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Understanding the recurrent large-scale green tide in the Yellow Sea: Temporal and spatial correlations between multiple geographical, aquacultural and biological factors

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ABSTRACT

The coast of Jiangsu Province in China – where *Ulva prolifera* has always been firstly spotted before developing into green tides – is uniquely characterized by a huge intertidal radial mudflat. Results showed that: (1) propagules of *U. prolifera* have been consistently present in seawater and sediments of this mudflat and varied with locations and seasons; (2) over 50,000 tons of fermented chicken manure have been applied annually from March to May in coastal animal aquaculture ponds and thereafter the waste water has been discharged into the radial mudflat intensifying eutrophication; and (3) free-floating *U. prolifera* could be stranded in any floating infrastructures in coastal waters including large scale *Porphyra* farming rafts. For a truly integrated management of the coastal zone, reduction in nutrient inputs, and control of the effluents of the coastal pond systems, are needed to control eutrophication and prevent green tides in the future.

1. Introduction

In the Yellow Sea, large-scale green tides have broken out for six consecutive years from 2007 to 2012 (Jiang et al., 2008; Leliaert et al., 2009; Liu et al., 2012a). Intensive field investigations have revealed that the causative free-floating green alga, *Ulva prolifera*, is distributed broadly in various niches along Jiangsu Province coast – including *Porphyra* rafts (Liu et al., 2009, 2010a; Keesing et al., 2011), coastal animal aquaculture ponds (CAAPs) (Pang et al., 2010), and intertidal seawater and sediments in its microscopic propagule form (Liu et al., 2010d, 2012a). Satellite data based on Moderate Resolution Imaging Spectroradiometer (MODIS) from NASA data distribution system indicated that the south part of Jiangsu Province coast from Sheyang to Rudong was the initial region where the floating green-tide algae were always firstly spotted every year (Hu et al., 2010).

The coast of Jiangsu Province is uniquely characterized with radial sand ridges on the shelf of the southwestern Yellow Sea, expanding over 200 km from Sheyang estuary to Changjiang estuary and 90 km from shore to open sea. This exposed large mudflat covers nearly 22,740 km^2, forming a strikingly unique extended intertidal mudflat zone in the world (Li, 2011). These radial ridges constitute an ideal environment for the growth of the commercially important red seaweed, *Porphyra yezoensis* (nori) (Fig. 1). Cultivation of nori at a scale of roughly 21,000 ha has been located here. Annually, 126,000 tons of fresh nori biomass is harvested (Pang et al., 2010). On the shore, multiple species of marine animals – including juvenile freshwater crabs (larval stage in seawater), clams and shrimps – have been farmed in CAAPs. Among the farmed animals, rotifers, a crucial live feed for juvenile freshwater crabs, are farmed by use of the called "natural ecological mud-pond method" (NEMPM) (Xu and Zhang, 2009). This method was developed from 2001 onwards firstly in Panjin City of Liaoning Province in the north of China, and rapidly spread to Jiangsu Province coast thereafter. Today, rotifer ponds cover roughly 1,400 ha from Sheyang to Rudong regions along the Jiangsu Province coast (Fig. 1).

Regarding the original source(s) of the floating *Ulva* biomass, Liu et al. (2009, 2010a) hypothesized and later reiterated that they were from the nori nets and pointed out that the expansion of nori

Abbreviations: CAAPs, coastal animal aquaculture ponds; FCM, fermented chicken manure; MODIS, Moderate Resolution Imaging Spectroradiometer; NEMPM, natural ecological mud-pond method.

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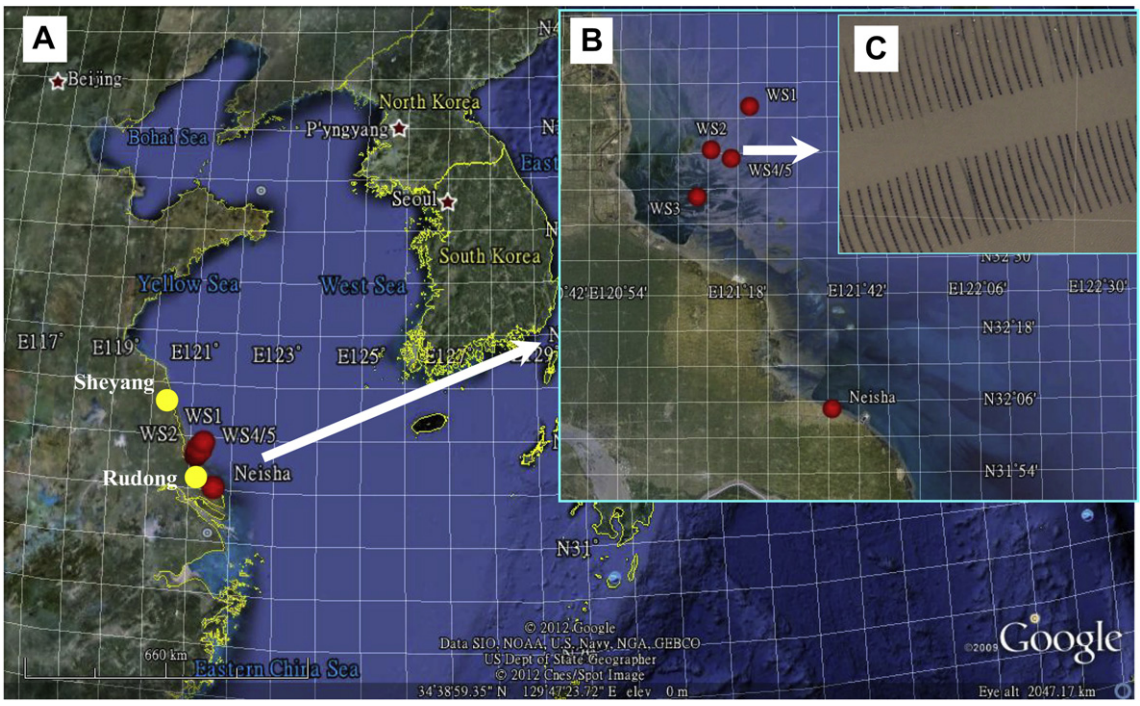

Fig. 1. (A and B) Maps of sampling locations in Jiangsu Province. (C) Close-up of *Porphyra* aquaculture rafts on the sandy shoals. The maps were obtained from the software Google Earth.

aquaculture along Jiangsu Province coast led to the occurrence of the green tides in the Yellow Sea. Our previous field sampling and identification revealed that the microscopic propagules of *U. prolifera* in the sediments and coastal waters of Jiangsu province's coast formed an overwintering "seed stocks". They constituted the precursor of the green tides in the spring in the Yellow Sea (Liu et al., 2010d, 2012a; Zhang et al., 2010, 2011). It is a well-known and widely accepted fact that blooming of green tides is closely related with eutrophication (Conley et al., 2009). However, it still remains a mystery why the *Ulva* blooms occurred along Jiangsu coast, and not along other eutrophicated coast of the south Yellow Sea given the fact that *U. prolifera* widely exists in the coastal marine environments. Furthermore, what are the local special/unique conditions that make it occurring continuously since 2007?

The objectives of this investigation were (1) to understand how and where the green tide algae initially started along the Jiangsu coast, and (2) to analyze the timing and spatial correlations of their occurrence with the particularly special geographical, aquacultural and biological factors of this area by employing field on-site net-installing experiments, laboratory cultures and molecular identifications.

2. Materials and methods

2.1. Selection of sampling locations

Waisha (WS), which represents the large area of mudflat, is periodically exposed during daily tidal events (Fig. 1A and B). A large part of the exposed sandy shoals in this mudflat are now used to install nori nets from November to May, which can easily be identified by satellite images (Fig. 1C). Four locations (WS1, WS2, WS3 and WS4/5) were selected in the main area of the radial shoal where the floating *Ulva* biomass was found each year. They represent the principal region of nori aquaculture in this area. Five cruises (WS1–WS5) were conducted from January 2011 to April 2012 (Table 1). A prerequisite for a shoal to be selected as a "land" to grow nori is that it must be fully exposed during low tides such that the nori on the nets could be exposed to air for several hours each

Table 1
Number of *Ulva* microscopic propagules in seawater and sediment samples collected from different locations in the Jiangsu Province radial shoals (Fig. 1), after 3 or 4 weeks of aerated culture in nutrient-enriched seawater at 18° C under 100 μmol photons m^{-2} s^{-1} in a 12 h light per day light–dark regime. Means and SE are shown ($n = 4$).

Location	Geographical coordinate	Collecting date	Surface water temperature (°C)	*Ulva* propagules in seawater (Individuals L^{-1}, ±SE)	*Ulva* propagules in sediment (Individuals g^{-1}, ±SE)
WS1	32°56′1″N, 121°20′29″E	7–8 Jan. 2011	2	16 ± 3^{a}	12 ± 5^{A}
WS2	32°40′43″N, 121°8′57″E	17–18 Mar. 2011	8	31 ± 5^{b}	26 ± 9^{B}
WS3	32°48′41″N, 121°14′41″E	27–28 Apr. 2011	16	37 ± 13^{bc}	–[a]
WS4/5	32°47′11″N, 121°16′47″E	13–14 Mar. 2012	5.5	28 ± 7^{b}	22 ± 4^{B}
WS4/5	32°47′11″N, 121°16′47″E	24–25 Apr. 2012	15.5	45 ± 10^{bc}	31 ± 7^{B}
Neisha	32°4′49″N, 121°36′51″E	13 Mar. 2012	6	56 ± 11^{c}	35 ± 11^{BC}
Neisha	32°4′49″N, 121°36′51″E	24 Apr. 2012	16	120 ± 21^{d}	52 ± 10^{C}

Values with statistically significant differences ($P < 0.05$) are indicated by different letters.
[a] Sediment sample was not collected.