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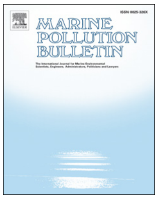

Remote sensing of early-stage green tide in the Yellow Sea for floating-macroalgae collecting campaign

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ABSTRACT

The world's largest green tide originated from the Jiangsu Shoal of the Yellow Sea was due to fast reproduction of floating green macroalgae (*Ulva prolifera*). It brought significant impacts on marine environment and ecosystem in the Yellow Sea. In this study, we examined the expansion of green tide from the Jiangsu Shoal during the period from 29 April to 25 June 2016. Using high-resolution satellite images, we revealed a declined growth rate during the northward drifting of early-stage green tide for the first time, i.e., the green tide had higher growth rate (up to 25% per day) in the turbid waters of the Jiangsu Shoal in May and a lower growth rate (low to 3% per day) in the relatively clear waters in the middle of the western Yellow Sea in June, which suggests that water clarity might not be the key factor controlling the growth rate of the floating macroalgae in the surface waters under natural conditions. The high growth rate led to shortened time windows for controlling the green tide by employing macroalgae collecting campaigns at the initial sites of the green tide, which was no more than 14 days in the 2016 case.

1. Introduction

Macroalgal blooms (MABs) caused by fast growth and accumulation of macroalgae, e.g., green macroalgae of *Ulva prolifera* and brown macroalgae of Sargassum, have been increasing in recent years in the global oceans (Liu et al., 2009; Gower et al., 2013; Smetacek and Zingone, 2013; Xing and Hu, 2016; Xing et al., 2017). These large-scale blooms can bring significant adverse ecological and economic impacts on marine and coastal areas (Wang et al., 2009; Xing et al., 2015a; Liu et al., 2016; Li et al., 2018).

The world's largest green tide caused by the *Ulva prolifera* blooms in the Yellow Sea was reported to occur in every late spring and summer since 2007 (Hu and He, 2008; Xing et al., 2009, 2011; Hu et al., 2010; Keesing et al., 2011; D. Liu et al., 2013; Hu et al., 2017). This led to the speculation that the green tide in the Yellow Sea was caused by recycling aquaculture facilities for growing seaweed - *Poryphyra yezoensis* - at the Jiangsu Shoal of the southern Yellow Sea at the end of April (Liu et al., 2009; D. Liu et al., 2013a; F. Liu et al., 2013; Wang et al., 2015); that is, green macroalgae originally grow on the seaweed aquaculture facilities of poles, ropes and nets. After the last round of seaweed harvesting in every April, green macroalgae thallus are removed and discarded into sea water when the facilities are recycled. The unattached macroalgae grow and expand in sea water, and eventually form large-scale green tide in the southern Yellow Sea during April–August, with a peak in June (Liu et al., 2009, 2013a; D. Liu et al., 2013; Keesing et al., 2011; Xing et al., 2015b; Liu et al., 2016; Qi et al., 2016; Hu et al., 2017).

Considering the fact that the green macroalgae may be used as fertilizer, food, biofuel materials, so on, the *Ulva* green tide may be controlled at the initial sites by collecting the macroalgae before the green tide is out of control due to the expansion of its biomass (Lotze et al., 1999; Liu et al., 2017). Compared to the fully-developed large-scale green tide, the initial early-stage small-scale MABs are more important for exploring the origin and causes of full-bloom green tide. So,

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monitoring the development of early-stage green tide is an essential step to carry out effective countermeasures.

Through satellite remote sensing, researchers reported the world's largest MABs of *Ulva prolifera* in Summer 2008, and explored their possible causes (Hu and He, 2008; Liu et al., 2009; Shi and Wang, 2009; Xing et al., 2009). The seasonal dynamics of MABs in the East China Sea (ECS) and the Yellow Sea (YS) have been documented (Keesing et al., 2011; Xing et al., 2011, 2015b; Qi et al., 2016; Hu et al., 2017); and the MABs in the YS were tracked back to the year of 1999 (Xing and Hu, 2016). However, most of the findings were based on low- and moderate-resolution images (250–500 m), which failed to reveal small macroalgae patches or wrongly classified them (Hu et al., 2010; Xing et al., 2011; Ding et al., 2015; Q. Xu et al., 2016; F. Xu et al., 2016; Zheng et al., 2016); consequently, the MABs may be overlooked or overestimated (Ding et al., 2015; Xiao et al., 2017), especially for the early-stage small-scale MABs.

The Normalized Difference of Vegetation Index (NDVI) may be the most used index for detecting MABs in offshore waters in the southern Yellow Sea (Hu and He, 2008; Xing et al., 2010; Cui et al., 2012). However, this index is very sensitive to environmental conditions, and is affected by aerosols, sea surface glints and water constituents (Hu, 2009; Garcia et al., 2013). To reduce spatial variation in large-size image, such an image is divided into small windows, and targets can then be identified window by window (Xing et al., 2011; Garcia et al., 2013; Meng and Xing, 2013). Specific indices for different satellite cameras were also designed to mitigate these impacts (Hu, 2009; Son et al., 2012, 2015; Wang and Hu, 2016). The band-difference indices, such as the Floating Algae Index (FAI), the Virtual Baseline Floating macroAlgae Height (VB-FAH), the Difference of Vegetation Index (DVI) between near-infrared and red bands for MABs detection, were tested and shown to be less sensitive to aerosol variation and sea surface glints than the NDVI, and are suitable for high-resolution images with limited blue, green, red, and near-infrared bands (Hu, 2009; Xing and Hu, 2016).

Since it is now known that the green tide (macroalgae) originated from the *Poryphyra yezoensis* farming rafts, can the green tide be controlled by adopting countermeasures at the initial sites of the Jiangsu Shoal? Many suggestions have been put forward to control the early blooms of green tide, such as disposing macroalgae when recycling the *Poryphyra yezoensis* farming rafts (D. Liu et al., 2013), recycling farming facilities as early as possible (Liu et al., 2017), cutting down nutrient input (F. Liu et al., 2013), removing the farming industry of *Poryphyra yezoensis*, adjusting the farming location, replacing the materials used for making rafts, raising macroalgae-eating animals, using chemicals to kill or control the macroalgae on the rafts, collecting the early-stage macroalgae, and so on (personal communications with Dr. Song Qin, Dr. Chuanming Hu, Dr. Song Sun, and so on). However, this is a difficult task when the environmental, ecological, economic and social effects, and the feasibilities are concerned. Relatively speaking, the early-stage collecting campaign has several major merits. First, it is environment-friendly. Second, the macroalgae may be used as resource, and thus there is a potential of collecting them in a commercial way. Third, the effectiveness can be seen immediately. Then, the question becomes, can the early-stage collecting work be done in a cost-effective and feasible way? In this work, high-resolution satellite images are used in a biomass-estimation model to explore the features in the expansion of early-stage green tide in the Yellow Sea, and to assess the feasibility of using the macroalgae collecting approach to control their spread.

2. Data and methods

2.1. The study area

Fig. 1 shows the study area of the Jiangsu Shoal and its vicinity. The true color image, a composite of satellite images bands 3 (red), 2 (green) and 1 (blue) acquired on 29 April 2016, shows the Jiangsu Shoal where the water was shallow and full of suspended sediments. Fig. 2 shows the tidal flat was dominated by the seaweed aquaculture of *Poryphyra yezoensis*.

2.2. Satellite images and processing

In this study, satellite images during the period of April–June 2016 were collected and used for MABs extraction, including the GaoFen-1 (GF-1), China-Brazil Earth Resources Satellite-4 (CBERS-4) and the Moderate Resolution Imaging Spectrometer (MODIS). Specifically, the red band (Red) and near-infrared band (NIR) data acquired by these sensors were processed to give top-of-atmosphere reflectance (R, unitless). Then, the DVI, the reflectance difference between the NIR band and the Red band (R_{NIR}-R_{Red}), which has a linear correlation to the coverage of floating plants at the sea surface (Xing and Hu, 2016; Xing et al., 2017), was calculated for each image. The spatial resolutions of GF-1, CBERS-4 and MODIS used in this work are 16, 30 and 250 m, respectively. In practice, the high-resolution GF-1 and CBERS-4 images were used to monitor the early-stage MABs, which might be overlooked in the lower- and moderate-resolution images (e.g., the MODIS).

Macroalgae pixels have higher DVI values than the background seawater. In this work, a dynamic threshold of DVI was used to extract macroalgae pixels. The DVI images were segmented into small windows, and a threshold was set to classify the macroalgae pixels window by window, i.e., pixels with their DVI values larger than the threshold (from −0.02 to 0.01) depending on the water surface optical conditions, were regarded as macroalgae pixels. Meanwhile, the R(band 4)-G(band 3)-B(band 2) false-color images were used for visual inspection of each window where macroalgae showed red or brown color in the enhanced 432 image. This approach can reduce the chance of misclassification, and is useful for extracting macroalgae pixels under optically complex water conditions. The areas of these macroalgae pixels were summed to give the total area (A_T, Km^2).

2.3. Estimation of total biomass of floating macroalgae

In order to estimate how much manpower would be needed to collect the floating macroalgae, managers need to estimate the potential total biomass of macroalgae (B_M, ton). In this study, the total area completely covered by macroaglae (A_{CCM}, Km^2) and the unit biomass (B_U, ton/Km^2) were used to calculate the biomass using Eq. (1) below:

$$B_M = A_{CCM} * B_U, \tag{1}$$

where B_U refers to the biomass per area (or pixels) for the study area completely covered by the aggregation of macroalgae.

A_{CCM} was estimated from the macroalgae coverage, which was derived from the satellite image via the above-mentioned procedures. In high-resolution images, it is reasonable to assume that there should be sites where the sea surface was completely covered by macroalgae and the corresponding pixels should have the largest DVI values. The DVI values of all the macroalgae pixels were normalized, so the minimum and the maximum are 0 and 1, i.e., a term of [01DVI] where 0 is set to present that the pixel has 1% of macroalgae while 1, for 100%. Then, the portion of macroalgae (POM, %) in each macroalgae pixel was calculated using Eq. (1), and A_{CCM} was calculated using Eq. (2).

$$POM = 99 * [01DVI] + 1, \tag{2}$$

$$A_{CCM} = \sum_{i=1}^{n} POM_i * PS_i, \tag{3}$$

where n is the number of pixels containing macroalgae; PS is the pixel size, e.g., 16 m ∗ 16 m for GF-1 images. For more details, please go to Xing et al. (2017).

The unit biomass of macroalgae (B_U, ton/Km^2) was measured during the cruise conducted in the Jiangsu Shoal on 25 May 2016. In the field work, the floating macroalgae slicks or patches were visually