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Spatio-temporal patterns of *Ulva prolifera* blooms and the corresponding influence on chlorophyll-a concentration in the Southern Yellow Sea, China

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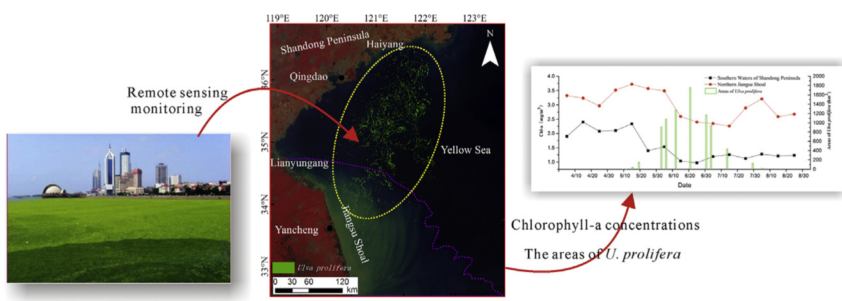
HIGHLIGHTS

- The world's largest macroalgal blooms have deteriorated the regional marine environment in Southern Yellow Sea.
- The development of *U. prolifera* blooms can be featured in five processes.
- The density of *U. prolifera* and chlorophyll-a concentration generally showed a negative relationship.
- *U. prolifera* showed strong inhibitory effect on the planktonic microalgae due to nutrient competition and allelopathy.

GRAPHICAL ABSTRACT



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ABSTRACT

The world's largest macroalgal blooms (MABs) caused by the *Ulva prolifera* outbreaks have occurred every summer since 2007 in the Southern Yellow Sea, China. Accumulating evidence showed that MABs may deteriorate the regional marine environment and influence the growth of some primary producers such as phytoplankton. In this study, we investigated the spatio-temporal patterns of *U. prolifera* green tides and chlorophyll-a concentration in the Southern Yellow Sea in 2015 using satellite images obtained from HJ-1 CCD, MODIS, and GOCI. The correlation between the distributions of *U. prolifera* abundance and chlorophyll-a concentration was analyzed quantitatively by setting up a series of 5 × 5 km experimental grids, and we also discussed the possible mechanisms about the influence of *U. prolifera* blooms on the other floating microalgae. The results showed that the development of *U. prolifera* blooms in the Southern Yellow Sea in 2015 could be featured as "appearance – development – outbreak – decline – disappearance", while the concentration of chlorophyll-a showed "increase – sharp decline – slow recovery – stabilization" from April to August. We also found that the concentration of chlorophyll-a had the following relationships with *U. prolifera* temporally: (1) the concentration of chlorophyll-a increased with the growth of *U. prolifera* from April to mid-May; (2) the chlorophyll-a concentration decreased sharply with the dramatically increased coverage of *U. prolifera* in June; and (3) the chlorophyll-a concentration slowly recovered and finally stabilized as *U. prolifera* decreased in July. Generally, there was a negative correlation between the

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occurrence of *U. prolifera* and chlorophyll-a concentration in the Southern Yellow Sea, China. Our results showed that the outbreak of *U. prolifera* does have a certain impact on the growth and reproduction of planktonic microalgae, and it suggests that *U. prolifera* blooms have potentially altered the ecological balance in the coastal waters of the Southern Yellow Sea.

1. Introduction

The macroalgal blooms (MABs) formed by the outbreaks of large green algae in the ocean have been recorded in Asia, North America, and Europe (Liu et al., 2009; Smetacek and Zingone, 2013). Most algal blooms occurring in estuaries, inner bays, and other shallow and brackish water in coastal areas are harmful to aquatic ecosystems (Ding and Luan, 2009). *U. prolifera* is non-toxic, but its massive accumulation during a bloom can result in significant environmental damage and cause economic losses to marine industries (Xu et al., 2014). From an ecological point of view, *U. prolifera* could inhibit the growth and reproduction of other planktonic microalgae by resource competition and the release of allelochemicals, which could greatly reduce the species diversity and community stability, and may threaten the survival of other species relied on phytoplankton (Fong et al., 1993; Jin et al., 2005; Keating, 1977; Liu et al., 2013; Lyons et al., 2014; Mcglathery, 2011; Paez-Osuna et al., 2013; Qiu et al., 1998; Sfriso and Pavoni, 1994; Smith and Horne, 1988; Song et al., 2011; Sun et al., 2010; Wang et al., 2012; Xing et al., 2015a, 2015b; Zhang et al., 2013; Zhao et al., 2012).

The chlorophyll-a concentration is an indicator of marine phytoplankton biomass, and its temporal and spatial variations reflect the changes in marine primary productivity. Extensive studies have showed that the concentration of chlorophyll-a had close relationships with *U. prolifera*. For example, Xing et al. (2015a, 2015b) used MODIS chlorophyll-a concentration algorithms to analyze the relationship between *U. prolifera* and phytoplankton microalgae in the Yellow Sea, and found that the outbreak of *U. prolifera* could result in a significant reduction of planktonic microalgae biomass; Liu (2015) laboratory research showed that the reproduction of *U. prolifera* was faster than that of the other algae and could affect the growth of other microalgae by allelochemical secretion and nutritional competition; Song et al. (2011) showed that the excessive growth of *U. prolifera* could affect the abundance and community composition of phytoplankton; and Zhang et al. (2013) also showed that high density *U. prolifera* could result in the dominance of a single kind of phytoplankton. Most of the above mentioned studies were microscopic about the relationship between *U. prolifera* and planktonic microalgae, which were tested using controlled simulations in the laboratory where much of the environmental factors are greatly simplified (Liu, 2015; Song et al., 2011; Zhang et al., 2013). Because the biological and abiotic factors in the marine environment are diverse and complex, the factors influencing the outbreak of *U. prolifera* and its relationship with phytoplankton microalgae are much complicated compared with the controlled experiments. As a natural phenomenon, the spatio-temporal dynamics of *U. prolifera* and their ecological effects in the marine environment are of particular interest to the offshore ecology studies. As a natural phenomenon, the spatio-temporal dynamics of *U. prolifera* and their ecological effects in the marine environment might be of interest to the offshore ecology studies, because it provides a unique opportunity to observe the competitions and stress responses between *U. prolifera* and the other algae (Xing et al., 2015a, 2015b).

Remote sensing has unique advantages compared with traditional experiment methods due to its large spatial coverage, relative short revisit cycle, and specific band composition purposely designed for certain monitoring tasks. For example, Geostationary Ocean Color Imager (GOCI), Sea-Viewing Wide Field-of-View Sensor (Seastar SeaWiFS), and Moderate Resolution Imaging Spectroradiometer (Terra MODIS) can all be used to collect ocean-color data with varying spatial resolutions and revisit cycles. Many studies showed that the satellite-based monitoring system was reliable and the estimated chlorophyll-a concentration was comparable to in situ measurements (Devlin et al., 2013; Harvey et al., 2015). Scholars analyzed the spatio-temporal variability of chlorophyll-a concentrations in various marine using multi-source remote sensing (Kahru et al., 2012; Kravchishina et al., 2013; Tiedje et al., 2010; Waite and Mueter, 2013; Xuan et al., 2011) and explored the relationships between Chlorophyll-a and environmental driving factors. A number of studies have used MODIS, GOCI, Environmental and Disaster Monitoring and Forecasting with a Small Satellite Constellation (HJ-1 for short), Landsat and synthetic aperture radar (SAR) data to map *U. prolifera* and document its spatial and temporal distributions by different algorithms (Garcia et al., 2013; Hu, 2009; Qi et al., 2016; Shen et al., 2014; Son et al., 2012; Son et al., 2015; Xing and Hu, 2016; Villa et al., 2015) and further explored the impact of environmental factors on the blooms of *U. prolifera*. For example, recent studies have shown that the outbreak of *U. prolifera* has a close relationship with the *Pyropia* aquaculture in the southern Jiangsu shoal (Keesing et al., 2016; Zhang et al., 2017), and the eutrophication in the offshore waters caused by the excessive nutrients such as nitrogen and phosphorus might be the main material basis for the outbreak of *U. prolifera* (Li et al., 2017; Shi et al., 2015; Xing et al., 2015a, 2015b; Zhou et al., 2015). In addition, the sea surface temperature (SST), and wind field and flow field are also key factors in the growth and drifting of the green tide (Fan et al., 2013; Son et al., 2015).

Since 2007, the world's largest macroalgal blooms of *U. prolifera* have been recorded for 10 consecutive years in the Southern Yellow Sea, China, and there is a pressing need to characterize the spatio-temporal patterns of *U. prolifera* and their relationship with chlorophyll-a concentration to evaluate the corresponding influences on the offshore environment (Fig. 1) (Wu et al., 2014). In this study, we firstly extracted the coverage area of *U. prolifera* and investigated the progression of its outbreak by using remotely sensed time series based on HJ-1 Charge Coupled Device (CCD) and MODIS data, and obtained the distribution of the floating microalgae from GOCI-based chlorophyll-a concentration estimates in the Southern Yellow Sea in 2015; we then quantitatively explored the spatio-temporal relationships between *U. prolifera* and chlorophyll-a concentration by setting up a series of 5 × 5 km experimental grids as the basic unit of analysis, and finally we discussed the potential mechanisms about the relationships between *U. prolifera* blooms and the floating microalgae.

2. Materials and methods

2.1. Study area

The Southern Yellow Sea (119° E-123° E, 32° N-37° N) (Fig. 1) is a semi-enclosed shallow sea with an average depth of 44 m. The surface flow is mainly controlled by wind and has the characteristics of wind currents. Affected by the temperate monsoon climate, the prevailing winds in this area are the north wind from October to the following March, and the southeast wind from May to August. This area is often under the influence of typhoons originated from the north of the East China Sea. The Southern Yellow Sea has complex hydrographic