Remote Sensing of Environment 192 (2017) 217–227

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Remote estimation of biomass of *Ulva prolifera* macroalgae in the Yellow Sea

Lianbo Hu [a,*], Chuanmin Hu [b], Ming-Xia HE [a]

[a] Ocean Remote Sensing Institute, Ocean University of China, 5 Yushan Road, Qingdao 266003, China
[b] College of Marine Science, University of South Florida, 140 Seventh Avenue, South, St. Petersburg, FL 33701, United States

ARTICLE INFO

Article history:
Received 18 July 2016
Received in revised form 9 January 2017
Accepted 27 January 2017
Available online 28 February 2017

Keywords:
Ulva prolifera
Green tide
MODIS
Remote sensing
Biomass
Carbon
Nitrogen

ABSTRACT

Since 2008, macroalgal blooms of *Ulva prolifera* (also called green tides) occurred every summer in the Yellow Sea (YS), causing environmental and economic problems. A number of studies have used satellite observations to estimate the severity of the blooms through estimating the bloom size and duration. However, a critical bloom parameter, namely biomass, has never been objectively determined due to lack of measurements. In this study, laboratory experiments were conducted to measure *U. prolifera* biomass (wet weight) per unit area and the corresponding spectral reflectance, through which a robust relationship has been established to link biomass per area to the reflectance-based floating algae index (FAI). The lab-based model has been validated with *in situ* measurements, with an estimated relative uncertainty of <16% for algae with FAI values <0.2 (corresponding to ~2 kg/m^2 biomass and accounting for >99.5% of the algae-containing pixels in satellite images). The model was further transferred to MODIS Rayleigh-corrected reflectance (R_{rc}), where aerosol impacts on the model were simulated under various atmospheric conditions. The simulations showed an average of 6.5% (up to 12.3% for the extreme case) uncertainties in biomass estimates when MODIS R_{rc} data were used as the model inputs. The dry biomass per wet biomass and carbon and nitrogen contents per dry biomass were also determined through lab experiments, thus making their estimation possible from MODIS R_{rc} data. The model was then applied to time-series of MODIS observations over the YS between 2008 and 2015 to determine the inter-annual variability of these critical parameters. Results showed maximum daily biomass of >1.7 million tons during June 2015 and minimum daily biomass of <0.09 million tons during 2012. The ability to estimate *U. prolifera* biomass at given locations from the near real-time MODIS images is expected to significantly enhance the capacity of an existing monitoring system to provide quantitative information for decision making.

1. Introduction

Green tides refer to the abnormal proliferation of floating green macroalgae, which usually occur in the eutrophic waters of bays, lakes, and other coastal waters (Nelson et al., 2003; Charlier et al., 2006; Yabe et al., 2009). In summer 2008, an extensive green tide of *Ulva prolifera* occurred in the Yellow Sea (YS, Fig. 1), especially in coastal waters off Qingdao (China), causing trouble in sailing practice by athletes to prepare for the upcoming Olympic sailing competition. The event caused serious economic losses and environmental problems, and caught national and international attention of news media and scientists (Qingdao News, 2008; Mail Daily, 2008; Hu and He, 2008; Lü and Qiao, 2008; Liang et al., 2008; Liu et al., 2009). Since 2008, similar green tides occurred in the YS every summer. The economic cost for mitigation (beach clean up and algae transportation) and aquaculture losses exceeded 200 million U.S. dollars in 2008 (Wang et al., 2009b; Ye et al., 2011) and 350 million U.S. dollars between 2008 and 2015 (China Marine Disaster Bulletin, 2008–2013). Meanwhile, recurrent green tides caused a series of adverse impacts on the marine environment (Liu et al., 2010; Liu et al., 2013a; Wang et al., 2015), and have been regarded by the Chinese government as another ecological disaster in addition to red tides along China's coasts.

Similar to most other single-species green tides worldwide (Taylor et al., 2001; Nelson et al., 2003), the dominant species of green tides in the YS is *U. prolifera* (Leliaert et al., 2009; Liu et al., 2009; Shen et al., 2012). *U. prolifera* is a seaweed worldwide that can grow rapidly under favorable conditions, leading to extensive blooms (green tides). For the green tides in the YS, satellite remote sensing, ocean circulation models, and field observations all indicate their origin in the Subei Shoal of Jiangsu province (Fig. 1). From the Subei Shoal, although coastal aquaculture ponds have been suggested to be the source of *U. prolifera* (Pang et al., 2010; Liu et al., 2013b), more evidences led to the conclusion that *Porphyra* aquaculture rafts should be the main source of *U. prolifera* (Liu et al., 2009; Hu et al., 2010; Liu et al., 2010; Liu et al., 2013a; Zhang et al., 2014; Wang et al., 2015). The initial *U. prolifera* in

* Corresponding author.
E-mail address: hulb@ouc.edu.cn (L. Hu).

http://dx.doi.org/10.1016/j.rse.2017.01.037

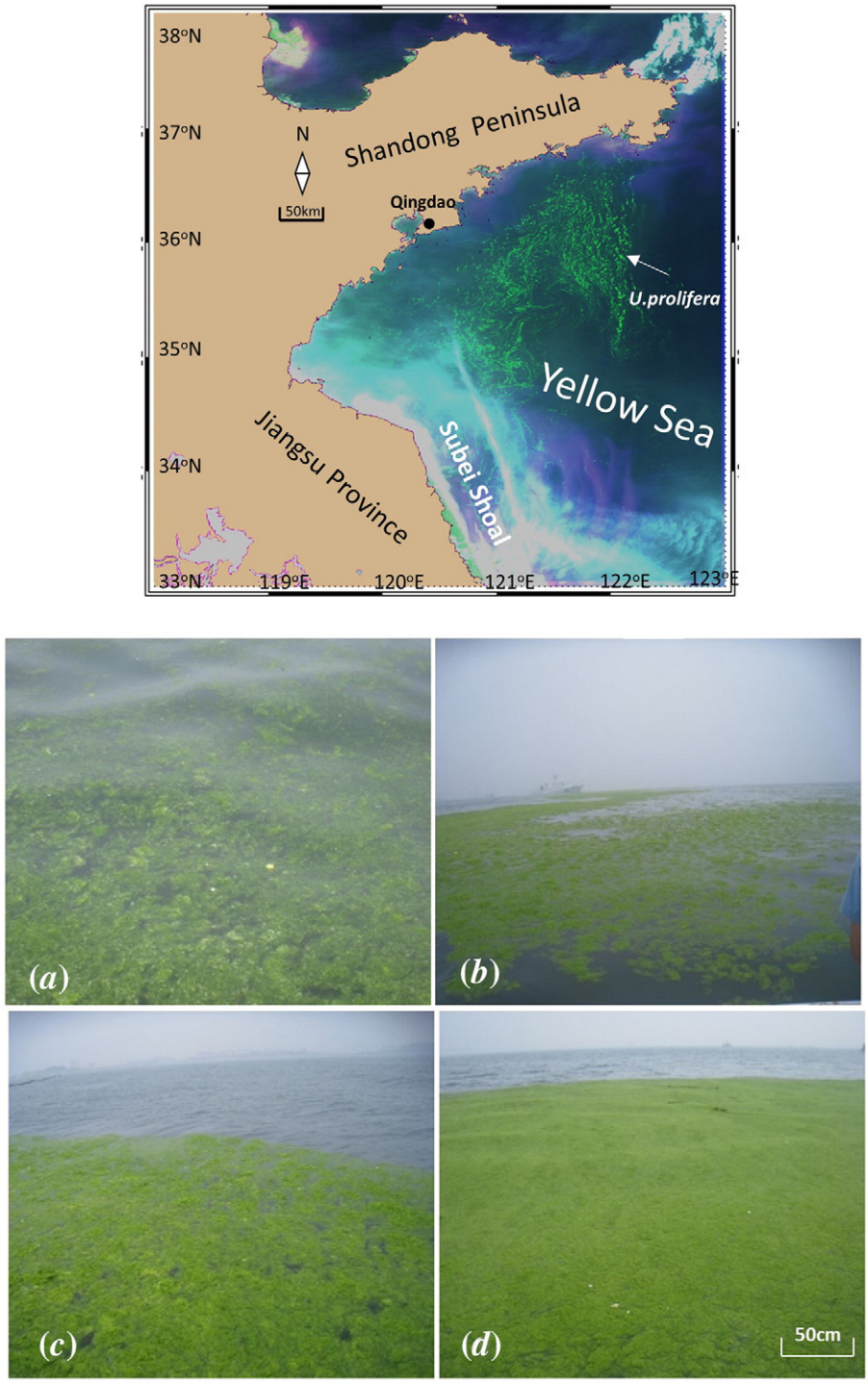

Fig. 1. Top: study region showing the Yellow Sea. The background image is MODIS false color Red-Green-Blue (R:Rrc_645, G: Rrc_859, B:Rrc_469) image on 12 June 2015, which shows the *U. prolifera* algae slicks in greenish colors. Bottom (a–d): digital photos of *U. prolifera* macroalgae floating on the ocean surface taken from boat in coastal waters off Qingdao (black dot in map) during the *in situ* experiment in July 2013.

the Subei Shoal first drifts to the YS following the dominant northward currents, develops into a green tide under favorable sun light and water clarity conditions, and then moves toward the Shandong Peninsula following the southeast monsoon and summer ocean surface currents (Hu et al., 2010; Liu et al., 2010; Keesing et al., 2011; Qiao et al., 2011; Xu et al., 2016).

Among the various methods, satellite remote sensing has been widely used to detect and track green tides in the YS due to it synoptic and frequent coverage. Indeed, the first report of the green tide origin was from analysis of MODIS data, where MODIS normalized difference vegetation index (NDVI) was used to examine image series to track the green tide origin (Hu and He, 2008; Liu et al., 2009). This is because *U. prolifera* is simply a vegetation floating on the sea surface. *U. prolifera* features a hollow tubular body composed of monolayer cells, which release oxygen in the body during photosynthesis. The oxygen increases the algae's buoyancy, making them float on the sea surface (Liang et al., 2008) and form algae mats under the influence of wind and current (Gower et al., 2006; Hu, 2009). Fig. 1a–d show photos of *U. prolifera* with different density floating on the sea surface.