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Validation of MODIS-based monitoring for a green tide in the Yellow Sea with the aid of unmanned aerial vehicle

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Abstract. Previous studies have shown that Terra moderate resolution imaging spectroradiometer (MODIS) has low detection and characterization efficiency when mapping a green tide (*Ulva prolifera*) in the Yellow Sea. To quantify the uncertainty in mapping of the green tide using MODIS data, comparisons were conducted between quasi synchronous MODIS images and *in situ* observation data, as well as an unmanned aerial vehicle (UAV) image. The results show that MODIS images could detect the location of large (>100 m) floating green algae patches with good positional accuracy but tended to ignore the existence of small patches less than 10 m in width. The floating macroalgae area extracted using MODIS was several times larger than the area mapped using the UAV image. The Sentinel-2 multispectral instrument, the Chinese high-resolution GF-1 wide field camera, and the Chinese HJ-1 charge-coupled device are recommended for early green tide detection, whereas MODIS is suitable for green tide monitoring. The UAV could also play an important role in regional green tide monitoring with the advantages of flexibility, smaller dimensions, high spatial resolution, and low cost. © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JRS.11.012007](https://doi.org/10.1117/1.JRS.11.012007)]

Keywords: green tide; MODIS; validation; unmanned aerial vehicle; research vessel.

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1 Introduction

Since 2008, a large-scale green tide disaster has occurred in the Yellow Sea due to the impact of fast-growing macroalgae, especially *Ulva prolifera*.¹ Millions of tons of *Ulva* macroalgae, covering an area of thousands of square kilometers, floated on the sea surface during the recurrent phenomenon.² Noxious odors (NH₃, H₂S) and anoxic conditions caused by algal decay processes result in a considerable reduction of cultured fish and shrimp and even cause marine organism fatalities.^{3,4} In addition, masses of *Ulva* also impact the coastal tourism industry, thus significantly influencing the coastal economy, ecological environment, and aquaculture industry.^{5–9}

Due to the extensive spatial distribution of the green tide, traditional monitoring is inadequate for conducting routine and real-time monitoring. Due to its timeliness, economic efficiency, and ability to survey large areas simultaneously,^{10,11} satellite remote sensing instruments, such as the sea-viewing wide field-of-view sensor, medium resolution imaging spectrometer, moderate resolution imaging spectroradiometer (MODIS), hyperspectral, Landsat multispectral scanner, thematic mapper, and enhanced thematic mapper, have been highly utilized in mapping floating cyanobacterial scum and seagrasses that have the similar characteristics as *Ulva*.^{12–17}

In particular, MODIS images have been widely applied to green tide monitoring due to its availability and temporal resolution (twice a day).¹⁸ Wu et al.¹⁹ extracted the bloom timing and areal coverage of green tides in the Shandong Peninsula from 2008 to 2012 by combining MODIS data with the normalized difference vegetation index (NDVI). A comprehensive comparison determined that the green tide exploded sharply in 2008 and 2009 compared to other

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years.¹⁹ Hu²⁰ proposed the floating algae index (FAI) and monitored the sea area near Qingdao, compared the results with NDVI, and proposed that FAI can help extract green tide information from satellite images. Keesing et al.²¹ and Liu et al.²² extracted the Yellow Sea green tide bloom information from 2007 to 2009 using MODIS data and the scaled algae index classification method with NDVI. They hypothesized that *Porphyra* aquaculture along the North Jiangsu Shoal, where the *Ulva* macroalgae attaching onto the *Porphyra* rafts would be cleaned up after harvest and enter into the sea water, might be the origin of the green tide.^{21,22} However, because of resolution and weather condition restrictions, the precision of the green tide monitoring using MODIS data is low.²⁰ Due to different measurement and comparison methods, scholars have hypothesized different ranges in error for green tide monitoring. Qiao et al.²³ argued that the monitoring error is at the magnitude level, whereas Zhong et al.²⁴ found that the error is ~30% by comparing results extracted using the Chinese HJ-1 charge-coupled device (HJ-1 CCD) with the MODIS monitoring results.

Knowing the positional, areal coverage, and magnitude uncertainties for green tide monitoring using MODIS is a prerequisite for its use to estimate floating macroalgae blooms and to supply a service for the prevention of green tide. Given the variable patch size of a surface bloom (tens of meters to many kilometers), the potential error in using a large spatial sensor (e.g., MODIS with 250 m to 1 km resolution) to quantify the bloom must also be known. Owing to its advantages, such as flexibility, maneuverability, low cost, and high resolution, the unmanned aerial vehicle (UAV) can be used for real-time monitoring in the study area.²⁵ In addition, the oceanographic survey capabilities of the research vessel can perform accurate cross-sectional studies of the green tide growth zones. However, few studies have quantified the MODIS green tide monitoring precision in terms of extent of areal coverage and position. To best accomplish this, accurate areal information and *in-situ* bloom properties are required. Therefore, this study combines an UAV equipped with an imaging system and cruise survey data to characterize the true distribution of the green tide. The objective of this study is to verify the detection efficiency for floating green tide using MODIS data. We compare MODIS monitoring green tide patches with the available field survey data and UAV image to verify whether the floating green tides were in the location detected by MODIS. Then, a green tide in 2016 was dynamically followed with MODIS Terra time series data to demonstrate the MODIS monitoring capability. In addition, the application of multisource data, including aerial imagery, *in-situ* observation data, and satellite images, is discussed.

2 Materials and Methods

2.1 Overview of the Study Area

The study area is in the South Yellow Sea at 32° to 37° north latitude and 119° to 124° east longitude. Within this area are several major coastal cities, including Lianyungang, Qingdao, Rizhao, and Weihai, as well as the North Jiangsu Shoal. As one of the primary green tide-stricken zones,²⁶ this area has seen the wild growth of green tide from May to August every year since 2008, causing losses to local tourism and aquaculture.

2.2 Field Observations

Three cruises employing the research vessel “Ke Xue San Hao,” were conducted on May 17, May 19, and May 24, 2016, in the Yellow Sea. The weather conditions of May 17 and May 19 were both sunny but cloudy on May 24. Algal bloom records, including the locations, spatial extent, and observation times of *Ulva* patches, were collected from 96 stations (Fig. 1). Floating *Ulva* macroalgae were classified into seven magnitudes in accordance with the green tide distribution around each observation station based on the characteristics shown in Table 1.

2.3 Unmanned Aerial Vehicle Images and Processing

DJI Inspire 1 systems were used in the study area. The devices included the Inspire 1 aircraft, two remote controllers (RC), and two mobile devices. A DJI X3(FC350) mounted below the

Fig. 1 Green tide observation stations and the site of the UAV photographed in the Yellow Sea in 2016.

Table 1 Magnitude levels of floating *Ulva* patches.

Levels	Specification of corresponding <i>Ulva</i> algae patches
0	No green algae observed
1	Less than five visible floating green algae patches; the magnitude is less than 1 m × 1 m
2	5 to 10 visible floating green algae patches; the magnitude is less than 5 m × 5 m
3	10 to 20 visible floating green algae patches that have formed a length over 10 m of a drifting macroalgae banded structure
4	Greater than 20 visible floating green algae patches that have formed a length over 20 m of a drifting macroalgae banded structure
5	A floating green algae patch length greater than 500 m
6	A floating green algae patch length greater than 1000 m

quadcopter aircraft was used to capture color (RGB) aerial images. The camera could capture color images with high longitudinal and lateral overlap controlled by RC and the mobile devices. The salvage ship of “Hai Zhuang Yuan,” which was performing the *Ulva* salvage operation, provided a launching platform in the sea. Color aerial images, with a pixel size of 12 cm, were taken vertically above the key *Ulva*-stricken zone at a height of 351 m on May 25, 2016. The aerial photography location is shown in Fig. 1.

The UAV images and the associated georeferencing information provided by the GPS in the UAV were orthorectified and orthomosaiced into one image covering the regional area using a laptop with Pix4Dmapper. Subsequent spatial projection was processed in ArcGIS 10.2 with a reference coordinate system of WGS1984_UTM51N. In general, the RGB value of sea water was above 110 and the Red band was higher than the other two bands due to suspended sediment. By contrast, the RGB value of the green tide was below 100 and the red band was lower than the other two bands. Therefore, a threshold of the red band value was adopted to discriminate green tide using the raster color slices tool of the Environment for Visualizing Images (ENVI) 5.1. Finally, a red band value of 98 was selected to discriminate the green tide in the image, and the result was shown in Fig. 2(d).

2.4 MODIS Data Processing

MODIS Terra Level-1B data with a spatial resolution of 250 m and a geolocation product of MODIS (MOD03), provided by the NASA Ocean Biology Processing Group, were obtained

Fig. 2 Orthophoto using UAV and the distribution of the green tide: (a) composite false color image at the UAV photographed location; (b) *Ulva* patch distribution (green patches) extracted using MODIS and the location of the captured UAV images (black dot represents the location of the UAV photograph and the empty red circle represents the corresponding *Ulva* patch); (c) Orthophoto of *Ulva* patches captured using UAV; and (d) the distribution of *Ulva* patches extracted from the UAV orthophoto.

from the level-1 and atmosphere archive & distribution system distributed active archive center website.²⁷ A total of 46 cloudless or partly cloudy images were screened out for evaluation of MODIS performance in dynamic monitoring of the green tide from May to August in 2016. These images contain the entire growth cycle of the green tide in the Yellow Sea, including germination, development, bloom, and disappearance phases.

The water leaving radiance, where *Ulva* floats, is low at visible wavelengths, whereas it is high at near-infrared wavelengths. According to the spectral characteristics of green tide and seawater at visible to near-infrared wavelengths, the NDVI method can be used to extract green tide information:²⁸

$$\text{NDVI} = \frac{B_2 - B_1}{B_2 + B_1}. \quad (1)$$

Either water leaving radiance or top of the atmosphere (ToA) can be applied to the NDVI calculation, but ToA was adopted in this paper because NDVI could also correct atmospheric and solar/viewing geometry effects to some extent with its normalization algorithm.²⁹ Radiometric calibration and NDVI were computed in batches with ENVI. In detail, B_1 represents ToA at red wavelengths, corresponding to the first channel of MODIS (0.620 to 0.670 μm), and B_2

represents ToA at near-infrared wavelengths, corresponding to the second channel of MODIS (0.841 to 0.876 μm). The spatial resolution of both B_1 and B_2 equals 250 m.

2.5 Mapping the Floating Ulva Patches

Ideally, the NDVI of *Ulva* patches is greater than zero; on the contrary, the NDVI of seawater is lower than zero. Hence, the threshold can be set to zero to discriminate green tide from seawater. However, some factors, e.g., sun glint and clouds, may interfere with the threshold. Therefore, the thresholds in this study were adjusted around zero and determined using the composite false color images. In the false color images, floating algae appeared jade green, while clouds appeared white, and seawater appeared purple or black, as shown in Figs. 2(a) and 3, suggesting a marked difference between the three features. Using this characteristic, we effectively identified and differentiated green tide and nongreen tide water after masking the land areas.

2.6 Comparison Between MODIS Ulva Mapping and Field Observations

The performance of MODIS for monitoring green tide was assessed by superimposing, and then comparing the satellite extracted location and magnitude with the corresponding field observation records, which were collected using the “Ke Xue San Hao” on May 17, May 19, and May 24, 2016. There is a time difference of dozens of minutes to several hours between satellite image collection and station observation. In addition, the green tide drifts spatially creating a mismatch between patches observed at the stations and the same patches in the satellite images. Therefore, buffer processing is adopted for the station observations. That is, we regard the green tide within a radius of each station as the result at the corresponding observation station. Based on the drift

Fig. 3 Superimposition of green tide at the observation points with buffers (numbers above the dots represent the magnitude levels of green tide patches at the field observation sites) on May 19, 2016.

Fig. 4 SSW field of the study area: (a) SSW field on May 19, 2016 and (b) SSW field on May 25, 2016, empty red rectangle represents the location of the UAV photograph.

velocity of the green tide, we evaluated the buffer distance using the observation times and the sea surface wind (SSW) speed. According to previous studies,^{28,30} the buffer radius is defined by Eq. (2):

$$R = 0.023 * w * \Delta t, \quad (2)$$

where R is the buffer radius, w is the speed of the SSW, and Δt is the time lag between the field observation and the satellite image acquired. The SSW were obtained from ERA-Interim datasets³¹ provided by the European Centre for Medium-Range Weather Forecasts. A case on May 19, 2016 is shown in Fig. 3, and the corresponding SSW is shown in Fig. 4(a).

3 Results and Discussion

3.1 Cruise-Based Verification of MODIS Green Tide Monitoring

A comparison between cruise observation data and intraday MODIS image interpretation (Table 2) shows that the monitoring (MODIS position relative to buffer position) of the green tide patch locations rose as the size of the patches increased. Except for the satellite image generated on May 24, which was affected by weather conditions, the *Ulva* monitoring ability for magnitude 1 bloom class (<1 m) was very low. Similarly, for cases with a magnitude 2 (<5 m) on May 17, May 19, and May 24, the detection efficiency was 33.33%, 50%, and 0%, respectively, which were higher than magnitude 1, but too low to utilize in a monitoring

Table 2 Precision of the monitored green tide using MODIS.

Levels	May 17		May 19		May 24	
	Precision (%)	Stations	Precision (%)	Stations	Precision (%)	Stations
0	100	5	100.00	9	50.00	4
1	21.43	14	0	9	0	4
2	33.33	3	50.00	4	0	6
3	80.00	5	100	3	10.00	10
4	100	5	100	2	25.00	12
5	—	—	—	—	100	1

application. However, the *Ulva* patches, whose sizes were tens of meters or longer (above magnitude 3), had high patch detection and discernment. Furthermore, the performance of the monitored green tide using MODIS was limited by weather conditions. Due to clouds and fog, the May 24 results showed that MODIS monitoring achieved a <25% detection capability. Bad weather will reduce detection capability due to the influence on energy radiation.³²

Previous work has documented that the spatial resolution of a satellite image is the primary limiting factor for detecting floating algae.²⁰ With the resolution of 250 m, the area of MODIS-derived *Ulva* patches was overestimated by an order of two times.²⁸ By contrast, the compared areal extent varied by an order of magnitude indicating that MODIS images would underestimate the distribution of floating *Ulva* blooms. As shown in Table 1, the detection performance for small patches was low, while it was up to 100% for the station sites with no green algae patches. Therefore, the MODIS images tended to ignore the existence of small *Ulva* patches. One explanation could be that the information of the corresponding pixel in the MODIS image was primarily composed of the surrounding seawater if the *Ulva* patches were small, especially <10 m in length. Hu et al.²⁶ have also suggested that an algae slick <5 m in width cannot be detected using 250 m MODIS FAI imagery. Similarly, Kutser³³ indicated that the Hyperion (hyperspectral sensor) image with a spatial resolution of 30 m is not sufficient to detect narrow stripes of floating cyanobacterial scum, which appears extremely patchy and has the similar characteristics as *Ulva* when multispectral sensors are used.

3.2 Unmanned Aerial Vehicles-Based Verification of MODIS Green Tide Monitoring

As shown in Fig. 2(a), *Ulva* patches extracted using UAV, and MODIS images have a separation distance of ~700 m. Images using UAV were photographed at UTC 4:09 on May 25, whereas the interpreted MODIS image was obtained at UTC 2:40 on May 25. Considering the continuous mobility of floating *Ulva* derived by the wind field,²⁸ spatial mismatching was expected. In addition, as per the SSW data shown in Fig. 4(b) and Eq. (1), the UAV-derived patches correspond to the patch derived by MODIS in the red circle [Fig. 2(a)].

The UAV provided for the most accurate location and highest spatial resolution of patch size. The UAV derived patches shown in Fig. 2(c) covered an area of 0.06 km², with a distribution density of 46.88%. However, the area of the corresponding patch in the red circle (satellite derived) was 0.375 km², which was 6.25 times that of the UAV-derived image. Analysis of other areas for the same *Ulva* patch indicated that the MODIS image had an abundance of mixed pixels consisting of seawater and floating algae information. In general, as shown in Figs. 2(b) and 5, the distributions of floating green algae patches were primarily branched and strip-shaped before beached, which was caused by the Langmuir circulation.^{34,35} Nevertheless, the MODIS-derived image depicted the patch distributions with grids of 250 m in width. Thus, the MODIS-derived area would overestimate the actual distribution area by several times. This could also explain why some studies showed that a difference in spatial resolutions could lead to a discrepancy of green algae bloom detection.^{24,28}

3.3 Monitoring Green Tide Using Multi-Source Data in the Yellow Sea

The performance results above indicated that the MODIS images will tend to underestimate the existence of small algae patches but overestimate the area of floating *Ulva* blooms. However, we can conclude that MODIS images are very suitable for green tide monitoring because of its large coverage and high temporal resolution and the blooms, generally large patch size. Determining the location and area of floating *Ulva* blooms is important for creating management plans.²⁰ The MODIS images can provide timely information on the location and area of green tide twice a day with coverage over the entire Yellow Sea, especially when floating biomass increased rapidly after mid-May.¹ Furthermore, floating macroalgae blooms in the Yellow Sea can be traced back to 1999,³⁶ the year MODIS Terra was launched. Hence, MODIS data can provide a long time series of information for macroalgae blooms, which could help to understand the occurrence mechanisms and influence factors as well as creating management plans.

Fig. 5 UAV images of green tide at different locations: (a) UAV image taken above the waters near Jiangsu Shoal on May 25, 2016, and (b) UAV image taken along the coastline of Haiyang on July 6, 2016.

In order to demonstrate the MODIS monitoring capability, the green tide in 2016 was dynamically followed with MODIS Terra time series data. The northern boundaries of the event are shown in Fig. 6. The figures show that the floating blooms moved parallel to the coastline from Jiangsu Shoal, which first moved north, then northeast, and finally arrived at Rushan and Rongcheng via Qingdao. *Ulva* patches remained stable around Rizhao, Qingdao, Rushan, etc., due to the landforms of the Shandong Peninsula and the resistance from ocean currents. During this period, large-scale blooms accumulated on the shore and caused great losses to local tourism and the aquaculture industry. The results are consistent with previous studies.^{37,38}

Figure 7 further shows that the tongue-shaped front edge of the floating *Ulva* blooms observed on June 1 morphed into a banded shape, as seen from Lianyungang to Qingdao on June 16. An explanation of the rapid increase in green tide may be the changes of light and temperature.³⁹ The green tide was primarily distributed in muddy water before June 1,

Fig. 6 The trend of the green tide northern boundaries in the Yellow Sea.

Fig. 7 The distribution of the green tide on June 1 and June 16.

where it grew slowly due to the sunlight restrictions. Subsequently, the green tide drifted to clear water due to wind action and ocean currents and achieved explosive growth under favorable conditions, where the seawater temperature rose and light intensity increased.^{40,41} During this period, the daily growth rate of *Ulva* macroalgae can reach 10% to 37% under proper conditions.⁴²

However, the satellite images with higher resolution and appropriate temporal resolution are still required to obtain detailed information of the green tide for decision making. Cui et al.²⁸ suggested that HJ-1 CCD data is one of the most suitable data types for early detection and warning of green tide disaster, with a 30-m spatial resolution, 2 days for the revisiting period, and a 700-km swath width. Furthermore, GF-1 WFM data can be another appropriate choice for early detection, which has been used in green tide monitoring.⁴³ It has a 2-day revisit period, 16-m spatial resolution, and 800-km swath width. Moreover, the Sentinel-2A multispectral instrument (MSI) is the Landsat-like spatial resolution (10 to 60 m) superspectral instrument of the European Space Agency,⁴⁴ which has been proven useful for cyanobacterial scum detection.⁴⁵ The Sentinel-2A MSI image includes 13 bands covering the visible and near infrared and shortwave infrared wavelength region. Specifically, 10-m resolution with multispectral bands and three 20-m resolution bands in the red-edge spectral domain, which is one of the best remote sensing-based descriptors of chlorophyll content, provide potential for green tide monitoring.^{46,47} Sentinel-2B, the second of the two-satellite Sentinel-2 mission, will be launched in 2017, and the revisit time will decrease to 2 or 3 days in China (5 days at the equator). Hence, Sentinel-2 MSI and GF-1 WFM, as well as HJ-1 CCD, are recommended as the preferred satellite data for early observation and monitoring of the green tide in the Yellow Sea. With the multiple coverage capabilities, and with various spatial resolutions, the integration and fusion of data and detection probabilities can potentially greatly enhance our monitoring abilities over MODIS.

Continuous, real-time and high-precision acquisition of floating *Ulva* patches is very important for coping with the massive bloom. However, as indicated, few satellites in operation can meet the monitoring requirements. By contrast, UAVs have advantages, including flexibility, smaller dimensions, high spatial resolution, and low cost. With these advantages, the UAV can be the best tool for monitoring the green tide patches, especially at a regional scale.^{48,49} Specifically, the UAV was successfully used on the salvage ship during the *Ulva* bloom disaster in 2016. As shown in Fig. 8, the UAV could be highly utilized in optimizing the salvage operation route and assessing salvage operations.

Fig. 8 UAV images for regional green tide monitoring: (a) UAV image used to optimize the salvage operation route and (b) UAV image used to assess the salvage operation.

4 Conclusions

For verifying the detection efficiency for green tide monitoring using MODIS, a comparison of MODIS green tide monitoring results with *in situ* observation data and UAV images was performed. The results showed that MODIS images could accurately detect the location of floating green algae patches but with higher uncertainty in size and cohesiveness when the patches were <10 m in width. For the low spatial resolution and banded structure of drifting macroalgae, mixed pixels were prevalent in the MODIS images, which resulted in an overestimation of the distribution area by several folds. However, MODIS images were very suitable for green tide monitoring due to their high temporal resolution, long time series, and large coverage area. In addition, Sentinel-2 MSI, GF-1 WFV, and HJ-1 CCD may provide and even greater early green tide detection capability due to their high spatiotemporal resolution and broad swath width. In addition, the UAV could play an important role in monitoring regional green tides with the advantages of flexibility, smaller dimensions, high spatial resolution, and low cost. Therefore, comprehensive utilization of multisource data, including MODIS, Sentinel-2, GF-1 WFV, HJ-1 CCD, UAV and cruise survey data, would provide high precision information for green tide detection, forecast, and management.

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