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Variations of morphology and photosynthetic performances of *Ulva prolifera* during the whole green tide blooming process in the Yellow Sea

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ABSTRACT

Since 2007, the world's largest macroalgal blooms have occurred along the coastal area of the Yellow Sea for 6 consecutive years. In 2012, shipboard surveying and satellite remote sensing were used to monitor the whole blooming process. The blooms originated in Rudong sea area of the South Yellow Sea where bloom patches were of dark green and filamentous thalli were the dominant morphology. The scale of the blooms reached its peak size in Rizhao sea area of the North Yellow Sea, and decreased promptly and became insignificant in Qingdao coast where the blooms turned yellow, mostly with air sac blades. Meanwhile, vegetative cells of the green tide algae changed into cytocysts gradually from which germ cells were released as the blooms drifted northward. Additionally, chlorophyll contents and fluorescence activity of free-floating thalli in the North Yellow Sea were both significantly lower than that in the South Yellow Sea. Those studies presented here contributed to increasing our understanding about how the green tide declined gradually in the North Yellow Sea.

1. Introduction

Green macroalgae are ubiquitous throughout the world in marine and estuarine habitats, where they show a great ability to acclimate to an adverse circumstance, and grow rapidly in nutrient-rich waters (Tan et al., 1999). The vast accumulations and rapid growth of unattached green macroalgae are called "green tides", intimately associated with eutrophicated marine environments (Raffaelli et al., 1998; Shimada et al., 2003; Charlier et al., 2007; Nelson et al., 2008). Green macroalgae blooms have been reported in the world's oceans (Fletcher, 1996; Blomster et al., 2002; Nelson et al., 2003a; Merceron et al., 2007). Particularly, green tides have been increasing in severity, frequency and geographic range, and become a growing concern globally in the last few decades (Largo et al., 2004).

Green tides were recognized as a special type of harmful algal blooms (HABs) (Nelson et al., 2003b). Green macroalgae blooms had negative effects on marine ecosystems, including changing ecosystem structures and decreasing biodiversity (Hernandez et al., 1997; McGlathery, 2001; Nelson and Lee, 2001; Franz and Friedman, 2002). In addition, green tides might lead to declining populations or reducing reestablishment capability of seagrass beds due to shading (Berger et al., 2003; Raberg et al., 2005). When the algae died and sunk to the bottom, the consumption of dissolved oxygen could cause a local "dead zone" with hypoxic conditions (Hu and He, 2008; Diaz and Rosenberg, 2008), resulting in a shift from a high-diversity mixture to low-diversity assemblages of fast-growing annuals (Worm et al., 2001). Besides, ecological services function was also damaged. Green tides were characterized by choking of waterways and preventing fisheries and marine aquaculture in the immediate area of the bloom (Nelson et al., 2008). When the floating algae were driven on the shore by wind and tide, they could be destructive to the coastal marine ecology landscape and tourism, causing economic losses.

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In the Yellow Sea, large-scale green tides had broken out consecutively from 2007 to 2012. Particularly, in late June 2008, the massive green algae bloom in the coastal region of Qingdao brought the world's attention because the algae bloom covered an area of approximately 13,000–30,000 km^2 and was thought to be one of the largest in recorded history (Leliaert et al., 2009; Liu et al., 2009). Various methods were employed to maintain an algae-free water area near Qingdao for the Olympic sailing games, with a total cost exceeding U.S. $100 million (Wang et al., 2009). More than 16,000 people using over 1000 transportation vehicles and 1600 fishing and transportation vessels volunteered to clean up the massive bloom. As of 15 July, more than 700,000 tons of algae were removed from beaches and nearby coastal waters (Hu and He, 2008).

Since the outbreak of the bloom in 2008, green tides have drawn considerable attention from scientists and governments all over the world. Four scientific questions were posed immediately to handle this disaster: species composition of the green tide algal population, the origin of the green tide, breaking out mechanism and controlling methods. A number of rapid-response studies including remote-sensing, shipboard surveys, field collections, and laboratory experiments were conducted by Chinese marine scientists these years and the former three questions had been resolved or explained recently. The dominating species was identified as the filamentous, intensively ramificated *Ulva prolifera* (Müller) J. Agardh (Chlorophyta, Ulvophyceae) (Ye et al., 2008; Leliaert et al., 2009), which possessed many ways of reproduction to support the massive biomass (Lin et al., 2008; Ye et al., 2008). Three main hypotheses on the original "seed" source of the green tides were put forward: the land-based animal aquaculture ponds (Pang et al., 2010), the *Porphyra yezoensis* aquaculture rafts (Liu et al., 2009, 2010; Keesing et al., 2011) and the somatic cells of settled vegetative fragments in benthic sediments (M.W. Zhang et al., 2010, 2011). However, few studies focused on how to control the problematic blooms. Therefore, the present study used both satellite remote sensing and morphological characteristics to identify the developmental process of the green tide in Yellow Sea and locate the sea area where the biomass of the bloom began to decrease gradually. Meanwhile, in order to find out feasible methods of eliminating or controlling the green tide, we analyzed the environmental factors that could cause the blooms breakdown.

2. Materials and methods

2.1. Consecutive tracking monitor of green tide

Satellite remote sensing is one of the most efficient tools in natural hazards monitor and assessment. In this study, daily HJ-1A/1B satellite images were provided by East China Sea Environmental Monitoring Center of State Oceanic Administration from 15 May to 16 July 2012. HJ-1A/1B are the new generation of small Chinese civilian earth-observing optical remote sensing satellites with a wide-coverage multispectral charge-coupled device (CCD) camera. The CCD camera has nadir pixel resolution of 30 m, width of view of 360 km and central-pixel matching accuracy of 0.3 pixels. These images obtained were examined to search for days that were sufficiently cloud free to observe floating patches of algae if they existed at the time. However, at the early stage of green tide, the blooms scale was not large enough to be observed or identified by satellite. Thus, systematic shipboard survey was conducted to monitor the early process and distributing characteristics of green tide. The field survey was conducted along three transects of Dafeng, Rudong and Lvsi, each transect extended off the shore for 100 km (Fig. 1).

2.2. Sample collection and morphological observations

Floating *U. prolifera* thalli were sampled from the sea surface of Rudong (RD), Dafeng (DF), Sheyang (SY), Binhai (BH), Lianyungang (LYG) of the South Yellow Sea and Rizhao (RZ), Qingdao (QD) of the North Yellow Sea. Only the RD samples were collected during the shipboard survey, and other samples were obtained by ship after the floating algae could be seen by satellite remote sensing. Afterward, the samples were examined carefully under the microscope and the isolated algae were cultured in seawater in 250 mL culture bottles under standard conditions at 15 °C in a 12 h light: 12 h dark photoperiod. Light microscopy observation was carried out using an Olympus CX310 microscope (KS OLYMPUS, Tokyo, Japan).

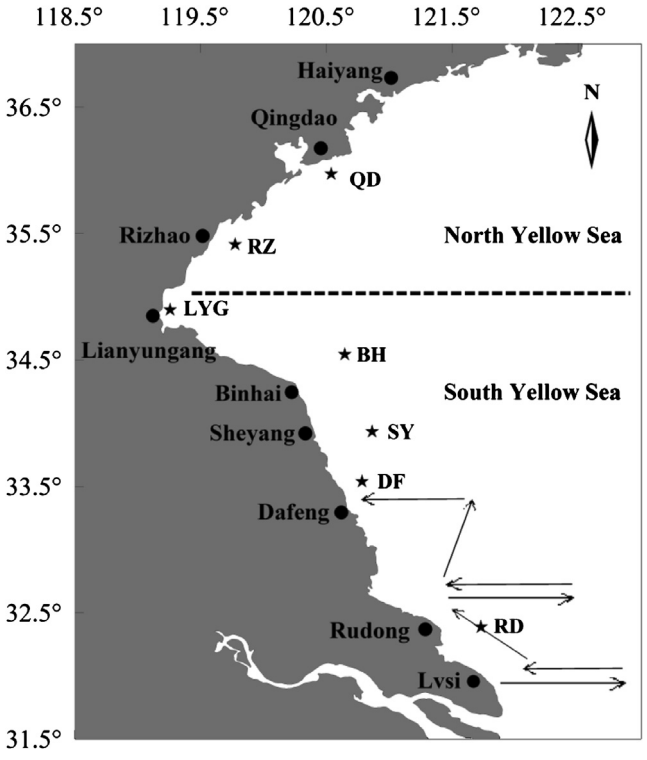

Fig. 1. Sites of floating green algae samples collection in Yellow Sea (the stars: sampling sites; the arrows: shipboard route).

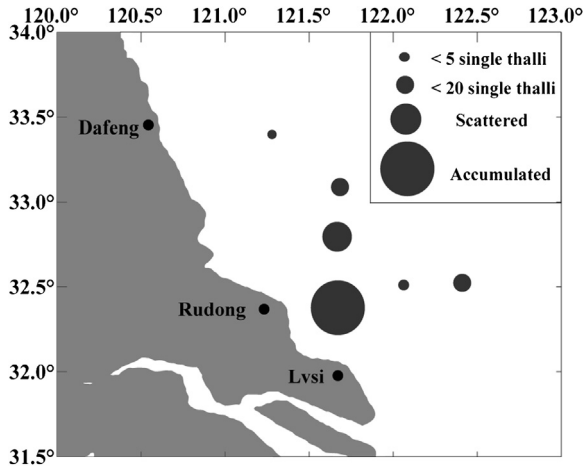

Fig. 2. Distributing characteristics of green tide algae in shipboard surveying sea area.