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The fast expansion of *Pyropia* aquaculture in "Sansha" regions should be mainly responsible for the *Ulva* blooms in Yellow Sea

Jianheng Zhang [a], Peng Zhao [b], Yuanzi Huo [c], Kefeng Yu [c], Peimin He [c, *]

[a] *College of Marine Sciences, Shanghai Ocean University, Shanghai 201306, China*
[b] *North China Sea Marine Forecasting Center, State Oceanic Administrator, Qingdao 266033, China*
[c] *College of Fisheries and Life Science, Shanghai Ocean University, Shanghai 201306, China*

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A B S T R A C T

Massive *Ulva* blooms became an environmental disaster in the Yellow Sea from 2007 to 2015. In this study, field shipboard observations indicated that *Ulva* blooms originated in *Pyropia* aquaculture area, and the morphology of initial floating *Ulva* seaweed have the structure of rhizoid, which is similar with the attached *Ulva* on the *Pyropia* rafts. The spatial distribution of *Ulva* microscopic propagules in the southern Yellow Sea also supported that the blooms originated in the *Pyropia* aquaculture area. Besides, numerical model was used in this study, showing the origin of macroalgal blooms was traced to "Sansha" regions which accounted for almost 70% of the total *Pyropia* aquaculture area. We conclude that the significant biomass (4252 tons) of *Ulva* species on the *Pyropia* rafts during the harvesting season in "Sansha" regions played an important role in the early rapid development of blooms in the Yellow Sea.

1. Introduction

Green tides are fast growth and vast accumulations of unattached green macroalgae associated with eutrophicated marine environments (Shimada et al., 2003; Charlier et al., 2007). Over the past few decades, green tides have been increasing in severity, frequency, and geographic range even in its public perception and become a growing concern globally (Fletcher, 1996; Blomster et al., 2002; Largo et al., 2004; Ye et al., 2011). The world's largest green tide events, caused by *Ulva prolifera*, have occurred annually from 2007 to 2016 along the coast of the Yellow Sea, China, seriously affecting marine environment and ecological services functions (Liu et al., 2009; Hu et al., 2010). Particularly, in late June 2008, a 600-km^2 green tide occurred along the coast of Qingdao, where the 29th Olympic sailing games were soon to start. To maintain algae-free water for the Olympic sailing events, over 10,000 people were organized to remove more than one million tons of algae from Qingdao's coastline. Totally, 100 million U.S. dollars was cost finally (Wang et al., 2009). So it is urgent to understand the forming process of the green tides and control it.

In the past decade, most scholars focused on the research of where the floating macroalgae came from. Initially, through the molecular and morphological evidences, the dominant species was identified as *Ulva prolifera* (Leliaert et al., 2009; Pang et al., 2010; Kong et al., 2011; Zhao et al., 2011, 2015), and the homology analysis of free-floating and attached *Ulva* species showed that the macroalgal blooms originated from the southern Yellow Sea, where the field investigations were also carried out, demonstrating approximately 4000–6500 t of *U. prolifera* were present on the *Pyropia* aquaculture rafts (Keesing et al., 2011; Liu et al., 2013; Xiao et al., 2013; Zhang et al., 2014; Wang et al., 2015). Meanwhile, satellite remote sensing and cruise observations were also applied to trace the floating path of macroalgal blooms, indicating the scattered floating *Ulva* macroalgae firstly appeared along the coast of Rudong, and accumulated in the Dafeng sea area (Zhang et al., 2013b, 2014; Wang et al., 2015), then the patches of free-floating green algae drifted into the northern Yellow Sea under the control of surface current (Qiao et al., 2011; Bao et al., 2015). Besides, during the field investigation, scientists found that clean-up of the attached *Ulva* macroalgae on the *P. yezoensis* infrastructures caused the initial formation of macroalgal blooms (Zhang et al., 2014).

* Corresponding author. Room B409, College of Fisheries and Life Science, Shanghai Ocean University, No. 999, Huchenghuan Road, Nanhui New Town, Shanghai China.
E-mail address: pmhe@shou.edu.cn (P. He).

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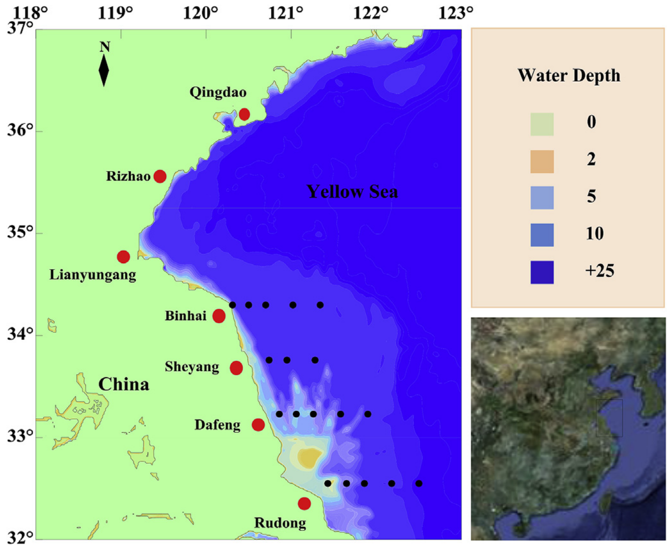

Fig. 1. Study area and monitoring transects during the period from January to June in 2013 in the southern Yellow Sea.

However, few studies explained a question of why there were no macroalgal blooms before 2007 when *P. yezoensis* aquaculture were always the traditional activities in the southern Yellow Sea.

Therefore, in this study, due to its wide coverage area, *P. yezoensis* aquaculture area was divided into six regions. In order to locate a more specific region where the free-floating green algae come from, we used a numerical ocean circulation model to trace back to the origin of the macroalgal blooms. And the shipboard monitor in the southern Yellow Sea was also conducted to investigate the blooming process and original sea area. In addition, the *Ulva* biomass on the *Pyropia* aquaculture infrastructures of six regions were all investigated to determine which region could provide the initial biomass to cause large *Ulva* blooms in the Yellow Sea.

2. Material and methods

2.1. Initial algal patches monitored by the satellite remote sensing

Satellite remote sensing is one of the most efficient tools in natural hazards monitor and assessment. In this study, MODIS satellite images were used in 2008, and HJ-1A/1B satellite images were provided by North China Sea Marine Forecasting Center of State Oceanic Administration to monitor the initial *Ulva* patches from 2009 to 2015. 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.

2.2. The source tracing of green tide algae in the southern Yellow Sea

A numerical ocean circulation model is a basic tool used to trace the source of green algae. The Princeton Ocean Model (Xia et al., 2004; Blumberg and Mellor, 2010) was used in this study. The model domain covers the geographical area (24°-41°N, 117.5°-135°E) with a horizontal resolution of $(1/24)° \times (1/24)°$and 16 sigma layers in the vertical. Open boundary conditions are provided by the Northwest Pacific model (Xia et al., 2006), which covers the area (0°-50°N, 99°-150°E) and whose grid is $(1/8)° \times (1/8)°$. To show the background flow field over study area, we extracted the monthly mean surface currents from Northwest Pacific model. The meteorological data was executed using the Advanced Research WRF model which is a fully compressible non-hydrostatic model with an Arakawa-C grid system (Klemp et al., 2000; Skamarock, 2006) and the model is driven by six-hourly NCEP (National Centers for Environmental Prediction) wind and eight tidal components (M2, N2, S2, K2, K1, P1, O1 and Q1).

Without consideration of the growth and reproduction of the macroalgae, the drift of the green tide algae can be considered as the movement of the particles under the influence of the current, surface wind etc. A particle tracking experiment was designed and implemented based on the theory of Lagrange method (Wu et al., 2011; Gao et al., 2014).

2.3. Forming process of macroalgal blooms monitored by shipboard

From January to May, 2013, before the *Ulva* blooms were identified by the satellites, monthly field studies at Rudong, Dafeng, Sheyang 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

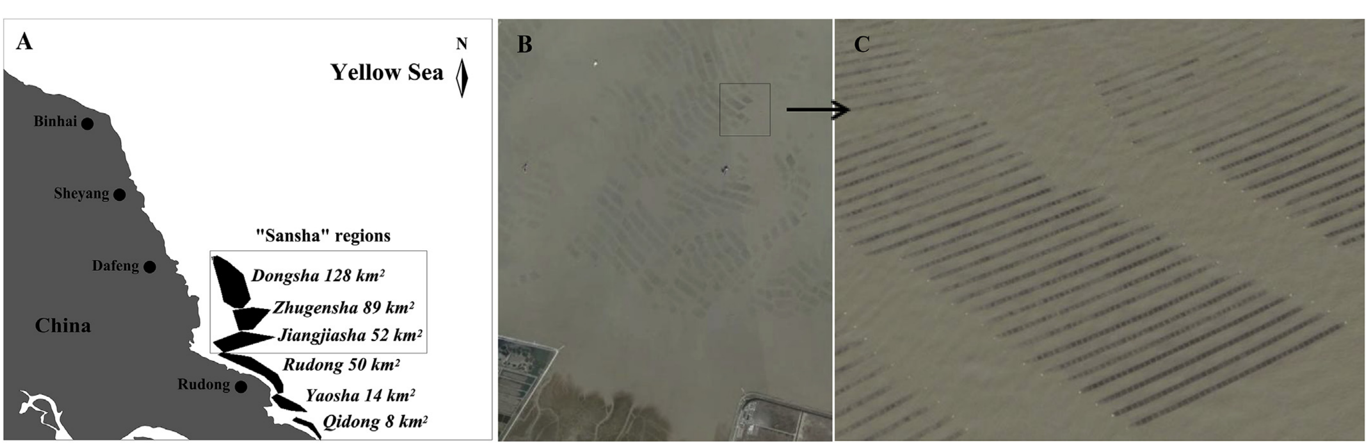

Fig. 2. (A) Sketch map on the six regions of *Pyropia* aquaculture in the radial sand ridge area; (B and C) Close-up of *Pyropia* aquaculture rafts on the sandy shoals. The maps were obtained from the software Google Earth.