tides may re-occur unless mitigation measures such as those proposed here are taken.

1. Introduction

The excessive growth of some species from green algae, such as, *Ulva*, *Enteromorpha*, *Chaetomorpha* and *Cladophora*, has been reported in the formation of macroalgal blooms or green-tide events in many parts of the world including Europe, North America, South America, Japan and Australia (Fletcher, 1996; Morand and Briand, 1996; Hiraoka et al., 2004; Morand and Merceron, 2005; Merceron et al., 2007). These green algae are able to respond rapidly to excess nutrients especially when water temperature conditions are favourable to their growth (Fletcher, 1996; Hernández et al., 1997; Valiela et al., 1997; Raffaelli et al., 1998; Morand and Merceron, 2005). Typically green-tides are characterised by choking of waterways in the immediate area of the bloom and subsequent local wind and tide driven local deposition on the shore, and this can be destructive to coastal marine habitats (e.g., seagrass) and cause economic losses to marine industries (e.g., fisheries and tourism) (Nelson et al., 2008).

In late June 2008, the waters and shores of the Olympic sailing events' Qingdao venue on China's north-eastern coast experienced a massive green-tide covering ~400 km^2 (China Ocean News, 2008a) (Fig. 1). The green-tide lasted over two weeks and the resultant cleanup involved more than 10,000 people and removed over one million tonnes of algae from the beach and coast of Qingdao (China Ocean News, 2008b). The green-tide was comprised of *Enteromorpha prolifera* (Muell.) J. Agardh (Chlorophyta, Ulvophyceae) which has been previously reported as one of the dominant benthic algae in the littoral zone of China (Lin et al., 2008), but the morphology and vegetative growth habit of the species means that it can also grow in drift form when dislodged from the substrate (Liang et al., 2008). The first reported bloom along the Chinese coastline was a small scale *E. prolifera* green-tide in Qingdao in July 2007 (China Ocean News, 2007). It did not arouse much attention until in June of 2008 when a large-scale bloom occurred with potential to impact the Olympic Games in August 2008. Although the water quality of Qingdao coasts has been greatly improved in recent years (Guo et al., 2007; Cui et al., 2008), the initial causes were attributed to coastal eutrophication and the action of tides and wind in bringing the algae ashore by the media and some scientists (China Ocean News, 2008b, c; Herald Sun, 2008; Daily Mail, 2008). Our investigation looked for events at a more regional scale and discovered the source for the green-tide occurred far from Qingdao and attributed the causes to the rapid expansion of *Porphyra yezoensis* aquaculture and favourable oceanographic conditions in Yellow Sea.

2. Material and methods

To investigate the possibility of non-local sources for the Qingdao green-tide, a time series of remotely sensed images and the related oceanographic parameters (wind, current and temperature)

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doi:10.1016/j.marpolbul.2009.01.013

Fig. 1. Green-tide of Qingdao, China, in summer of 2008.

in Yellow Sea were compared and analyzed in order to explain the formation and translocation of the green-tide.

The satellite data using to seek out the area of green-tide are Moderate Resolution Imaging Spectroradiometer (MODIS) level1b data from NASA data distribution system (NASA data distribution system, http://ladsweb.nascom.nasa.gov), which are composed of bands red, green and blue (7, 2 and 1). The treatment of georeferencing, land–water demarcation and clouds removal was given in these satellite data for obtaining the clear images. The area of green algae was calculated by setting a threshold value of NDVI (normalized difference vegetation index) for green-tide pixels and summing up the areas of detected small green patches. Based on these scattering green patches, the bound was circled using ellipse and the elliptical area was calculated for assessing the influence region.

Daily sea surface temperature (SST) and vector wind were obtained from MODIS (NASA data distribution system, http://oceancolor.gsfc.nasa.gov) and SeaWinds scatterometer (Remote Sensing Systems in Santa Rosa, California, USA, http://www.ssmi.com/qscat/) for calculating the monthly average.

Hydrodynamic model output was taken from the Japan Coastal Ocean Predictability Experiment (JCOPE) (Kagimoto et al., 2008; Miyazawa et al., 2008) and accessed at http://www.jamstec.go.jp/frcgc/jcope/. The results of this ocean forecasting system have been applied with caution. The model uses both wind and satellite altimeter data and the latter is limited utility in nearshore situations.

To determine the extent of expansion in *P. yezoensis* aquaculture, the official reported data from the Jiangsu Ocean and Fisheries Bureau (http://www.jsof.gov.cn) and previous publications (Ni, 2006; Shang et al., 2008) were used in this study. The photos showing the *E. prolifera* fouling of the *P. yezoensis* aquaculture system were taken in situ at Lianyungang.

Calculation of nitrogen load in algae removed in cleanup of Qingdao green-tide was as follows. About one million tonnes of *E. prolifera* were removed in the cleanup of the Qingdao green-tide in the lead up to the Olympics (China Ocean News, 2008b). The wet weight of the congeneric algae *E. intestinalis* is known to be seven

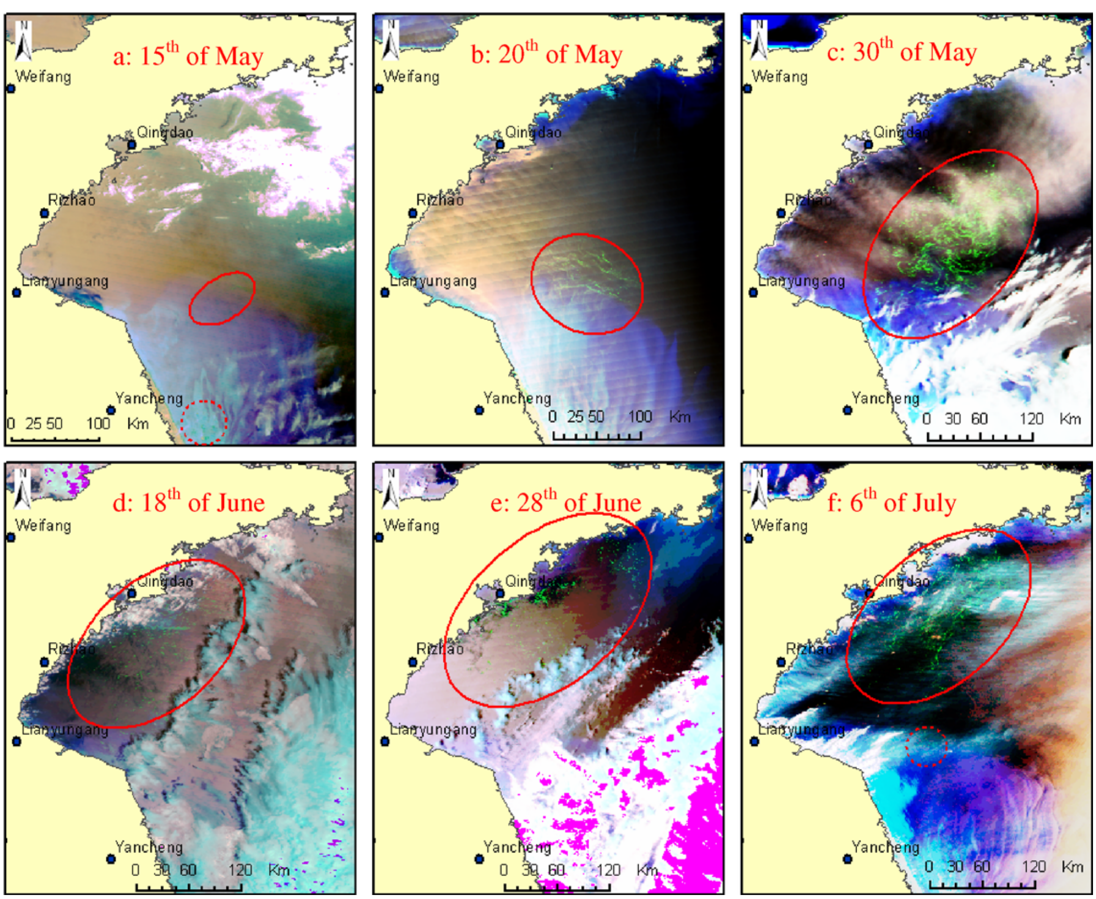

Fig. 2. (a–f) The pathway of green-tide formation in the north-eastern coast of China, in summer of 2008, showing in satellite images (Data source: NASA data distribution system, http://ladsweb.nascom.nasa.gov; the patches of green-tide in red circles).

times its dry weight (Kamer and Fong, 2000), thus the dry weight equivalent of algae removed was 142,857 tonnes. The nitrogen content of *E. intestinalis* is 20 mg per gram dry weight (Fong et al., 1994). Thus the nitrogen content of algae removed was 2857 tonnes. The average nitrogen content of human sewage is 4.5 kg per person per day (Drangert, 1998). Thus the nitrogen content of algae removed from the Qingdao green-tide was the equivalent of sewage load from just 634,921 people in one year.

Table 1
The area of green-tide during the transportation in Yellow Sea (area covered: the sum value of total small algal patches; area impacted: the area of red ellipse in Fig. 2).

Date (DD-MM-YYYY)	Area covered (km^2)	Area impacted (km^2)
15-05-2008	80	1000
20-05-2008	160	5000
31-05-2008	1200	40,000
28-06-2008	600	24,000
06-07-2008	650	25,000

3. Results

3.1. The pathway of green-tide

Analysis of the remotely sensed images of the Yellow Sea off north eastern China (Fig. 2a–f) confirmed the possibility of non-local sources for the Qingdao green-tide. The period of 15th May to 28th June 2008 shows an evolving algal bloom as numerous large green patches, spreads across as much as 40,000 km^2 (e.g., Fig. 2c), and demonstrates the time course in growth of algal biomass and the direction of movement of the patches (Fig. 2a–f). On the 15th of May (Fig. 2a) some small green patches covered about 80 km^2 (Table 1) were evident near the coasts of Yancheng and Lianyungang, Jiangsu province. Five days later (20th of May), the green patches from Yancheng moved away from the coast and accumulated a green area about 160 km^2 affecting a total of 5000 km^2 along the nearby coast of Lianyungang (Table 1 and Fig. 2b). Ten days later (30th May, Fig. 2c), the green patches had grown rapidly and covered about 1200 km^2 impacting 40,000 km^2 (Table 1), and they crossed out of the Jiangsu province and moved into the middle of

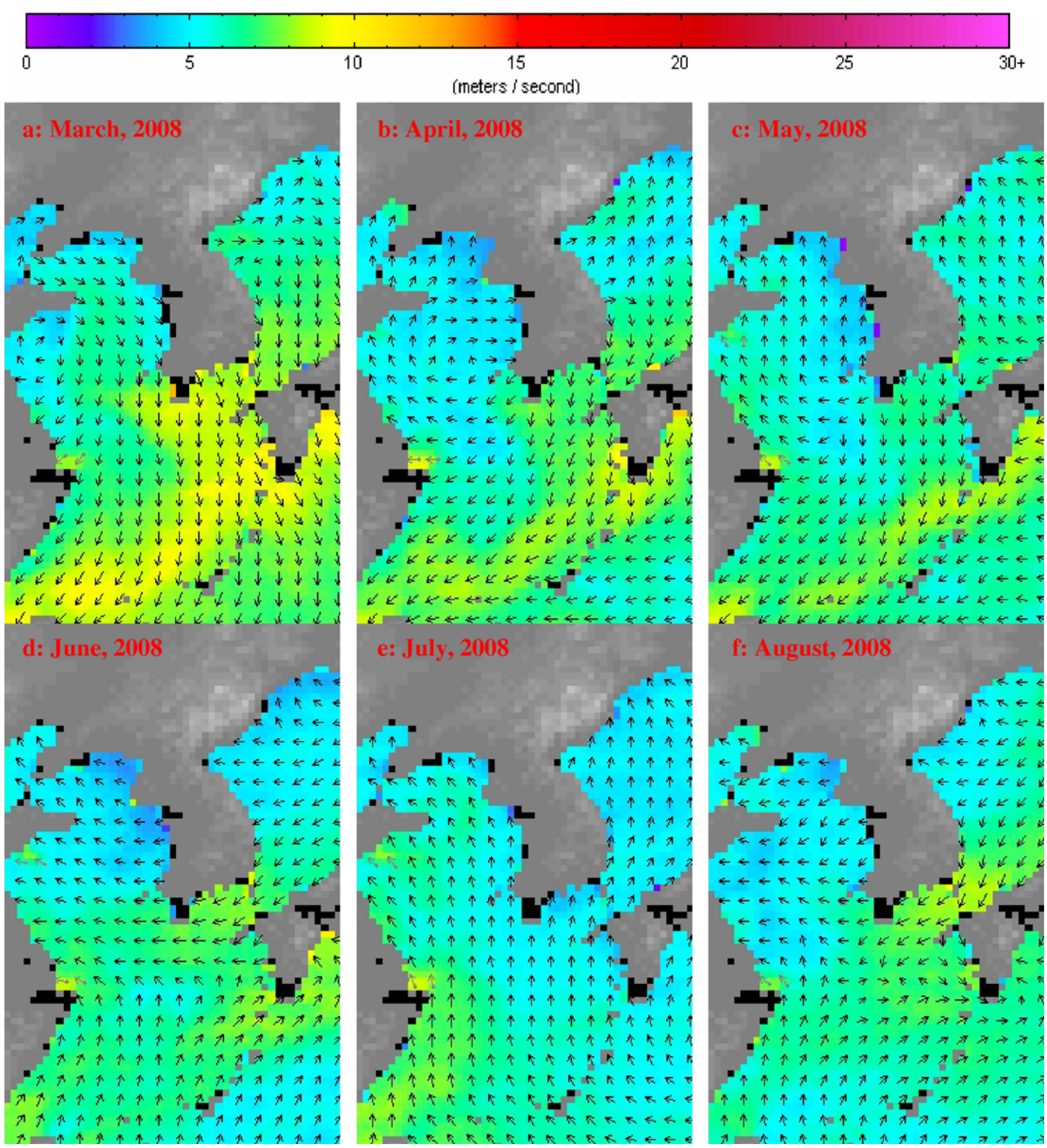

Fig. 3. (a–f) The monthly wind speed and direction in spring and summer of 2008 in the north-eastern coast of China (Data source: Remote Sensing Systems in Santa Rosa, California, USA, http://www.ssmi.com/qscat/; the grey part stands for the land and black for no data).

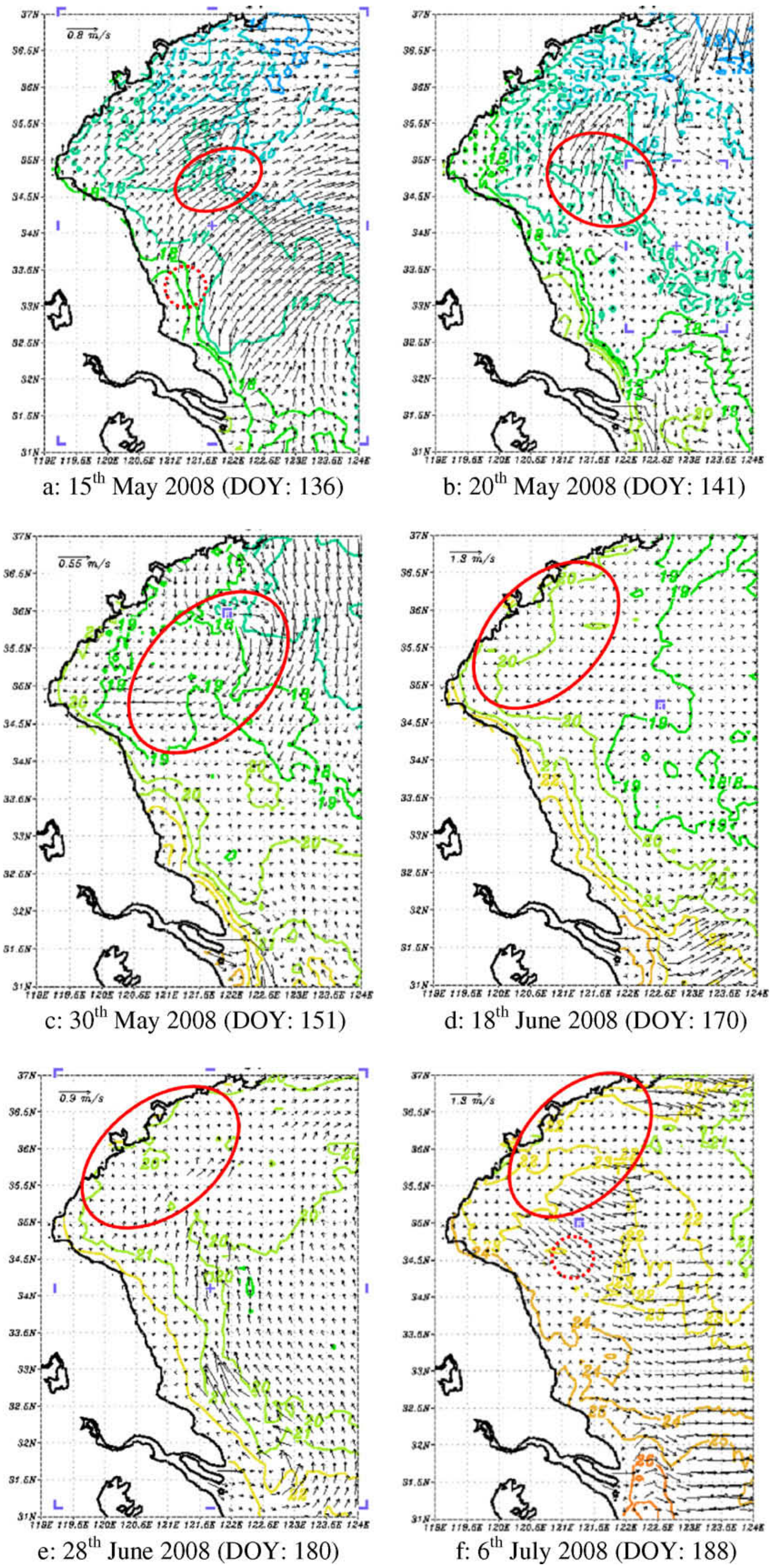

Fig. 4. Modeled current direction and speed for western region of the Yellow Sea. The red ellipses correspond to those on Fig. 2. (Source: Japan Coastal Ocean Predictability Experiment (JCOPE); a description of the model and how it is forced can be found at http://www.jamstec.go.jp/frcgc/jcope/htdocs/jcope_system_description.html).

the Yellow Sea near to Qingdao, Shandong province. On the 18th of June (Fig. 2d), the large green patches began to move towards the coast of Qingdao, and landed on 28th of June (Fig. 2e) and formed a massive green-tide covering 600 km^2 along the coast of Qingdao (Table 1 and Fig. 2f). Thus we are able to trace the evolution and transport of the *E. prolifera* bloom from near the coasts of Yancheng and Lianyungang in Jiangsu province in mid May 2008 until its deposition as a green-tide in Qingdao in late June.

3.2. The oceanographic conditions in Yellow Sea

There is still no clear understanding of the circulation patterns of the Yellow Sea. However, previous studies showed that the circulation of Yellow Sea is under the influence of a monsoon wind-system and of oceanic current changes at its southern boundary (e.g., the Yellow Sea Warm Current (YSWC), the Yellow Sea Bottom Cold Water (YSBCW) and the Changjiang Diluted Water (Su and Weng, 1994; KORDI, 1998). Surface ocean current patterns in eastern Yellow Sea are predominantly wind driven controlled by the East Asian Summer Monsoon (Naimie et al., 2001). During May to July 2008 the pattern of south-west and south-east summer winds (Fig. 3a–f) were consistent with the movement of the *E. prolifera* patches from near Yancheng to Qingdao. Analysis of the predicted current patterns for the area is also consistent with this pattern of movement (Fig. 4a–f). Modelled current direction and speed for western region of the Yellow Sea in May 2008 (Fig. 4a and b) indicates the possibility to bring the green algae off shore and to the north, then, during the period of bloom development, transport and deposition, there are slight and variable currents which could have kept the bloom in the same region over an extended period and gradually moved it on shore (Fig. 4c–f).

Although these figures are model output and cannot be regarded as exact, there are no patterns that would shape to move the bloom out of the west-central Yellow Sea and when considered with the wind data (Fig. 3a–f) and the known climatology for currents in the region (Naimie et al., 2001), these patterns support our interpretation of the timing and direction of development and transport of the bloom. Thus, wind and current patterns provide a clear mechanism to assist the northward drift of the bloom and to facilitate the onshore transport of the large accumulated biomass of algae.

The sea surface temperature (SST) (Fig. 5a–e) during the time of the bloom growth and translocation ranged from 13–16 °C in May to 16–20 °C in June. Much lower temperatures (4–10 °C) occurred before this period from March to April and much higher, up to 26 °C in July after the peak of the bloom.

3.3. The origin of the *E. prolifera*

Having confirmed the pathway of bloom growth and transport and identified the possible source of the bloom, we next sought to

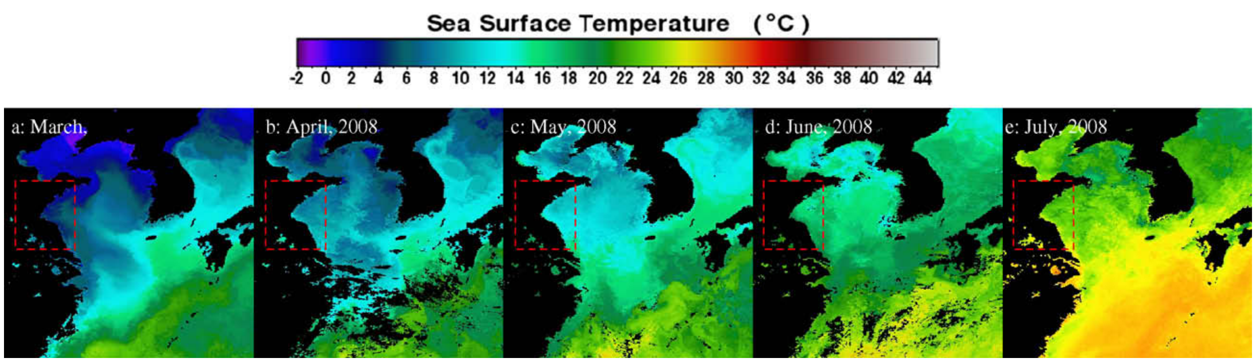

Fig. 5. (a–e) The variations of sea surface temperature (SST) during the formation of green-tide (Data source: NASA data distribution system, http://oceancolor.gsfc.nasa.gov; the part showing in black colour is land or clouds; red rectangles showing the area of green-tide).

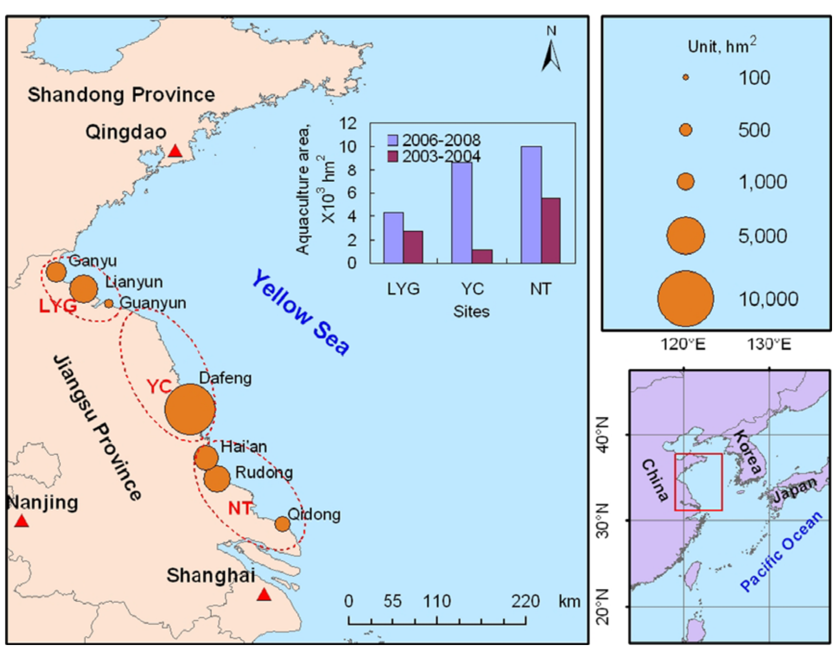

Fig. 6. The distribution and increased areas of *Porphyra yezoensis* aquaculture in Jiangsu province, China during 2003–2008 (LYG: Lianyungang; YC: Yancheng; NT: Nantong; Data source: Jiangsu Ocean and Fisheries Bureau and previous publications (Ni, 2006; Shang et al., 2008)).

Fig. 7. (a–c) The semi-floating rafts for the aquaculture of *Porphyra yezoensis* (a: coast of *P. yezoensis* aquaculture; b: *E. Prolifera* growing on the raft; c: the harvesting time of *P. yezoensis* for showing the *E. Prolifera* attached on ropes and rafts).

determine the origin of the *E. prolifera* which seeded the bloom. Lianyungang, Yancheng and Nantong are three main coastal cities near to the appearance of small green patches in satellite image (Fig. 2a). Over the last 5 years, the coastal area used for *P. yezoensis* aquaculture in these cities has increased from 9460 ha in 2003 to 22,974 ha in 2008 (Fig. 6). As well, *E. prolifera* is the main green algae reported to affect the production of *P. yezoensis* aquaculture (Wang et al., 2007; China Ocean News, 2008d). Our investigations centred on the possible relationships between the troublesome association of *E. prolifera* with the recent rapid expansion of the edible seaweed *P. yezoensis* aquaculture in the Jiangsu province of China and the culture method and seasonal harvesting procedures.

P. yezoensis is cultured on the coast with semi-floating rafts made of bamboo and rope net curtain (Fig. 7a), which are seeded in the middle of October and harvested at the beginning of May (Shang et al., 2008). *E. prolifera* grows along with *P. yezoensis* by attaching to the net curtain and rafts used for aquaculture (Fig. 7b). The thalli of *E. prolifera* are able to drift in the water following their removal during the harvesting and washing of the seaweed and during cleaning of ropes, rafts and other attachments (Wang, 1992; Personal communication) when *P. yezoensis* is harvested in May (Shang et al., 2008). We hypothesize that these floating fragments kept growing in the water and due to the actions of tide or winds formed small green patches visible in satellite photos. The appearance of these patches of green algae in the satellite photos in 15th of May (Fig. 2a) near to the area of *P. yezoensis* aquaculture support this hypothesis and lead us to suggest this is the source of the bloom which resulted in the green-tide at Qingdao 6 weeks later.

4. Discussion

Our investigation provides compelling evidence that the Qingdao green-tide was a result of:

1. The biomass of *E. prolifera* associated with the rapid expansion of aquaculture of *P. yezoensis* seaweed in the coastline of Jiangsu province, China together with its method of culture and harvesting.
2. The pathway of *E. prolifera* transportation through the Yellow Sea offshore from the coastline of Jiangsu province.

Here we discuss the coincident favourable oceanographic conditions (temperature, wind and current) for the transportation and rapid growth of the *E. prolifera* bloom and their deposition in Qingdao, combined with the physiological characteristics of *E. prolifera*.

The observed pattern of south-west and south-east winds and surface current during the time of formation and transport of the bloom is typical and prevalent in the summer (May–August) of 2008 in the coastal areas of the Yellow Sea and these oceanographic patterns provide a clear mechanism to assist the northward drift of the bloom and to facilitate the onshore transport of the large accumulated biomass of algae.

During the period of transport the size of the *E. prolifera* bloom grew very significantly and this growth is consistent with the physiological growth parameters known for this and other green-tide algae and the environmental conditions at the time. Previous studies on eight marine algal species associated with green-tides have found that temperature plays a vital role on controlling their growth rate (Taylor et al., 2001; Largo et al., 2004). These species included species of *Enteromorpha* and *Ulva* closely related to *E. prolifera.* The optimal growth rates for all eight species were between 15 and 20°C. *E. prolifera* has been estimated to grow at a rate of 10–37% per day in the field and was measured to grow at 23% per day under laboratory conditions (Liang et al., 2008). The closely related *E. linza* grows optimally at 15 °C at a rate of 14% per day (Taylor et al., 2001). The sea surface temperature (SST) for the region during the time of the bloom growth and translocation was 13–16 °C (May average) at the start and 16–20 °C (June average) at the end (Fig. 4a–e), which indicated that the optimum temperature for the growth of *E. prolifera* ranged from mid of May to end of June. Thus optimal temperature conditions for *E. prolifera* existed at the time of the formation and growth of the Qingdao bloom. Although sufficient light and nutrient availability is also important for optimal growth, conditions favouring the growth of *E. prolifera* are likely to have been encountered during the 42 day period of bloom growth and translocation, and depending on the growth rate it is conceivable that the biomass of the *E. prolifera* may have increased by between 10^2 and 10^5 times.

The 2008 Qingdao green-tide was a new phenomenon while the coastal eutrophication of the Yellow Sea are typical (Cui, 2000; UNDP/GEF, 2008). Monitoring data for the Yellow Sea over the past eleven years indicates that there has been an overall decline in the concentration of active phosphate and inorganic nitrogen (UNDP/GEF, 2008). For example, active phosphate was at a peak of 0.024 mg/L in 1995 but declined to 0.003 mg/L in 2003; the concentration of inorganic nitrogen in the Yellow Sea was 1.90 mg/L in 1995 but declined to 0.58 mg/L in 2004 (UNDP/GEF, 2008). Indeed our calculations indicate that the nitrogen content of the *E. prolifera* removed from the Qingdao coast is equivalent to the amount of nitrogen in human sewage produced by just 635,000 people in a year. However, there are approximately 4.4×10^7 people living in the coastal provinces of the Yellow Sea (UNDP/GEF, 2008), and there are about 4.68×10^6 people in Lianyungang and 4.6×10^6 people in Yancheng. Thus, eutrophication can not be the primary cause of green-tide and that any measures to reduce nitrogen pollution in the short term are unlikely to prevent future green-tides sourced by *P. yezoensis* aquaculture.

Although this event indicates an increasingly urgent need to reduce the nutrient pollution of coastal seas, this problem is likely to be intractable in China in the medium term. The rapid expansion of *P. yezoensis* aquaculture in Jiangsu province provides a greatly enhanced source of *E. prolifera* and seems very likely to be responsible for the massive green-tide that occurred in Qingdao. Such green-tides may re-occur if similar oceanographic conditions were to prevail in future years. As an urgent alternative we propose to prevent the source of the bloom occurring through improved hygiene; preventing disposal of *Enteromorpha* into the sea during the harvesting of *P. yezoensis* and cleaning of culture rafts.

5. Final considerations

In comparison with previous reviews of green-tide events (Fletcher, 1996; Morand and Briand, 1996; Hiraoka et al., 2004; Morand and Merceron, 2005), this is the largest green-tide ever reported anywhere in the world. It also represents the largest known translocation of any green-tide and the satellite images presented here demonstrates that similar to phytoplankton blooms (Gjøsæter et al., 2000), under suitable oceanographic conditions green-tides can move large distances adding huge biomass and causing significant damage far from their source. Mass cultivation of valuable seaweed has been encouraged as a remediating measure for tackling eutrophication of coastal waters in China and some other countries (Cuomo et al., 1993; Lüning and Pang, 2003; Fei, 2004). However, consequences such as those we have described here can not only outweigh intended benefits but also transmit the negative consequences far from the source, even potentially from one country to another.

Acknowledgements

We thank Shanglin Wang for the photo of *P. yezoensis* aquaculture and Peter Thompson and Ming Feng of CSIRO for reviewing the manuscript and for helpful discussions on prevailing ocean currents. Tennille Irvine of CSIRO helped prepare some of the figures. This work was supported by two projects from CAS and Shandong (Nos. 2007GG2QT06019 and KZCX2-YW-Q07-04) and by CSIRO's Wealth from Oceans Flagship.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.marpolbul.2009.01.013.

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