Chapter 16
Green Tides of the Yellow Sea: Massive Free-Floating Blooms of *Ulva prolifera*

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16.1 Introduction

Marine and estuarine ecosystems are undergoing various environmental pressures ranging from anthropogenic nutrients to climate change, which have resulted in a series of negative consequences, including biodiversity loss, ecosystem function deterioration, species outbreaks, and many other changes (Duarte 2009). Macroalgal blooms, an expanding worldwide phenomenon, are a form of HABs that frequently occurs along many coasts and estuaries. The macroalgal blooms formed by green algae [e.g., *Ulva* (*Enteromorpha*), *Chaetomorpha*, and *Cladophora*] are usually referred as "green tides" (Fletcher 1996). Most studies have demonstrated that increased nutrient loads, most often derived from land and human activities, are the dominant causes for these macroalgal blooms (Lapointe 1997; Valiela et al. 1997). In oligotrophic coral reefs and rocky shores, reduced grazing pressure related to overfishing has also been identified as being involved in a cascading effect controlling algal biomass and buffering the impact of nutrient enrichment (Burkepile and Hay 2006). Macroalgal blooms can produce a number of undesirable effects on marine and estuarine ecosystems, e.g., reducing benthic diversity and abundance, replacing seagrass meadows and algal beds, impacting the health of coral reefs, killing commercial shellfish and fish, releasing hydrogen sulphide (H_2S) and ammonia (NH_3) with harmful effects on fauna and humans during decomposition, and

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stimulating phytoplankton blooms after decomposition (Valiela et al. 1992, 1997; Raffaelli et al. 1998; Nelson et al. 2008). Recent studies revealed that *Ulva* is an efficient carrier of toxic organic pollutants and heavy metals, and a bloom can greatly increase the risk of mid-trophic-level consumers and pose a health threat to humans (Cheney et al. 2014).

Generally, macroalgal blooms are confined within estuaries or coastal bays, but in recent years, massive free-floating macroalgal blooms have appeared, including two extraordinary cases, the "green tide" caused by *Ulva prolifera* in the Yellow Sea, China, since 2007 (Liu et al. 2013; Zhou et al. 2015), and the "golden tide" caused by *Sargassum* spp. in the Atlantic Ocean, USA (Gower and King 2011). Such blooms can cover thousands of square kilometres, have trans-regional or transnational impacts, require expenditure of billions of dollars for cleanup and emergency responses, and create large financial losses in aquaculture and tourism industries (Liu et al. 2013; Smetacek and Zingone 2013). Therefore, it is important to understand much more about this novel phenomenon, e.g., the mechanisms stimulating these massive macroalgal blooms, the species involved, and their ecological consequences. In this chapter, we summarize current knowledge on the massive free-floating macroalgal blooms in the Yellow Sea, China, and present the scientific questions for future research related to the ecological and economic impacts, aiming to provide sufficient information for understanding this important phenomenon.

16.2 Green Tides in the Yellow Sea

In summer of 2007, China Ocean News gave the first report on the free-floating green tide in the Yellow Sea (China Ocean News 2007, http://epaper.oceanol.com/zghyb/20070720/index.htm>). The bloom had been detected using satellite images and had reached a sea coverage of approximately 82 km^2 (Keesing et al. 2011). That report did not arouse much attention until late June 2008 when millions of tons of algal biomass blocked the waters and shores that were being used for the Olympic sailing events in Qingdao (Fig. 16.1). Eventually, over 16,000 people and 600 boats were involved in the algal cleanup to guarantee that the Olympic Games events could proceed and the safety of coastal activities. This involved removal of more than 1 million tons of green algae from the coast (Zhou et al. 2015). Costs for the cleanup and the emergency response were estimated at about 200 million RMB (approximately equal to US$30 million), and the economic losses for marine aquaculture industries and tourism were more than 500 million RMB (approximately equal to US$71 million) (Ye et al. 2011). In the following 8 successive years, green tides with a magnitude of at least a million tons of biomass and a coverage of thousand square kilometres have reoccurred every summer in the Yellow Sea (Table 16.1), and it is hard to see this situation changing in the near future. Since 2008, numerous reports and scientific articles related to the onset of green tides in the Yellow Sea have been published discussing the causative species, environmental mechanisms, and proposed mitigating policies. Here, we summarize the known information on this unique phenomenon.

Fig. 16.1 Green tides in Qingdao coast (from Zhou et al. 2015)

Table 16.1 Records of green tides in the Yellow Sea during the summer of 2008–2015

Year	Maximum distribution (km^2)	Maximum coverage (km^2)	Location of early-bloom occurrence (Jiangsu coastline)	Date of bloom formation	Date of bloom disappearance	Bloom duration (days)
2008	25,000	540	Yancheng	May	September	110
2009	58,000	2100	Yancheng	May	August	94
2010	29,800	530	Yancheng	May	August	76
2011	26,400	560	Yancheng	May	August	82
2012	19,160	267	Yancheng	May	August	106
2013	29,733	790	Yancheng	May	August	96
2014	50,000	540	Yancheng	May	August	95
2015	52,700	594	Yancheng	May	August	93

Data sources are from the Bulletin of Marine Environmental Status of China (2008–2015) published by the State Oceanic Administration People's Republic of China

Although the initial search for the cause of the green tide during these events focused on the coastal eutrophication of the Qingdao environment, and the action of tides and winds in bringing the algae ashore (e.g., Sun et al. 2008), a series of satellite images clearly demonstrated that the massive green tide actually formed in a broad regional area across the southern Yellow Sea (Fig. 16.2a–e). Small floating green algal patches were found to have initiated in the coast of Jiangsu province

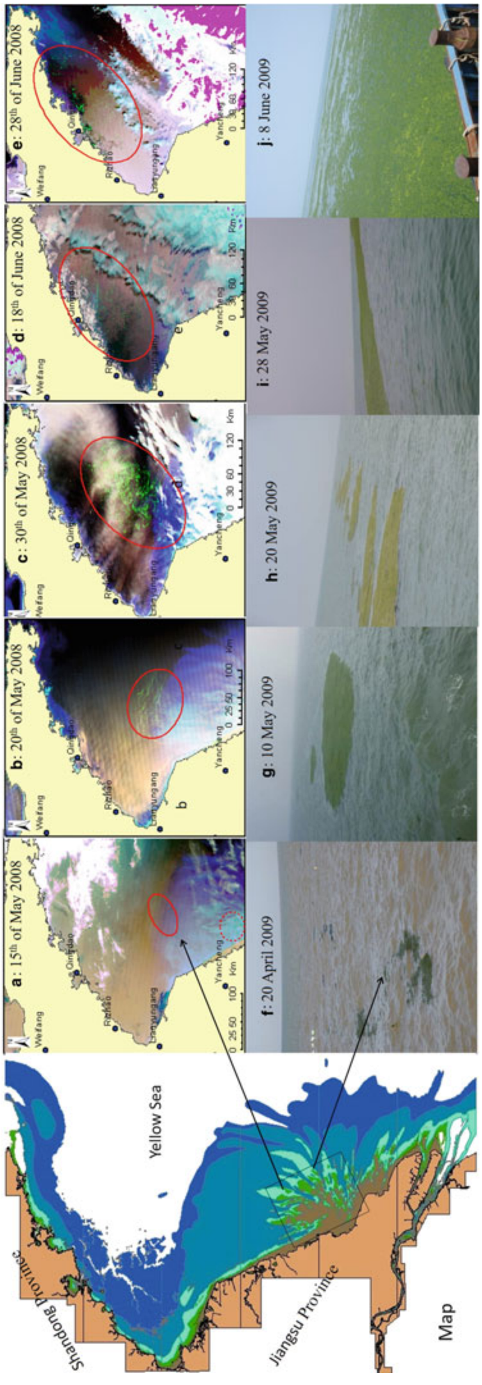

Fig. 16.2 Satellite and field observations of green tide formation in the Yellow Sea (Map, showing the initial location of *Ulva* source (black square: Subei Shoal) along the Jiangsu coastline; (**a–e**), satellite images during May to June of 2008 showing the trajectory of the green tides in the Yellow Sea initially originated from the Jiangsu coast and drifted to Shandong Province over time (the images are cited from Liu et al. 2009); (**f–j**), field observations during April–June of 2009 showing the development and aggregation of free-floating algal mats drifting from the coast of Subei Shoal to the offshore area (from Liu et al. 2010)

near to Subei Shoal (Yancheng) in early May (Table 16.1; Fig. 16.2f–h). In the process of drifting during May to July of 2008, these small patches aggregated and grew rapidly (Fig. 16.2i–j), producing extraordinary amounts of algal biomass, which were eventually scattered across an area of coastal sea of about 84,109 km^2, with a maximum algal mat coverage of 3489 km^2 (Keesing et al. 2011). Similar bloom processes in the Yellow Sea have repeatedly occurred since 2008, and the bloom duration in each summer can last approximately 3 months, but the first location of bloom formation always started from the Subei Shoal (Yancheng) (Table 16.1). Driven by surface currents and southwest and southeast winds, these floating green algae are transported more than 200 km northward in the Yellow Sea, from the Jiangsu coast to the Shandong coast, with most of the biomasses landing in the southern coast of Shandong resulting in severe ecological and environmental damage (Liu et al. 2009; Keesing et al. 2011).

A few species have been identified from the floating green algal canopies based on morphological and genetic analysis, including *Ulva compressa*, *U. flexuosa*, *U. intestinalis*, *U. linza*, *U. pertusa*, and *U. prolifera*, although *U. prolifera* was confirmed to be the dominant species (e.g., Liu et al. 2010; Wang et al. 2010; Duan et al. 2012; Zhang et al. 2015). Evidence from experimental and physiological ecology showed that *U. prolifera* has a number of adaptive physiological traits, including efficient photosynthesis, rapid growth rates, high capacity for nutrient uptake, and diverse reproductive systems which allow it to form impressive biomass within 2 months, when weather in the Yellow Sea is optimum in summer. Xu et al. (2012) found photosynthesis genes of C_3 and C_4 in *U. prolifera* and the key enzymes of C_4 metabolism which can enhance the algal capacity for carbon (C) fixation, biomass accumulation, and environmental adaptation. *U. prolifera* has a diverse reproductive system, including sexual, asexual, and vegetative propagation (Lin et al. 2008); 1 square centimetre of blade can release up to 6 million spores or 27 million gametes, and 92–97% of the spores can germinate (Zhang et al. 2013). The growth rate of this species can reach to 10–37% per day in the field depending on the weather conditions (Liang et al. 2008; Li et al. 2009; Tian et al. 2010). The important reproductive routes to guarantee growth rate of *U. prolifera* during green tide formation are propagation of vegetative fragments and asexual zoospores (Zhang et al. 2011). Moreover, *U. prolifera* displays a high capacity for nutrient uptake, its V_{max} has been shown to increase with increased NH_4^+ concentrations, and it can reach a maximum of 421 mmol g^{-1} DW h^{-1} (Tian et al. 2010). These physiological advantages are important for sufficient proliferation to generate a massive green tide.

16.3 Source of Green Algae in the Yellow Sea

Satellite images in 2008 clearly indicated that the trajectory of the green tides in the Yellow Sea originated from the Jiangsu coast. Liu et al. (2009, 2010) proposed that the biomass source came from the cleaning of fouling green algae at facilities used for more than 20,000 ha of *Porphyra* aquaculture along the Jiangsu coastline. These mariculture activities have expanded nearly 10,000 ha since 2006 in Subei Shoal (Fig. 16.3a, b), a region characterized by large-scale coastal sand ridges (Fig. 16.2). These fouling green algae, including *U. prolifera*, grow on the bamboo poles and ropes used for *Porphyra* aquaculture (Fig. 16.3c), and they are routinely scraped off the poles and ropes after the harvest of *P. yezoensis* in mid-April. The dates of routine removal of green algae coincided with satellite observations of the first occurrence of green patches in the Yellow Sea in late April or early May, just 2 weeks after the *Porphyra* harvest. Although there were different theories about the initial source of propagules for green tides of the Yellow Sea, e.g., Pang et al. (2010) proposed that the propagule source of green tides might have been microscopic germlings of *U. prolifera* produced in coastal crab and shrimp aquaculture ponds situated along the northern coast of Jiangsu province, most satellite evidence and field surveys over the last 5 years point to the *Porphyra* culture rafts in Subei Shoal as an important nursery source for green tides (Zhou et al. 2015; Wang et al. 2015; Fan et al. 2015).

Subei Shoal is the largest intertidal mudflat in China, with an approximate area of 22,740 km^2. It is about 200 km long and 100 km wide and has a pinwheel shape (Fig. 16.2). The unique radial geomorphology of the sand shoals affects the tidal current and results in eddies forming in the deep channels between the sand shoals (Du 2012); tidal residual currents, combined with dominant southeast wind-driven currents and resultant upwelling between the Jiangsu coast and the western Yellow Sea during May to July, appear to play important roles in transporting the floating algae from coast to offshore (Keesing et al. 2011; Liu et al. 2013; Bao et al. 2015). Sea surface temperatures (SST) in the Yellow Sea during May to June generally ranged from 10 to 24 °C, which is optimal for *U. prolifera* (Keesing et al. 2011, 2016). Meanwhile, high dissolved inorganic nitrogen (DIN) concentrations in coastal waters of the Yellow Sea support the growth demand of green algae. Monitoring data shows that DIN concentrations in more than 50% of the coastal areas have exceeded 14 μM since 2003 (State Oceanic Administration 2008–2012). Li et al. (2015) reported that DIN concentrations in the summer survey of 2012 were generally more than 23 μM in the adjacent sea of Subei Shoal. Isotopic N signatures of samples of green tide thalli confirmed sources of nutrients present in the Yellow Sea were available to the macroalgae (Liu et al. 2013; Keesing et al. 2016). $\delta^{15}N$ signatures in the thalli of green algae attached to the mariculture rafts ranged from 14 to 25‰, indicating the significant impact of aquaculture, agriculture, and wastewater discharges on coastal water quality in the Yellow Sea (Keesing et al. 2016).

These findings clearly support the conclusion that the extraordinary macroalgal blooms in the Yellow Sea are triggered by a chain of complex events, with human activities (*Porphyra* aquaculture, nutrient-enriched seawaters) interacting with natural geohydrodynamic and climatic conditions (sand shoals, currents, temperature, wind). This has allowed *U. prolifera*, with distinct physiological traits (efficient photosynthesis, rapid growth, high nutrient uptake rates, and diverse reproductive strategies), to proliferate sufficiently to generate massive green tides.

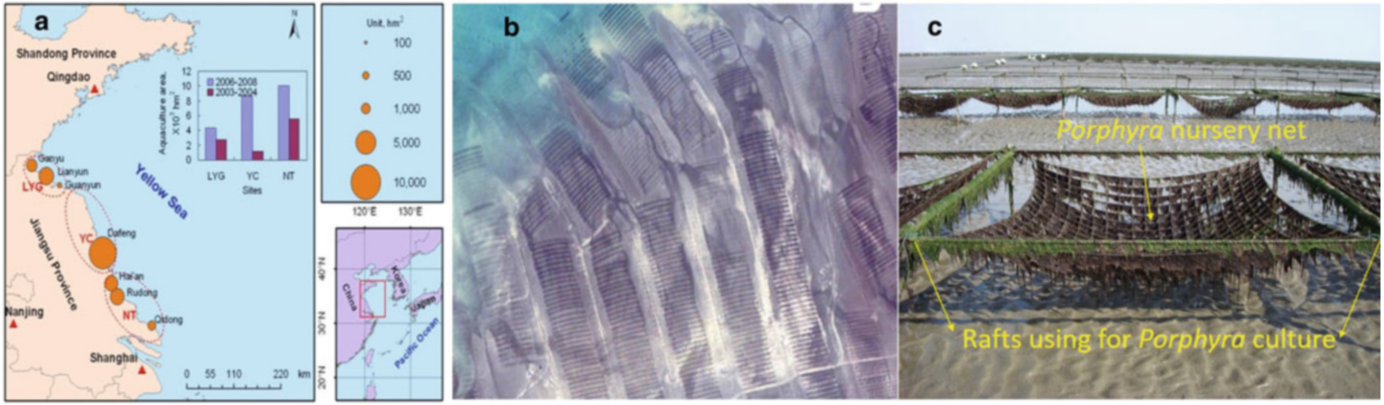

Fig. 16.3 The links between *Porphyra* aquaculture and fouling green *Ulva* fronds. (**a**) Expansion of *Porphyra* aquaculture area (hm^2) along the Jiangsu coastline (cited from Liu et al. 2009); (**b**) Google Map showing the *Porphyra* aquaculture facilities on sandy shoal; (**c**) green *Ulva* fronds growing on support facilities used in *Porphyra* culture (cited from Liu et al. 2010)

16.4 Implications and Future Research

Massive green tides are challenging for management and science. Although reducing eutrophication for long-term benefits is required, a short-term strategy for managing these blooms is also necessary, and it might include controls on macroalgal-related processes and a predictable warning model to mitigate ecological risk. Alternative uses of biomass to profit from the green tide events might be a possible way to partly offset the bill for the environmental damage. For example, *U. prolifera* can be used as food or for medical purposes, because it is rich in polysaccharides, proteins, and essential mineral elements for human health (Cai et al. 2009).

Research in basic knowledge about green tides has provided useful information for understanding the tides of the Yellow Sea. However, an in-depth understanding of these mechanisms in massive green tides is still needed to unravel the complex biological–chemical–physical interactions in coastal ecosystems. For example, in order to reduce nutrient inputs, we need to know the major sources of nutrients from, e.g., river inputs, atmospheric deposition, or others. Regarding the fate of the macroalgal biomass, we need to discover how it is transported and what the consequence is of unchecked growth at sea. In the future, developing a scientific network and interdisciplinary research programme at an international level might be helpful for solving the problem of these massive free-floating seaweed blooms.

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