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The origin of the *Ulva* macroalgal blooms in the Yellow Sea in 2013

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ABSTRACT

Green algal blooms have occurred in the Yellow Sea for seven consecutive years from 2007 to 2013. In this study, satellite image analysis and field shipboard observations indicated that the *Ulva* blooms in 2013 originated in the Rudong coast. The spatial distribution of *Ulva* microscopic propagules in the Southern Yellow Sea also supported that the blooms originated in the Rudong coast. In addition, multi-source satellite data were used to evaluate the biomass of green algae on the *Pyropia* aquaculture rafts. The results showed that approximately 2784 tons of *Ulva prolifera* were attached to the rafts and possessed the same internal transcribed spacer and 5S rDNA sequence as the dominant species in the 2013 blooms. We conclude that the significant biomass of *Ulva* species on the *Pyropia* rafts during the harvesting season in radial tidal sand ridges played an important role in the rapid development of blooms in the Yellow Sea.

1. Introduction

Green algal blooms have occurred along the coastal areas of the Yellow Sea for seven consecutive years since 2007. The large-scale blooms of *Ulva prolifera* have resulted in tremendous economic loss due to the destruction of marine ecosystems and damage to ecological service functions. The estimated cost of maintaining algae-free water near Qingdao for the Olympic Games sailing events in 2008 was more than 100 million U.S. dollars (Wang et al., 2009). Since then, green tides have received considerable attention from scientists and governments worldwide and have aroused concerns regarding the marine environments in China. Focusing on the macroalgal blooms at the early developmental stages, by identifying the source, could be a direct way of tackling this issue. Thus, the source of the problem may have been resolved immediately after the macroalgal blooms in 2008.

The excessive growth of green algae which causes the formation of macroalgal blooms has been reported in oceans worldwide (Fletcher, 1996; Blomster et al., 2002; Nelson et al., 2003; Merceron et al., 2007; Ye et al., 2011). However, unlike the bloom events in the Yellow Sea, these were restricted to small coastal areas. The satellite data played a critical role in monitoring the floating route and size of the green tide to further predict its impact in the Yellow Sea for the public and the local administration. To date, the large-scale green tide has been traced by satellite image analysis to the nearshore of the Jiangsu coast, which is about 400 km from Qingdao (Liu et al., 2009; Hu et al., 2010; Zhang et al., 2013).

There are different opinions concerning the origin of the green tide in the Yellow Sea, although the Southern Yellow Sea was confirmed to be the original area of the bloom using satellite data. Pang et al. (2010) first suggested that the *Ulva* blooms originated from land-based animal aquaculture ponds on the Jiangsu coast. Their conclusion was based on the analyses of rbcL and internal transcribed spacer (ITS) molecular markers, as well as morphological analyses. However, the green algae in these aquaculture ponds appeared to be different from the *Ulva* found in the bloom when a different molecular marker, ISSR, was used (Liu et al., 2011). Zhang et al. (2010, 2011) suggested that somatic *Ulva* cells and the settlement of vegetative fragments may serve as a potential propagule bank to support the bloom in subsequent years. Due to the small biomass of *U. prolifera* at the bottom of the Yellow Sea, the settled *Ulva* vegetative fragments could not be more than a supplement for the blooms. Liu et al. (2009, 2010, 2013a), Hu et al. (2010) and Keesing et al. (2011) suggested that the blooms originated

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from the cleaning of fouling green algae during *Pyropia* aquaculture along the Jiangsu province coast. However, Pang et al. (2010) reported that *Ulva* from the floating populations and *Pyropia* rafts were not the same species. To date, there is no clear agreement on the source of the blooms in the Yellow Sea.

In this study, we used high resolution HJ-1A/1B data and a systematic shipboard survey to identify a more accurate source of the blooms. In addition, a field investigation which included the species composition and the biomass of *U. prolifera* on the *Pyropia* aquaculture rafts was conducted to determine if *Pyropia* farms in the radial sand ridge area could provide the initial biomass to cause large *Ulva* blooms in the Yellow Sea.

2. Material and methods

2.1. Study area and survey methods

The tidal flats along the Southern Yellow Sea are unique in terms of their huge geometric scale, abundant sediment supply associated with large rivers, silt-dominated sediments and an offshore radial sand ridge (He et al., 2012). Due to the complex sediment transport dynamics driven by the wave and current interactions, the tidal flats in this area are well-developed and range in width from several kilometers to tens of kilometers.

The Southern Yellow Sea was monitored daily by HJ-1A/1B satellites which 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 and central-pixel matching accuracy of 0.3 pixels (Wang et al., 2010). In the early stage of the blooms, we confirmed when and where the first floating patches were observed.

From January to May, 2013, before the *Ulva* blooms were identified by the satellites, monthly field studies at Rudong, Dafeng, Sheyang (SY) and Binhai were conducted to monitor the distribution characteristics of floating green algae (Fig. 1). Each transect extended offshore for 100 km with five sampling stations, except for the SY transect which extended offshore for 50 km with three stations (Fig. 1). Recording criteria for the status and size of the patches of green algae were described by Huo et al. (2013).

2.2. Quantification of Ulva microscopic propagules

In April 2013, 500 mL water samples from a depth of 0 m, 5 m and the bottom at each station were collected and filtered through a 150 μm mesh size sieve, then transported to the laboratory in dark conditions within 48 h. Although *Ulva* microscopic propagules are invisible to the naked eye, *Ulva* seedlings were observed and quantified after the water samples were cultivated in the laboratory for 3–5 weeks under nutrient enrichment conditions. The cultivation and quantification of *Ulva* propagules have been described by Liu et al. (2013b).

2.3. Biomass measurement of Ulva on Pyropia aquaculture rafts

The water depth is less than 10 m in the radial sand ridge area (Fig. 2A), which is an ideal place for *Pyropia* aquaculture. Semi-floating raft cultivation techniques are widely adopted in these *Pyropia* farms, combining the strong points of the pillar and the floating methods, especially for intertidal cultivation. At high tide the net floats on the water, maximizing the light available to the seaweed; at low tide the net rests on the ground by short legs.

The whole aquaculture area is divided into six regions including Dongsha, Jiangjiasha, Zhugensha, Rudong, Yaosha and Qidong (Fig. 2C). In each region, ten rafts were randomly chosen to collect samples of the attached green algae in early April 2013. Each raft, covering 7.5 m^2, consists of two bamboo poles, two pieces of rope and one nursery net. All the green algae on the selected rafts were removed to estimate the biomass of *Ulva* spp.

To estimate the total aquaculture area, multi-source satellite images including radar satellite ERS-2 PRI, Landsat TM/ETM, CBERS-2B and HJ-1A/1B, were collected by the East China Sea Branch of State Oceanic Administration. The obtained satellite images were examined to identify days which were sufficiently

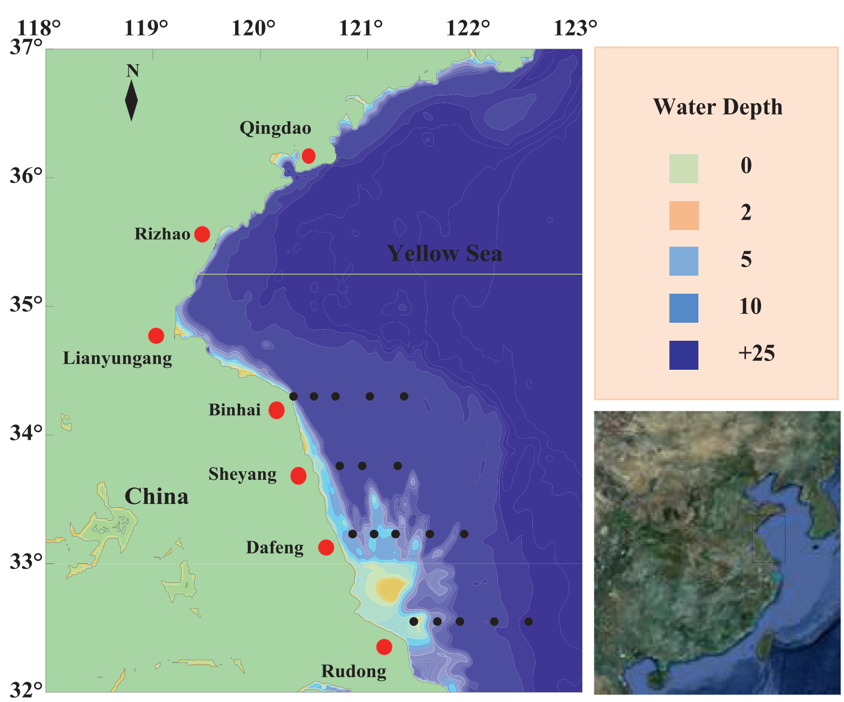

Fig. 1. Study area and monitoring transects in Rudong, Dafeng, Sheyang, and Binhai from January to April, 2013.